Sleep, Circadian Behaviour, Physical Activity, Social Networks and Psychological Health: Factors Helping to Preserve Healthy Memory Performance in Normal Ageing

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The work in this thesis is based on research carried out at the Department of Psychology, University of Durham, England, UK. No part of this thesis has been submitted elsewhere for any other degree or qualification and it is all my own work unless referenced to the contrary in the text.

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Abstract

Introduction: Although dementia today blights the lives of nearly 1 million people in the UK, the majority of older people will never have to live with it; but they are likely nevertheless to suffer the unwelcome loss of memory function that accompanies normal ageing. Maximising the cognitive health span of an ageing population is critically important to the efficient use of increasingly limited public health resources. In examining those factors that may preserve healthy memory performance in normal ageing, this study is not directly concerned with developing strategies to prevent or forestall dementia. However, it is likely that any memory-protective factors which help to preserve good cognitive health in normal ageing may well extend also to clinical-level memory impairment.

Methods: A large sample of cognitively normal subjects (N=145, M=55 years) underwent two separate phases of neuropsychological testing in different memory domains, including a new two-week delayed recall test of verbal episodic memory. Actigraphy was used to measure subjects' sleep, Circadian behaviour patterns and physical activity levels over two weeks. In addition, subjects completed a range of psychological health and other questionnaires, including the Pittsburgh Sleep Questionnaire (PSQ). Factor analysis was used to reduce tested memory domains into four discrete domains: (1) short-term verbal episodic memory (2) long-term forgetting in verbal episodic memory (3) face memory and perception and (4) working memory. The same factor analysis process was used to reduce psychological health measures into three main constructs; (1) social experience (positive and negative), (2) social confidence and fearfulness, and (3) social connectedness. Comparison groups were established for age (younger, M=36 years, older, M=66 years), sleep quality (PSQ good and poor sleepers), and Circadian behaviour (owls and larks).

Results: Younger subjects outperformed older subjects in all memory domains *except* long-term forgetting (p=.16). Good sleepers outperformed poor sleepers in long-term forgetting (p=.0001), but not in any other memory domain. Older subjects had lower levels of Circadian dysfunctional behaviours, such as Sleep Debt and Social Jet Lag, than younger persons (p=.002 and p<.0001 respectively). However, neither Sleep Debt nor Social Jet Lag had any bearing on

sleep quality (or on long term memory consolidation) and they did not differ between owls and larks (p=.18 and p=.67 respectively). Owls though tended to have larger social networks than larks (p=.007). Being more active (and less sedentary) protected working memory, and the levels of beneficial activity were different for older subjects (more light to moderate activity) than they were for younger subjects (more sustained and vigorous activity). Older subjects had better psychological health than younger subjects (p<.0001) but had no difference in social networks (p=.9). Poor sleepers had lower psychological mood than good sleepers (p=.001) but did not differ in sociability. Importantly, better psychological mood contributes to better long-term forgetting alongside good sleep.

Discussion: This study revealed a number of new findings that are important to the preservation of healthy memory performance in normal ageing. First, the double dissociation between age groups and good/poor sleep quality groups in long-term forgetting provides good evidence for the benefit of sleep to long-term memory consolidation, regardless of age. Second, while Sleep Debt and Social Jet Lag are dysfunctional behaviours, they are not necessarily embedded within ordinary chronotype differences between owls and larks, and they appear to have no relationship to sleep quality. As such, they have no overt bearing on long-term forgetting or sleep-based memory consolidation. Third, good and poor sleepers differ extensively in measures of psychological mood but do not differ in sociability, even though many of the measures of psychological mood and sociability are themselves strongly correlated. For example, poor sleepers are lonelier than good sleepers but do not have smaller social networks, although higher loneliness is strongly correlated with having smaller social networks. Also, being an owl appears to confer advantages in terms of size of friendship networks. Most importantly, good sleep *and* better psychological mood together predict better (lower) long-term forgetting. Finally, it is not necessary for physical activity in older age to be at similar intensity levels to that achieved by younger persons in order to secure comparable benefits to working memory. It is clear from these results that older subjects find it easier to maintain lighter levels of physical activity with increasing age, and the cognitive benefits of doing so are not to be under-estimated.

CHAPTER 1: GENERAL BACKGROUND and INTRODUCTION

1.1. Background to this Project

1.1.1. Introduction to the Present Study

Research into cognitive ageing tends to fall into one of three broad areas. First, there are those studies that show the (generally negative) effects of ageing on certain cognitive domains; see, e.g., Foster, 2007; Gazzaley, 2005; Grady& Craik, 2000; Hayes, 2016. Second, there are those studies that demonstrate (again, generally negative) effects of ageing on specific functions, such as, for example, sleep, Circadian behaviour, physical activity or psychological health, and how these factors may be associated with age-related cognitive decline; see, e.g., Blackwell, 2006; Bherer, 2013; Laurin, 2001; Mohlenhoff, 2018; Nebes, 2009; Scullin, 2019. Third, there are those studies that seek to differentiate between the effects of 'normal ageing' and impairment in certain cognitive domains and functions; this often involves comparisons between 'healthy control' (HC) subjects and impaired subjects; see, e.g., Estevez-Gonzalez, 2003; Friedland, 2001; Spieler, 1996; Sliwinski & Buschke, 1997. The aim of the present study is to cross between the boundaries of these broad categories and, whilst accepting that ageing does inevitably have some bearing on cognitive performance and specific functions, to explore the relationship between these functions and cognition in order to identify specific factors which may help to preserve healthy cognitive ageing.

In this project, a wide range of factors are examined, including sleep, Circadian behaviour, physical activity and psychological health, together with a detailed analysis of how these different factors affect multiple cognitive and memory domains. The study is underpinned by extensive community-sample testing and data collection, using face-to-face cognitive testing over an extended two week period, self-report of multiple factors through use of questionnaires, and in-depth actigraphy assessment of sleep, Circadian behaviour and physical activity data collected continuously for two weeks.

The approach taken to reporting the findings of this multi-factorial project is to start with an examination of normal age-related performance in the examined memory domains before overlaying the influence on performance of the various factors examined in detail in each of the main chapters. Accordingly, this Chapter 1 explains in more detail the background to the research before Chapter 2 describes over-arching methodology, the numerous cognitive tests used, and how these have been compressed into four main domains. Chapter 2 will also report

descriptive statistics, together with basic age-related results for each of the four cognitive domains. The remaining four chapters (Chapters 3-6) will then systematically examine separately how each of four specific areas may overlay the basic age-related findings and may contribute to or detract from performance in the four main cognitive domains. The four specific areas are Sleep, Circadian behaviour, Physical Activity and Psychological Health. Whilst the approach is to examine these areas separately, the relationship between them will build a layered analysis of their respective contributions to the preservation of healthy cognitive ageing. For example, it will be seen in Chapter 3 that 'good sleep' may help to reduce long-term forgetting and therefore improve long-term memory consolidation; Chapter 4 will then examine certain Circadian dysfunctional behaviours (i.e., aspects of poor sleep timing) and will analyse whether these too may be a factor influencing sleep quality and thereby contributing to performance in long-term forgetting or any of the other measured cognitive domains. Factors independently helping to predict different memory domain performance will therefore be added cumulatively, chapter by chapter. Finally, in Chapter 7 (Conclusions), the different layers of contributory factors in each measured domain will be summarised in a 'best model' for those factors that appear to promote longevity of performance in the different memory domains. As Chapter 7 shows, there is only one domain, Face Memory & Perception, where age is the sole factor in predicting performance. In the other measured domains, different factors will contribute alongside age to better performance, and in one notable case, replace age altogether. In this way, potential areas will be identified where specific interventions may afford protective benefits to cognitive ageing.

There are several reasons why the present study is important. **First**, and perhaps self-evidently, prolonging healthy cognitive ageing is beneficial at the individual level. Not only is cognitive impairment a feared condition (Bystad, 2016) but older persons may be liable to misinterpret small lapses of memory or functioning as the first step on a slippery slope of inevitable and debilitating cognitive decline; this can occasion anxiety and distress, perhaps even precipitating changes such as deterioration in sleep, social confidence and psychological health which may then in turn make unwelcome contributions to cognitive functioning. Highlighting the normal effects of ageing on cognitive performance across multiple domains (Chapter 2) therefore helps to raise awareness of the extent to which some age-related decline is normal and inevitable. The present study is specifically *not* concerned with cognitive impairment or determining where the category boundaries may lie between normal ageing and impaired functioning. However, many of the cognitive tests used, and most of the specific areas examined (e.g., sleep

and physical activity), have been previously shown to be different between healthy subjects and subjects who are clinically impaired. In the interests of clarity, the following detailed Chapters will also explain how those cognitive tests and specific functions have been found to be affected by, or associated with, cognitive impairment. This analysis is not to suggest that determining impairment-level performance by individuals in either cognition or factors such as sleep and physical activity plays any major role in this study; all subjects at the time of testing were healthy and cognitively normal; it is merely to place 'normal ageing' into the full context of what has previously been shown concerning these various tests and functions.

Second, the present study is important because encouragement of healthy cognitive ageing is beneficial at the societal level. In an ageing population, with increasing pressure on healthcare costs and resources, including in particular funding of social care, the prevention of cognitive decline and reducing levels of dependency in older age may lead to significant cost savings. Put simply, if more older people are able to take specific actions or undergo targeted interventions that can ameliorate cognitive functioning into later life, i.e., to build resilience; this will potentially secure major advantages for public finances. In particular, it is possible that small changes in behaviour in areas such as sleep and Circadian behaviour may occasion large benefits in cognitive performance and the results described in this study suggest very strongly that this may indeed be the case.

Finally, although the major focus of this study has been on the factors helping to preserve healthy cognitive ageing, taking action to improve cognition later in life is not a matter that can simply or safely be deferred until middle age or later. For the most part, this study has reported results where age is a continuous variable in order to show most clearly the relationship (if any) between age and (e.g.) performance in different memory domains, as well as, for example, development of patterns in sleep and physical activity. However, in addition, comparisons have been made between younger and older age groups in certain key domains and attributes. The purpose here is to focus on how younger and older subjects may or *may not* differ in relation to certain factors; this in turn may highlight how younger persons may also take specific actions at an earlier point in life which may be similarly beneficial to those suggested in this study for healthy older subjects. For example, it seems clear from the results that being a 'good sleeper' reduces long term forgetting for both younger and older subjects alike; it may even be easier for younger subjects, earlier in life, to change their sleep behaviours so that they have a lasting, positive bearing on sleep quality. In addition, some findings in the present, such as the tendency for disproportionate Circadian dysfunctional behaviour in younger subjects indicate how these

behaviours may develop across the lifespan, albeit that this study is cross-sectional only. Such findings make an important additional contribution to those studies that have pinpointed specific risks between deleterious sleep and Circadian behaviours in younger people and (e.g) work-related performance (McClelland, 2017; O'Connor, 2019), behaviours such as driving (Lucidi 2006, Scott, 2007), and outcomes such as stress (Verlander, 1999), vigilance (Perrault, 2019) and psychological mood (Oginska & Pokorski, 2006). In short, some of the findings in the present study transcend studies of cognitive ageing and will help to inform other studies in areas such as sleep, Circadian behaviour, physical activity and pschological health more generally.

1.1.2. Purpose of the Project: Identifying Factors Helping to Preserve Healthy Memory Performance in Normal Ageing

The purpose of this project was to examine the factors which help to preserve performance across different memory domains in older persons and it was approved by the Psychology Department Ethics Sub-Committee of Durham University on 17 December 2018, subject to conditions and changes made in early 2019. As explained above, although the project was not directly concerned with dementia or cognitive impairment, its central aim of examining healthy cognitive performance in normal ageing complements dementia research generally, as well as specific Durham University initiatives such as Detecting Dementia Earlier and Durham Against Dementia.

Subjects were cognitively-healthy adults, mainly recruited in the North of England. The initial aim was to test a minimum of 200 subjects, with broadly equal numbers in younger and older groups. However, this aim was severely curtailed by the restrictions imposed from March 2020 on face to face subject testing (particularly of older, more vulnerable community-living persons) as a result of the COVID 19 pandemic. Face to face testing for periods of an hour or more was still not permitted by the time the project had been running for three years (1 October 2021) and no external testing could be resumed in time to increase subject numbers before the scheduled end date of the project (31 March 2022). In the event, 145 subjects completed all testing phases by March 2020, the majority of whom (N=93) were aged 50 or above at the time of testing. This shortfall in anticipated subject numbers placed a substantial practical limitation on the project, but was not an insurmountable drawback.

1.1.3. Relevance and Aims of the Project: What are the Factors that may Positively Influence Normal Age-related Cognitive Decline?

As lifespan extends, a major focus of ageing research is increasingly on improving health-span; increasing longevity is not so appealing if any extra years are merely characterised by poor health (Armstrong, 2019). Central to this aim of improving health-span is the prolongation of healthy cognitive ageing (see, e.g., Harada, 2013). Ageing inevitably brings with it some physical limitations, and sometimes, a decline in general health. It is important to understand, for example, whether relatively small changes to physical activity or sleep behaviour can make a positive difference to prolonged good health and specifically to healthy cognitive functioning.

In the public perception, normal age-related cognitive decline may be conflated with incipient dementia; it is hard to know what to expect from normal ageing and any perceived reduction in cognition can be met with alarm. Along with cardiovascular disease and stroke, dementia is one of the most feared diseases of ageing (Bystad, 2016) and this fear is not misplaced; increasing age is the most significant risk factor for Alzheimer's dementia (AD) and does not diminish or level out with older age (Kawas & Katzman, 1999). Good memory is important because it defines who we are and have been as human beings. Despite this widespread fear of dementia, and even though its incidence continues to rise in the UK and globally (Livingston, 2017: Green & Zhang, 2016), the majority of older persons will, fortunately, never acquire the disease. On the other hand, normal age-related cognitive decline, a gradual failing of memory and cognitive processes, will affect many more older persons than who suffer from dementia. Like general health, everyone would like to hold onto good mental health for as long as possible. Examining those factors that may *positively influence* normal age-related cognitive decline is the main aim of this study.

Examining normal age-related cognitive decline necessarily involves some consideration of, and comparison with, abnormal cognitive decline. Sometimes, the borders between the two can be hard to discern. As explained later, any normal, cognitively-healthy sample may include a sizeable minority of persons with pre-clinical or undiagnosed impairment (Sliwinski, 1996). Distinguishing such undiagnosed impairment from early-stage AD has been described as 'an impossible task' (Elias, 2000 at page 812) and the same difficulty applies to the distinction between milder, abnormal functioning and normal age-related decline. This blurring of the lines is a major obstacle to the early, pre-clinical detection and treatment of dementia; i.e., once it is detected and differentiated from normal age-related decline, it may already be developed to an extent that is beyond any effective current treatment. It is also a reason why understanding

what is, and what is not, characteristically "normal" age-related cognitive and memory functioning is so important. As will be seen, there are some memory domains (such as memory for unfamiliar faces) where age-related decline may be strongly discernible and inevitable, but such decline may not presage any wider cognitive impairment, and may not be as responsive as other domains to (say) physical activity or sleep interventions. Some age-related decline may be unpreventable but essentially normal and relatively harmless. Identifying this normal decline is arguably as important as early detection of clinical impairment; being able to delineate the difference with greater speed and precision is critical in the context of an ageing population and under-resourced, over-burdened health resources (Waldemar, 2007).

Accordingly, preserving the cognitive health-span of the majority, normally ageing population is, or should be, a key public health concern. In short, it is necessary both to identify those at risk of cognitive impairment *and* to raise everyone to the highest possible level of cognitive functioning, in order to conserve limited health resources and target them most effectively. Given the levels of fear surrounding dementia onset, it is also critical for the psychological health of all older persons to clarify the differences between normal and abnormal cognitive ageing, particularly in the area of memory performance. It is neither healthy nor helpful to depleted and under-pressure health resources, for an older person to interpret every minor lapse of memory, or small failure of judgment, as the feared onset of irreversible clinical cognitive decline. An ageing population needs, and wants, to know what they can do to maximise their cognitive health-span and preserve their memory into older age. They need therefore to understand the difference between those memory changes that are inevitable and those where small lifestyle changes may make important, positive differences. This is even more important in the aftermath of a global pandemic which has left health services struggling to meet current demands alongside serious backlogs; older persons must now take on more personal responsibility for safeguarding and prolonging their own good health.

There is already much research on the effects of normal ageing on cognitive function (see, e.g. Harada, 2013; Holliday, 2004; Salthouse, 2010) and on those protective measures, such as physical activity and sleep, that may attenuate decline in, or even improve, cognitive performance. However, there are also many unanswered questions about what is normal age-related performance in particular memory domains, and whether, and if so how, any decline can be arrested or reversed from a practical perspective. For example, does keeping physically active help to improve *all* cognitive domains or does it have a more selective effect and just help certain types of memory performance? Is it necessary to exercise as strenuously in later

life and what level of physical activity might bring about improvements? How does sleep affect memory in normal ageing and are there practical steps that can be taken to improve memory functioning? Do the well-reported benefits to cognition afforded by wider social networks depend upon attributes or behaviours (such as, say, joining activity friendship groups) that can be changed or developed? This project aims to cast some light on fundamental questions such as these.

1.2. Normal Cognitive Ageing

1.2.1. Some Neurobiological Changes in Normal Ageing are Natural and Inevitable

If it is accepted that the brain has not evolved to last any longer than any of the body's other vital organs, cognitive decline in normal ageing may simply be seen as one facet of the whole body's decline in the normal ageing process (Holliday, 2004; López-Otín, 2013). Bodily ageing involves molecular and cellular changes which may be primary causes of ageing, such as genetic or DNA breakdown, or secondary accompanying causes, such as faulty cellular repair systems, which may accelerate or exacerbate the primary causes (Armstrong, 2019; López-Otín, 2013). These ordinary age-related changes may be viewed as both natural and inevitable.

In cognitive ageing, the changes at cellular or molecular level are manifested in structural and functional changes in brain biology (Sowell, 2003; Andrews-Hanna, 2007). For example, in normal ageing, there may be changes in the size of certain brain structures, changes in brain functional performance, or connectivity between different brain regions, changes in gene expression and/or changes in accumulation of agents or toxins (Raz, 1998; Hedden & Gabrieli, 2004; Berchtold, 2013; DuPre & Spreng, 2017; Erraji-Benchekroun, 2005; Dickstein, 2007; Kann, 2014; Siman-Tov, 2017). These normal age-related changes, which of themselves do not suggest any underlying pathology (Panagiotou, 2021) may however be accentuated or accelerated in abnormal cognitive decline, for example, as in the runaway accumulation of amyloid beta and tau proteins in AD, (Buckner, 2005; Hedden, 2009; Sheline, 2010; Morris, 2010; Risacher, 2015; Hong, 2010).

1.2.2. Brain Structure Changes in Normal Ageing include Reductions in Size and Complexity of Certain Brain Regions and Connections

Normal ageing is associated with brain volume shrinkage, by as much as 5% every decade (Svennerholm, 1997; Resnick, 2003) and general cortical thinning (Fjell, 2009). Grey matter volume in the brain generally decreases relatively steadily from as early as age 20, especially

in prefrontal cortex (PFC) (Terry & Katzman, 2001; Fotenos, 2008; Bondareff, 1982) in contrast with white matter which declines more rapidly with increasing age (Salat, 1999, 2009; Rogalski, 2012; Vinke, 2018). White matter volume, which is important to functional connectivity between brain regions, has been shown to decline substantially in the PFC and corpus callosum (Hedden & Gabrieli, 2004; Bartzokis, 2003) and it has been shown that the preservation of white matter mediates age-related cognitive performance (Madden, 2009). The hippocampus, an area of the brain critical to memory, is also highly susceptible to age-related decrease in volume (Morrison & Hof, 1997; 2007; Fotuhi, 2012), but there may be minimal change in adjacent and related brain areas, such as entorhinal cortex, in normal ageing (Raz, 2004; Rodrigue & Raz, 2004; Jack, 1998), although entorhinal cortex has been seen to decrease in AD (Braak & Braak, 1996).

Changes in age-related brain structure complexity include reduced dendritic arborisation and synaptic density decreases (Dickstein, 2007). Extrapolating such rates of decline, it has been estimated that, by age 130, a cognitively normal person would have the same synaptic density as an AD patient (Terry & Katzman, 2001). It follows therefore that if age-related brain structure decline is inevitable, there will be a practical limit to any normal cognitive health-span. Cognitive impairment such as dementia may be a qualitatively different process to normal cognitive ageing, or alternatively, it may perhaps represent this same natural age-related brain deterioration process, but very substantially accelerated.

1.2.3. There is Evidence of Differential Brain Function Changes in Normal Ageing

Unsurprisingly, brain function changes accompany these brain structural changes in normal ageing. For example, it has been shown that age-related decline in frontal lobe functionality occurs in the dorsolateral PFC, although functionality in the ventromedial PFC is relatively spared (MacPherson, 2002). Older adults have also been seen to have decreased 'default mode network' activity (Moran, 2012). In broad terms, the default mode network (or DMN, Raichle, 2001) means those brain areas that are still active when other regions are not engaged (put very simply, the brain regions that are most active when the subject is instructed to 'think of nothing'). Previous research suggests that DMN activity is principally directed at self-referential social cognition (Molnar-Szakacs & Uddin, 2013; Poerio, 2017; Gottlich, 2017) and the decreased DMN activity in older adults has been accompanied by less accurate performance (than younger adults) in social-cognitive tasks (Moran, 2012). It has been suggested that these

resting state cognitive processing networks may decline faster in normal ageing than other networks, such as for example, emotion-processing networks (Nashiro, 2017).

1.2.4. Changes in 'Between Network' Connectivity is a Characteristic of Brain Network Connectivity in Normal Ageing

As well as changes in brain structure and function, normal ageing brings about changes in brain network connectivity. Older adults may show higher 'between network' connectivity whereas younger adults may show higher 'within network' connectivity (Grady, 2016; Li, 2015), or perhaps putting it a little simplistically, older people tend to 'go wide' whereas younger people tend to 'go deep'. This has been reported to be the case both at rest, and when undertaking a task that requires performance across different brain regions (Grady, 2016). There is also lower flexible brain network interaction in older persons (Avelar-Pereira, 2017) and, seemingly despite the preference of older persons for between-network connectivity, the co-occurrence of activity in brain regions, including the default network, (still) tends to decrease with age (Andrews-Hanna, 2007; Spreng & Andrews-Hanna, 2015; Damoiseaux, 2008; 2017). In some cases, it has been found that an older person may recruit entirely different brain regions altogether from those recruited by a younger person when undertaking the same task, or when switching from a resting state to a goal-directed task (Avelar-Pereira, 2017).

This declining activity in certain brain networks may be accompanied by the biological markers of AD pathology, such as amyloid beta accumulation (Buckner, 2005; Hedden, 2009; Sheline, 2010). Beta-amyloid protein accumulation may contribute to grey matter loss in normal ageing (Harada, 2013). However, this same beta-amyloid accumulation is also found in the cortex of approximately 20-30% of cognitively normal adults (Rodrigue, 2009; Dickson, 1992; Pike, 2008; Sperling, 2009). For this reason, it has been argued that the build-up of intracellular tau protein may be a stronger biological predictor of AD than amyloid beta (Morris, 2010; Risacher, 2015; Hong, 2010) and possibly, as a result, a more reliable brain-change differentiator between incipient AD and normal ageing.

1.2.5. Brain Molecular Changes and Risk of Cognitive Decline has been Associated with Particular Gene Variations

A particular gene variation, APOE e4, has also been strongly associated with increased risk of dementia (Corder, 1993; Petersen, 1995; Lemaître, 2005; Genin, 2011; Hashimoto, 2012; El Haj, 2016). However, in one study it was found that the APOE e4 variant, older age and cognitive status were all associated with increased amyloid beta binding in brain regions in

persons *without* dementia, i.e. in normal ageing (Small, 2009). It has been suggested that APOE genetic variation status may act as a 'precipitator' for beta-amyloid deposition, so that a deterioration process, that otherwise occurs slowly in normal cognitive ageing, when subject to the particular variant allele, accelerates uncontrollably (Small, 2009; Sheline, 2010). The impact of APOE e4 status therefore leads to an expectation, rather than an inevitability, of faster memory decline with increasing age (Rawle, 2018).

1.2.6. Widespread Brain Changes in Older Age are Reflected in Specific Cognitive Changes in Normal Ageing

These biological and brain changes in normal ageing are manifested in clearly observable cognitive changes. For example, older adults are slower to learn, and perform less well on tasks involving working memory, attention and executive function (Grady & Craik, 2000; Jonides, 2000; Reuter-Lorenz, 2000; Foster, 2007; Reuter-Lorenz & Cappell, 2008; Park & Reuter-Lorenz, 2009). However, within this generalisation, there is substantial variation, with some areas of cognitive functioning and memory being much more resilient than others. As described further below, some brain structures and functions, and the cognitive or memory functions that they support, may be more susceptible to improvement by natural measures, such as physical activity and sleep interventions.

The cognitive tests used in this project were broadly confined to three main memory-related domains: verbal episodic memory, working memory and face memory/social cognition. As described below, many of the tests undertaken have been used extensively elsewhere in examining normal age-related performance, as well as the progression of clinical-level cognitive decline. Their use in this study is deliberate; using tests with strong, established evidence for age-related performance changes should potentially simplify identification of the factors helping to improve performance. A detailed explanation of the tests themselves is given in the General Methods section of Chapter 2.

1.3. Verbal Episodic Memory

1.3.1. Testing Verbal Episodic Memory: Two Well-Reported Tests were used in the Present Study

Recall of past events and experiences, or episodic memory, has long been considered as a separate memory system (Tulving, 1983) and is one of the first memory systems to be most adversely affected by AD (Petersen, 1994; Desgranges, 1996; Gainotti, 1998). The specific domain of verbal episodic memory (VEM) is known to involve activation of different brain

regions for different memory functions, such as (e.g.) memory encoding and retrieval (Shallice, 1994). Different brain regions have also been shown to be activated in the different elements of specific VEM tasks, such as Rey's Auditory Verbal Learning Test (or RAVLT; Rey, 1964). For example, the hippocampus is strongly associated with the delayed recall component of the RAVLT (Wolk, 2011).

Naturally, AD patients perform worse than healthy controls on VEM tasks (Remy, 2005) and decline in performance in the relatively straightforward recognition component of a VEM task is associated with proportionate loss of hippocampal grey matter (Lewin, 2001; Herlitz & Rehnman, 2008). Differences are sometimes found between males and females in VEM performance (Herlitz, 1997; Manoli, 2018) although this should be approached carefully because these differences tend to be smaller in older age, and it has recently been suggested that gender differences could simply be due to much greater variance in male performance (Asperholm, 2019; 2020).

Although a wide variety of tests has been used in research studies to assess verbal learning and memory, two specific verbal learning and memory tests were selected for use in this project; the Buschke Verbal Selective Reminding Test ('VSRT'; Buschke, 1973) and the RAVLT (Rey, 1964). Both the Buschke VSRT and RAVLT have been used extensively in previous studies which show clear and consistent normal age-related patterns of performance against which it may be possible to examine more easily those factors (such as physical activity and sleep) which may be key differentiators in performance.

1.3.2. There is Evidence for Age-related Decline in the Buschke Verbal Selective Reminding Test ('VSRT')

There is substantial evidence for age-related decline in most VSRT measures (Campo & Morales, 2004; Larrabee, 1988; Sliwinski & Buschke, 1997; Stricks, 1998; Wiederholt, 1993). VSRT can distinguish normal adults from individuals with early-stage dementia (Campo, 2003; Albert, 2001; Tabert, 2006; Sarazin, 2007; Lemos, 2015; 2017; Kuzis, 1999; Masur 1989; 1990; Sabe, 1995). AD patients' performance is generally worse across a range of categories (Campo, 2003). Different elements of the VSRT may be differentially sensitive to hippocampal and non-hippocampal memory deficits (Gurvit, 2017).

Some components of the VSRT such as long-term storage (or LTS) and consistent long term retrieval (or CLTR) decline more markedly than other components after age 50 (see, e.g., Larrabee, 1988). Different VSRT scores have also been shown to provide good information

about aspects of cognitive performance, including the number of intrusions, or words recalled that are not on the list (Didic, 2013), percentage savings between immediate and delayed recall (Tabert, 2006) and recognition or multiple choice, which has been described as a less stressful component of VSRT (Didic, 2013). However, VSRT delayed recall is probably one of the most useful measures and has been shown to have strong predictive value in healthy cognition (Trahan & Larrabee, 1993). Delayed recall can distinguish between groups with very high and very low probability of developing dementia (Masur, 1994) and difficulties with delayed recall is one of the earliest indicators of probable AD, by as much as a decade (Elias, 2000). Using fMRI, it has been shown that, in cognitively normal subjects, the size of the entorhinal cortex is associated with delayed recall, but not with immediate recall (Brickman, 2011) and delayed recall has also been associated with the shape of the subiculum of the left hippocampus, which is involved in episodic memory (Tallarico, 2016). Typically, delayed recall in VSRT is tested (without any reminding) after a comparatively short period of 30-45 minutes, although other longer delay periods have been used, e.g., a 7 day delay period (Manoli, 2018).

1.3.3. There is Evidence for Age-related Decline in Rey's Auditory Verbal Learning Test ('the RAVLT')

The RAVLT (Rey, 1964) also assesses verbal learning and memory using discrete measures that generate scores for different aspects including 'acquisition', 'learning', 'retention', 'forgetting' and 'recognition' (Woodard, 1999; Bleecker, 1988). RAVLT free recall and forgetting both deteriorate in normal ageing, MCI and dementia (Incalzi, 1995; Estévez-González, 2003; Dunlosky & Salthouse, 1996; Mitrushina, 2005; Uttl, 2005a, 2005b). The RAVLT can differentiate between subjects who are ageing normally and subjects who are either pre-clinical AD or who have MCI (Estévez-González, 2003). Specific RAVLT scores have also been shown to predict specific AD-related brain structure changes; for example, RAVLT immediate recall predicts changes in the medial temporal lobe and amygdala whereas RAVLT forgetting predicts changes in the angular gyrus, hippocampus and amygdala (Moradi, 2017). Less variation in RAVLT performance may be expected within and between younger age-groups than in older age-groups (Vakil & Blachstein, 1997).

1.4. Working Memory

1.4.1. Two Different Tests of Working Memory have been used in the Present Study

As a generalisation, VEM is a form of long-term memory, the primary loss mechanism for which may be interference (Gazzaniga, 2014 at page 380). Interference may, for example,

prevent memory consolidation, which is why a period of sleep is usually better for memory consolidation than an equivalent period spent awake (Cherdieu, 2014); see also Chapter 3 below. By contrast, working memory is a form of short-term memory in which decay, rather than interference, accounts for most loss (Atkinson & Shiffrin, 1968). Working memory has a limited capacity for maintaining information, because essentially it functions to allow short-term manipulation of information, for example, when using mental arithmetic (Baddeley & Hitch, 1974). Verbal and spatial working memory activate different brain regions (Smith, 1996) and, in this study, two different tests of working memory, the Stroop test and the Four Mountains test have been included so that the effect of potential protective factors may be considered for both long-term and short-term memory.

1.4.2. Working Memory: The Stroop Test is a test of both 'Goal Neglect' and 'Conflict Resolution'

Exercising cognitive control requires the use of working memory (Goldman-Rakic, 1995); this is seen, for example, in the ability to suppress a pre-potent response to a particular stimulus, in favour of a different response, or for planning and staying focussed 'on goal'. In the Stroop test (MacLeod, 1991; 1992), (the methodology is described in Chapter 2), the relevant information to the task goal (the colour of the word) must be enhanced while the irrelevant non-goal information (the word name) must be suppressed. The test has been variously described as a test of executive functioning, attentional selection or inhibitory breakdown (MacLeod, 1991, 1992; Spieler, 1996; Balota, 2010). The different descriptions are important because, it has been suggested, not all these different components of the Stroop test are necessarily affected by normal ageing (Spieler, 1996).

Attentional selection theory explains that Stroop interference arises because of a dual process of 'maintaining the task goal' whilst at the same time 'resolving response competition' (Kane & Engle, 2003). Importantly, both components are said to engage working memory and are reflected in the Stroop interference effect, but age may only affect the 'goal maintenance' element; older adults may not differ from younger adults in resolving response competition (Spieler, 1996). Normal ageing (and some neuropsychological conditions) can give rise to substantial difficulties in the task goal maintenance component (Kane & Engle, 2003) and, as a result, the Stroop test usually shows a reliably large age-related effect. It is for this reason, namely, that older persons may find it most difficult to maintain the Stroop rule (i.e., 'ignore the word and name the colour') that the Stroop test has been included under the umbrella label 'Working Memory' in the present study, although it is acknowledged that different terms may

be preferred or used elsewhere (e.g., 'executive functioning'). It has also been shown that AD subjects were more prepared to settle for the "first available well-formed" response, rather than undertake the longer processing required to reach the correct response (Spieler, 1996 at page 477). The goal maintenance component may be a function of the dorsolateral pre-frontal cortex (DPFC) (West & Alain, 2000b) whereas the conflict resolution component may be activated by anterior cingulate cortex after an incongruent stimulus has been presented (West & Alain, 1999, 2000a). If older persons are impaired in 'goal neglect' but not 'conflict resolution', (Kane & Engle, 2003), their lower Stroop performance may suggest a greater decline in the DPFC system.

1.4.3. There is Evidence for both Age-related decline and an Effect of Education in the Stroop Test

The Stroop interference effect (see Chapter 2 for a full description of the test used) has been shown to be fairly stable in middle age but increases substantially from age 65 (Comalli Jr, 1962). Performance decline on the Stroop test has also been associated with both age and dementia (Ivnik, 1996; Houx, 1993); impairment of inhibitory processing results in larger Stroop interference in AD patients (Koss, 1984; Fisher, 1990) and has also been shown to predict conversion to AD, albeit in a small sample (N=47) (Balota, 2010). Although memory decline is typically the major cognitive marker in early-stage AD, attention plays a critical role in the encoding and retrieval stages of memory (Balota, 2010; Kawas & Katzman, 1994). Attentional deficits may be predictive of progression to cognitive impairment (Faust & Balota, 1997; 2007; Twamley, 2006) but the Stroop test itself has not consistently differentiated between AD converters and non-converters (compare, for example, Sarazin, 2007 and Balota, 2010).

Goal neglect in the Stroop test, which is a feature of both normal ageing and AD (Comalli Jr, 1962; Koss, 1984; Fisher, 1990) has also been shown in other non-Stroop studies involving failure of inhibition with older age (see e.g. Gazzaley, 2005; Darowski, 2008; Lee, 2018). Age-related changes in the frontoparietal network (activated by the locus coeruleus-norepinephrine system) have been shown to result in older persons being less successful in inhibiting task irrelevant information (Lee, 2018), i.e., older persons have lower selective attention. In a large sample (N=1856, aged 24-81), performance on the Stroop test was also found to be affected by an interaction between older age and lower education levels (Van der Elst, 2006). One explanation advanced for this is that lower education may lead to lower cognitive reserve and thus declining executive function (Van der Elst, 2006; White, 1994; Wilson, 2009).

1.4.4. Working Memory: The Four Mountains test (4MT) is a Test of Spatial Memory, like the Stroop test, requiring strong Attentional Control

The 4MT is a test of spatial memory in which the subject must identify a previously seen scene (which is viewed for 8 seconds) from a new viewpoint after a brief delay of two seconds. The new viewpoint of the scene must be selected from a choice of four different pictures. The 4MT is not so well or long established as the VSRT, RAVLT and Stroop tests, but has still been reasonably well-used in recent years as a reliable and informative neuropsychological test of hippocampal-based spatial memory (Hartley, 2007; Bird, 2010; Pengas, 2010; Hartley & Harlow, 2012; Moodley, 2015; Wood, 2016; Chan, 2016). The 4MT has been labelled in this project (alongside the Stroop test) as a test of 'working memory' because, as described in Chapter 2, Principal Component Analysis (PCA factor analysis) has grouped these two tests into a single factor and both tests require subjects to manipulate, enhance and suppress (or 'work') different informational and memory demands. Whilst it is clear they have some common components (e.g. the requirement to exercise strong attentional control) the two tests may also involve different functional memory systems.

1.4.5. Some Evidence exists for Age-related Decline in the 4MT

Testing patients with hippocampal damage alongside normal controls has shown that the 4MT is a reliable differentiator of hippocampal spatial memory performance (Hartley, 2007). Right and left hippocampal volume is positively associated with 4MT score (Pearson's r=0.59 and Pearson's r=0.57 respectively) (Hartley & Harlow, 2012). Strong 4MT performance therefore depends on unimpaired hippocampal function and 4MT is a strong predictor of AD (Bird, 2010; Moodley, 2015; Wood, 2016; Chan, 2016). While there is no published data on normal age-related performance in the 4MT, there is some evidence (albeit in different research studies) of age-related decline in cognitively normal persons. For example, a group of younger persons (M=25.9 years) scored 22.63/30, SD=4.06 (Hartley & Harlow, 2012), equivalent to 75%, whereas a group of healthy older persons (M=68.7 years) scored comparatively lower at 9.8/15, SD=1.8 (Pengas, 2010), equivalent to 65%.

1.5. Social Cognition and Memory

1.5.1. Social Cognition and Cognitive Ageing: Face Recognition and Memory may Decline but other Areas, such as Mentalizing, may be Better Preserved in Normal Ageing

As described above, there has been substantial research in the field of those memory domains that are subserved by the brain structures first targeted by the neuropathology of dementia, such

as the medial temporal lobe, entorhinal cortex and hippocampal formation. However, AD pathologies progress to other brain areas and structures (Scahill, 2002; Apostolova, 2008; Weiler, 2015) and thus impact other areas of memory and cognition, such as social cognition (Goodkind, 2015). In the progression of AD, subjects may advance from fairly normal age-related difficulties with unfamiliar face recognition and memory to having difficulties with more straightforward tasks of familiar face recognition and memory (Hawley & Cherry, 2004). Such impairment may even progress to the stage where they are unable to recognise a spouse, or even themselves (Kurth, 2015).

However, whilst some social cognition and memory normally declines with increasing age, some aspects of social cognition may be comparatively well-preserved (Grossmann, 2010). For example, studies have tended not to show any age-related differences in mentalizing tasks, such as the Reading the Mind in the Eyes test (Baron-Cohen, 1997; 2001; Happé, 1998; Castelli, 2010). In order to examine what may underly these differences, the social cognitive tests used in this project have included the Reading the Mind in the Eyes test as well as tests of unfamiliar face memory and perception.

1.5.2. Social Cognition: A Common Factor (labelled 'f') may underlie Performance in Tests of Face Memory and Perception

A fairly recent study has proposed a term 'f' (comparable to the factor 'g' in intelligence testing; Mackintosh, 2011) as a common factor underlying performance on tests of unfamiliar face processing, although, the authors note, "f, like g, is no more than a summary of a pattern of correlations" (Verhallen, 2017 at page 224). In that study, associations between several different well-established tests of social cognition were examined and it was found that the highest shared variance (23%) was between the Cambridge Face Memory Test (Duchaine & Nakayama, 2006) and the Glasgow Face Matching Test (Burton, 2010) (Pearson's r=.48) (Verhallen, 2017). This shared variance was unexpected, given that the Glasgow test is one of face discrimination and is quite different from the Cambridge test of facial recognition or memory. As described in Chapter 2, both the Cambridge and Glasgow tests were combined in a single PCA memory domain factor, meaning that the effect of measures such as sleep and physical activity on subjects' 'f' was effectively tested for the first time in this study alongside other memory domains.

1.5.3. The Cambridge Face Memory Test is a Test of Unfamiliar Face Memory which may Decline in Older Age

Face recognition (based on the CFMT) has been shown to be a specific, heritable cognitive ability (Wilmer, 2010). Face learning ability has been reported to peak around age 30 and, despite greater experience with older age, does not appear to improve after that point (Germine, 2011). The CFMT (Duchaine & Nakayama, 2006) does show age-related decline, and possibly clinical impairment, in face recognition but is not age-biased (i.e., it does not vary in difficulty for different age-groups; Cho, 2015). In a sample of 50 young people, (M=20.2 years), the average score was 57.9/72 or 80.4% (Duchaine & Nakayama, 2006). This compares very closely to the average score for the younger group in this study (M=36.1 years) of 57.5/72 or 79.9% (see further in Chapter 2).

1.5.4. The Glasgow Face Matching Test (GFMT) is a Test of Unfamiliar Face Matching or Perceptual Processing which may Decline in Older Age

The GFMT (Burton, 2010) is thought to be a test of face matching or perceptual processing, rather than face memory; performance has again been shown to deteriorate with older age (Dolzycka, 2014). Face matching ability deteriorates in older age as a result of difficulties in the perceptual encoding of unfamiliar faces, as distinct from any deficiency in face memory (Megreya & Bindemann, 2015). In a recent study, it was suggested that after controlling for such age-related difficulties in perceptual processing, effects of age on face memory in the Cambridge Face Memory Test effectively disappeared (Stantic, 2021). In a sample of 194 subjects, (M=26 years), average accuracy on the GFMT was 81.3% (SD=9.7) (Burton, 2010) which is consistent with the view that perceptual processing remains strong in late younger and early middle age (Megreya & Bindemann, 2015).

1.5.5. Social Cognition: The Default Mode Network has been associated with Perspective Taking which is an Aspect of Mentalizing

Earlier research suggests some interaction between the Default Mode Network (DMN; Raichle, 2001) and social cognition; specifically, the activitation of the DMN is often characterised by self-referential, or self-reflective, perspective taking; a process that involves both social and emotional elements of cognition (Gusnard, 2001; Gusnard & Raichle, 2001). Certain tasks that require thinking about the beliefs or intentions of other people (i.e. mentalizing) activates similar brain regions to the DMN (Buckner & Carroll, 2007; Mitchell, 2009). Self-referential thinking and social cognition (mentalizing) may be a natural, resting state that requires deactivation when specific task performance becomes the priority.

1.5.6. Some Evidence suggests that Age-related Performance on Reading the Mind in the Eyes Test is Relatively Stable

Impaired performance on the Reading the Mind in the Eyes test has been seen in depressed older persons (Szanto, 2012), and facial expression recognition is also impaired in AD (Torres, 2015). A review found gender differences in 6/17 studies, with females out-performing males (Cohen's d, range 0.22 to 0.94) (Vellante, 2013) but, more recently, it has been suggested that males show greater variance than females, and that with older age, variance in test scores (in a German version) increased in both males and females (Kynast, 2021). Performance on an Italian version of the test has been shown to be relatively stable across the lifespan and into older age, although age-related reduction in white matter connectivity in fronto-temporal regions is associated with poorer test performance (Cabinio, 2015).

As explained in Chapter 2, the Reading the Mind in the Eyes test score did not load onto any memory domain factor to a statistically acceptable level. Results for the test have been provided separately, wherever they are relevant or significant.

1.6. Factors Preserving Memory Performance and Cognition in Ageing

The following is a short summary of some of the major factors which have been found to affect memory performance and cognition in ageing. A more comprehensive review of this earlier research is included in the separate chapters on sleep, Circadian behaviour, physical activity and social psychological factors (see Chapters 3 to 6 below).

1.6.1. Sleep and Circadian Behaviour Undergo Important Changes in Older Age

Good sleep plays a critical role in learning and memory, social and emotional functioning and cognitive health generally (Diekelmann & Born, 2010; Goldstein & Walker, 2014; Walker & Stickgold, 2010; Walker, 2017). Sleep, ageing and cognition are three areas that are separately highly complex and, in combination, can be difficult to tease apart; for example, in normal ageing, both cognitive decline and sleep problems appear to co-occur, posing difficult questions of directional effect (Dzierzewski, 2018). There are well-recorded changes in sleep across the normal adult lifespan, involving different sleep phases, as well as sleep patterns (Ohayon, 2004; Helfrich, 2018). For example, both slow wave sleep and REM sleep decline in older age (Morgan, K in Lichstein & Morin, 2000) and a developing pattern of sleep disturbances is common in adults over 60 (Walker, 2017; Bliwise, 1993; Redline, 2004). Sleep disruption is associated with medial PFC atrophy in older adults, leading to loss of

hippocampal-dependent memory function (Mander, 2014) and Aβ accumulation similarly disrupts sleep-related memory consolidation (Mander, 2015; Spira, 2013).

In addition, recent research shows that some measures of 'poor sleep', such as sleep duration, may have a more complex relationship with healthy cognitive functioning than hitherto imagined (Lucey, 2021)—getting too much sleep may be as problematic as too little (Faubel, 2009; Tworoger, 2006). Indeed, the two extremes may be associated with poorer performance in the specific domains of verbal memory (Kronholm, 2009). Short sleep duration in older persons may reflect their lower sleep need than any sleep impairment (Fox, 2018). Other sleep characteristics, such as higher sleep latency (Bastien, 2003), greater sleep fragmentation (Oosterman, 2009) and higher sleep disturbance (Blackwell, 2006) have all been shown to affect cognition adversely. Sleep disturbances, such as reduced time asleep, Circadian rhythm disruption and increased nocturnal awakenings, are common in individuals with AD and MCI (McCurry, 1999; Coogan, 2013; Lucey & Bateman, 2014; Peter-Derex, 2015; Lucey & Holtzman, 2015, Ju, 2013, 2014; Guarnieri, 2012). Disturbed sleep is characteristic of MCI long before AD diagnosis (Hita-Yañez, 2012). Greater sleep fragmentation is associated with increased risk of AD (A.S. Lim, 2013) and self-reported sleep disturbance in cognitively healthy men has been associated with a significantly higher risk of dementia (Benedict, 2015). In addition, certain Circadian behavioural effects of modern living, such as Social Jet Lag and Sleep Debt, which tend to show strong age-related trends, can substantially affect cognitive performance (Roenneberg, 2019; Fox, 2018; Taillard, 2021). Chapters 3 and 4 describe earlier research into matters such as sleep duration, sleep quality and Circadian behaviour in more detail and explain the methods used to assess sleep and Circadian behaviour in this study (broadly, a combination of actigraphy, sleep diaries and questionnaires).

1.6.2. Higher Levels of Physical Activity (PA) may protect the Ageing Brain

There is substantial evidence linking higher levels of PA to neuroprotection of the ageing brain and to improved memory and cognitive functioning in older persons (Bauman, 2016; Hillman, 2008; Gow, 2012; Erickson, 2012), to reduced risk of dementia and cognitive decline, and to improved psychological health and well-being (Laurin, 2001; Wojtek, 2009; Zhang & Chen, 2019). Persons with higher levels of mid-life exercise have a significantly decreased risk of dementia and MCI (Ahlskog, 2011). Physical exercise may even slow down the normal course of AD (Scarmeas, 2011). It is becoming increasingly clear that fairly low levels of activity can still be beneficial (compared with no activity at all); in one recent, well-publicised study, it was

found that higher levels of both light and heavy housework were associated with improved memory and attention in older persons (Lee, 2021).

Chapter 5 sets out in more detail the relationship between PA and brain structure and function. It also examines what type and level of activity/exercise has been shown to be most beneficial for different memory domains and aspects of cognitive functioning and describes in detail the methods that have been used in this study to measure PA and exercise (broadly, a combination of actigraphy and questionnaires).

1.6.3. Social Networks and Psychological Health: Smaller Social Networks have been extensively associated with Age-related Cognitive Decline

Cognitive decline in older age has been strongly associated with smaller social networks (Bassuk, 1999; Cornwell, 2008; Cornwell & Waite, 2009; Krueger, 2009; Stevens & Van Tilburg, 2011; Holtzman, 2004; Hughes, 2008; Seeman, 2001). Even in cases of severe dementia pathology, cognitive function is still higher for those who are not lonely or isolated and who have larger social networks (Bennett, 2006). Social isolation increases with age (Cornwell & Waite, 2009; Aartsen & Jylha, 2011; Cohen-Mansfield, 2009) and is associated with increased dementia risk (Rafnsson, 2020). Lifelong single people reportedly have 42% increased risk of dementia, compared to married people (Sommerlad, 2017). In short, engagement in larger and more complex social networks, both friendship and family networks, provides clear cognitive benefits (Crisp & Turner, 2011; Crisp & Meleady, 2012; Hodson, 2018). However, the exact mechanism by which stronger social networks afford protection against cognitive decline remains unclear.

1.6.4. Having Larger Social Networks may act as a Buffer to Stress

One candidate mechanism underlying the benefits of larger social networks may be that they help to reduce chronic stress, i.e. increased social contact provides a stress-buffer to allow healthy cognitive functioning (Cohen & Wills, 1985; Fillit, 2002; Fiori, 2006; Litwin, 2015; Ertel, 2008; Berglund, 2016; Cornwell & Laumann, 2015; Hennessy, 2009). Chronic stressors often cause prolonged production of the stress hormone cortisol (Sapolsky, 1998; Segerstrom & Miller, 2004), which damages the brain. Chronic feelings of being overwhelmed are linked to cognitive decline and increased risk of dementia (Wilson, 2005; 2006; 2011). Loneliness is itself a chronic stressor (Steptoe, 2004; Eisenberger, 2003; Williams, 2007) and loneliness and smaller social networks increase circulating levels of cortisol (Pressman, 2005). People with poor social skills risk greater psychosocial problems when dealing with stress (Segrin, 2019)

whereas people with good social skills successfully extract support from their broader social networks (Mortenson, 2009; Nilsen, 2013). It is possible therefore that strong social skills (high 'f' ability: Verhallen, 2017) may be a prerequisite for stronger social networks.

1.6.5. Larger Social Networks may Afford more Opportunity for Social and Cognitive Stimulation

The protective effect of social networks on cognition may not stem simply from the size of social networks, but also from their complexity (Litwin, 2015; Cornwell & Laumann, 2015; Ellwardt, 2015; Giles, 2012; Zunzunegui, 2003). Greater complexity means having a rich personal network of different relationship types, rather than a network of homogenous relationship types (Litwin, 2015; Meleady & Crisp, 2014; Prati, 2015; DiBella & Crisp, 2016; Goclowska & Crisp, 2013). Accordingly, it may be regular exposure to complexity in social situations which helps to preserve cognitive function by providing varied cognitive stimulation and helping to promote cognitive flexibility and build cognitive reserve (Bennett, 2006; Fratiglioni, 2004; Stern, 2002; Giles, 2005; Valenzuela & Sachdev, 2006a, 2006b; Marioni, 2012).

In Chapter 6, the relationship between healthy cognitive ageing and social psychology, including social connectedness and psychological health generally, will be examined in more detail.

1.7. Summary of Chapter 1

The first part of this Chapter explained why understanding the limits, and the possibilities, of healthy cognitive ageing is so important in a post-pandemic environment where health resources are under extreme pressure, and where an ageing population may need to take on greater responsibility for preserving and prolonging its own good cognitive health.

The second part of this Chapter examined some of the structural and functional brain changes that occur in normal ageing and related these to the main memory domains studied in this project: verbal episodic memory, working memory and face memory and perception. It also described earlier findings in relation to some of the specific tests used in this project to assess performance in those memory domains.

The final part of this Chapter briefly considered some of the main protective measures of healthy cognitive ageing which will be considered separately in each of the main chapters on

sleep (Chapter 3), Circadian behaviour (Chapter 4), physical activity (Chapter 5) and social networks and psychological health (Chapter 6).

Chapter 2 will now examine the general methods used in this project and report a number of general results.

CHAPTER 2: GENERAL METHODS & GENERAL AGE-RELATED RESULTS

2.1. Cognitive Testing

2.1.1. Participation and Recruitment of Subjects in the Present Study

Subjects were recruited through opportunity sampling. Some advertising for volunteers was undertaken in publications such as school, church and parish magazines. Some presentations were made to different groups of older subjects e.g. to University of the Third Age (U3A) groups in North Yorkshire in order to explain the aims and objectives of participation in the project. Participation was entirely voluntary. The main requirement was that subjects had no history or diagnosis of cognitive impairment. In order that physical activity levels could be measured by accelerometery, subjects also had to be in reasonably good physical health.

During recruitment, each potential subject was given an information sheet (Appendix 1) which outlined the aims of the project and explained what they would do if they agreed to take part. They were informed that participation would involve two separate testing sessions (Phases 1 and 2) which would each last about 60-70 minutes and would take place approximately two weeks apart. In addition to selecting their preferred time for testing, subjects were also allowed to choose their preferred location for testing, with the main requirements being that testing should be quiet, undisturbed and uninterrupted. With very few exceptions, most older subjects were tested in their own homes. Members of the younger group (aged below 50) were also tested in their own homes, or sometimes, in their offices or workplaces. Testing was principally confined to the North of England.

Subjects were advised that each of the two phases would involve four different cognitive tests which were carried out in the same order for all subjects. At Phase 1, before any testing began, subjects were provided with a 'Privacy Notice' (Appendix 2) and were asked to sign two separate Consent Forms (Appendix 3). The first Consent Form dealt with the cognitive tests to be administered during Phase 1 and Phase 2 testing. The second Consent Form dealt with wearing the physical activity and sleep accelerometer and completing the online questionnaires. Subjects were given the opportunity to ask questions about the project or testing before and after each Phase of testing. At the end of Phase 1 testing, subjects were informed that they would be sent an e-mail with a link to the online questionnaires and confirmation of the agreed date and time for Phase 2 testing.

2.1.2. Procedure: Supervised Testing was Undertaken in Two Phases that took place Two Weeks Apart

Details of the two separate supervised cognitive testing sessions (Phases 1 and 2) which took place approximately two weeks apart are shown in Table 2.1.

Table 2.1: Outline of Test Phases

Phase 1 Testing (Day 1)		Phase 2 Testing (Day 15)	
Test	**Approximate Duration**	**Test**	**Approximate Duration**
Buschke Selective Reminding Test (VSRT)	20 mins	New Long-Term Delayed Recall (VSRT)	5 mins
Jenkins & Burton: Unfamiliar Face Learning—Free Sort	10 mins	Stroop Test	10 mins
Jenkins & Burton: Unfamiliar Face Learning—Forced Choice	5 mins	Rey Auditory Verbal Learning Test (RAVLT)	15 mins
Reading the Mind in the Eyes Test	15 mins	Four Mountains Test	15 mins
Cambridge Face Memory Test	10 mins	Glasgow Face Matching Test	15 mins
Standard Delayed Recall (Buschke VSRT)	5 mins	Standard Delayed Recall (RAVLT)	5 mins
Total Duration	65 mins		65 mins

Table 2.1 shows the schedule of supervised testing at Phase 1 and Phase 2 (two weeks later)—see text for full details of each named test. Each phase was scheduled to last for approximately 65 minutes but this varied because some of the tests were not subject to time constraints. All subjects performed the tests in the same order as they are shown here.

The tests were arranged in two separate supervised phases mainly in order not to make excessive testing demands on older subjects, but also to allow testing of long term delayed recall in Buschke's VSRT (Buschke, 1973; see further below). The reasons for the selection of the specific tests shown in Table 2.1 is explained below, but dividing the testing process into two sessions, two weeks apart, also allowed the separation of two different tests of verbal episodic memory (VEM), namely Buschke's VSRT (Buschke, 1973) and the RAVLT (Rey, 1964) as well as the separation of two tests of unfamiliar face memory and perception, namely the Cambridge Face Memory test (Duchaine & Nakayama, 2006) and the Glasgow Face

Matching test (Burton, 2010), the scores on which have been shown to be strongly associated (Verhallen, 2017). Using more than one test enabled these particular cognitive demains (VEM and unfamiliar face memory and perception) to be examined in greater depth.

2.1.3. Subjects were Permitted a Free Choice as to Time of Day of Testing

This study was not specifically designed to consider the possible effect of time of day on performance and so subjects had a free choice when scheduling their preferred times for testing. However, for the purpose of exploratory analysis of any Circadian effect on cognitive performance (see Chapter 4 on Circadian behaviour), time of day of testing was recorded as either "AM" (testing begins before midday) or "PM" (testing begins after midday). There were no subjects who were tested at a very late or unsociable time (e.g. after 8/9 pm). Table 2.2A shows that there were generally more subjects tested in the afternoon than in the morning for both phases. However, this may reflect the fact that there is a shorter total time period for morning appointments (9AM to midday, 3 hours) than afternoon appointments (midday to 5PM, 5 hours). It can also be seen from Table 2.2B below that older subjects appeared to prefer afternoon testing in both phases, but this preference is not shown in the younger group. Again, this may merely reflect the different time periods available for normal morning and afternoon testing.

Table 2.2A: Time of Day of Testing: Phases 1 & 2

Time of Day	Phase 1 (FCSRT, Face Error, Mind in Eyes, Cambridge)	Phase 2 (Stroop, RAVLT, 4MT, Glasgow)
AM	N=50	N=63
PM	N=95	N=82
Total	N=145	N=145

Table 2.2B: Time of Day of Testing by Age Group

Time of Day	Younger P1	Older P1	Younger P2	Older P2
AM	N=24	N=26	N=29	N=34
PM	N=28	N=67	N=23	N=59
Total	N=52	N=93	N=52	N=93

Tables 2.2A and 2.2B provide details of time of day of testing for each phase of testing. This study was not designed to study effects of time of day on testing and subjects were therefore given a free choice on scheduling their testing phases. Notes: In Table 2.2B, P1 and P2 mean supervised testing phases 1 and 2 respectively.

2.1.4. The Order of Tests in the Supervised Testing Phases was the same for all Subjects

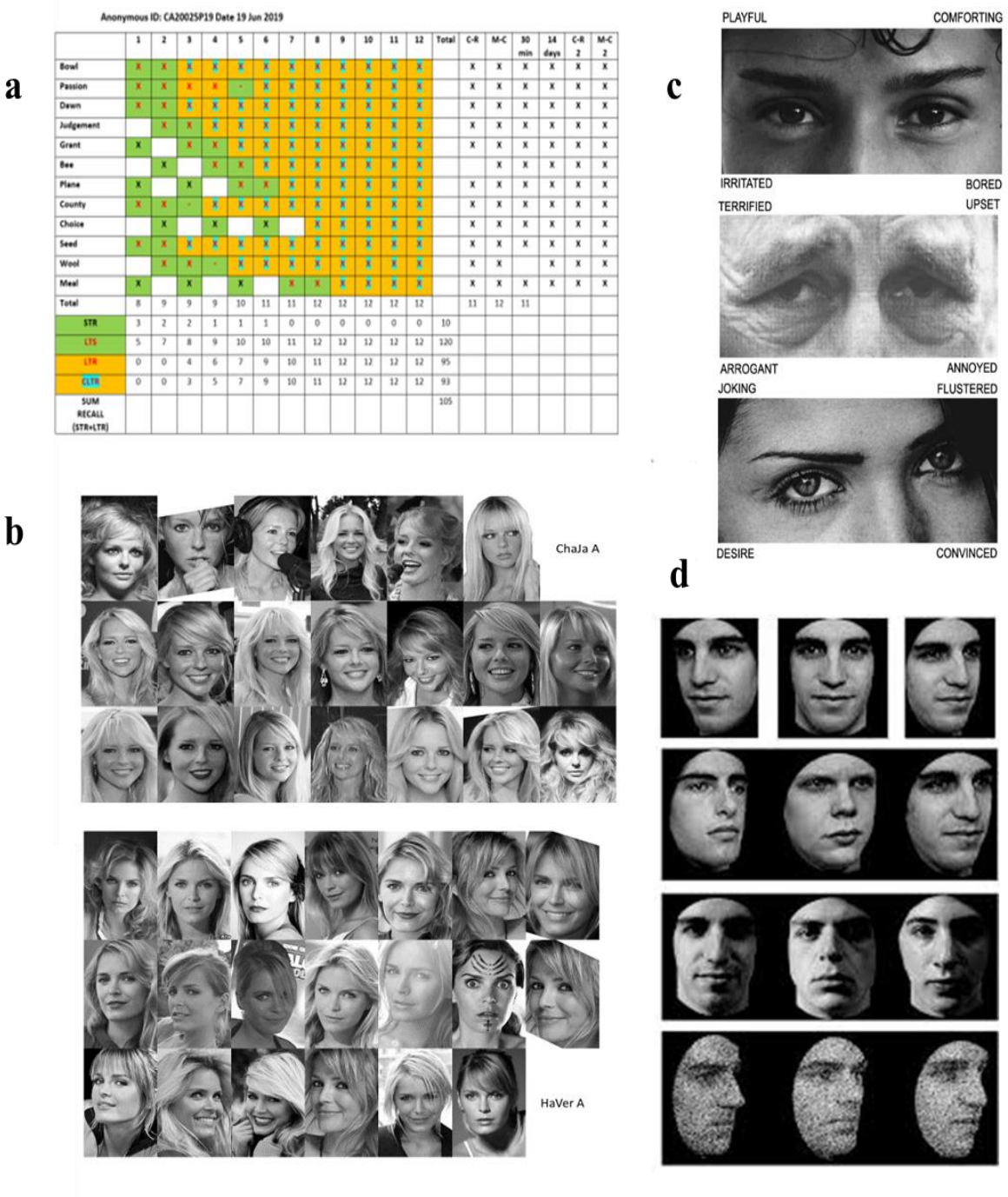
The tests in each phase were undertaken in the same order for all participants, as shown in Table 2.1. Phase 1 tests comprised Buschke's VSRT (Buschke, 1973), the Jenkins & Burton unfamiliar face learning test (Jenkins & Burton, 2011), the Reading the Mind in the Eyes Test (Baron-Cohen, 1997) and the Cambridge Face Memory Test (Duchaine & Nakayama, 2006). Phase 2 tests comprised the novel addition of long-delayed free and cued recall in the VSRT, the Stroop Test (MacLeod, 1991), the RAVLT (Rey, 1964), the Four Mountains Test (Hartley, 2007) and the Glasgow Face Matching Test (Burton, 2010). For an illustrative guide to the composition of the two test phases, see Figures 2.1A and 2.1B.

2.1.5. Non-Supervised Testing included Wearing Accelerometer Devices for Two Weeks and Answering a Series of Online Questionnaires

In between the two supervised testing phases, subjects wore a GENEActiv Original^{R} accelerometer configured at 50Hz to provide for 15 days of continuous activity measurement. The actigraphy component of the study is described in greater detail in Chapters 3 to 5 below (on sleep, Circadian behaviour and physical activity). Scheduling the supervised testing phases across two weeks also allowed for delivery to and collection of devices from subjects.

Subjects also completed a series of online questionnaires which was sent as a link between testing phases. A total of 5 subjects failed to complete any of the questionnaires and two subjects only completed some of the questionnaires. These questionnaires are described more fully in Chapter 6.

Figure 2.1A: Supervised Testing: Phase 1



	1	2	3	4	5	6	7	8	9	10	11	12	Total	C-R	M-C	30 min	14 days	C-R 2	M-C 2
Bowl	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Passion	X	X	X	X	-	X	X	X	X	X	X	X		X	X	X	X	X	X
Dawn	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Judgement		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Grant	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Bee		X		X	X	X	X	X	X	X	X	X			X	X	X	X	X
Plane	X		X		X	X	X	X	X	X	X	X		X	X	X	X	X	X
County	X	X	-	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Choice		X		X		X		X	X	X	X	X		X	X	X	X	X	X
Seed	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Wool		X	X	-	X	X	X	X	X	X	X	X		X	X		X	X	X
Meal	X		X		X		X	X	X	X	X	X		X	X	X	X	X	X
Total	8	9	9	9	10	11	11	12	12	12	12	12		11	12	11			
STR	3	2	2	1	1	1	0	0	0	0	0	0	10						
LTS	5	7	8	9	10	10	11	12	12	12	12	12	120						
LTR	0	0	4	6	7	9	10	11	12	12	12	12	95						
CLTR	0	0	3	5	7	9	10	11	12	12	12	12	93						
SUM RECALL (STR+LTR)													105						

Figure 2.1A shows examples of materials from the supervised testing of subjects at phase 1: **a**. Buschke's Verbal Selective Reminding Test (VSRT) was the first test administered. This is a sample scoresheet showing the words used from Form 1 of the VSRT. **b**. Jenkins & Burton's unfamiliar face learning test was the second test administered. This shows the actual 40 images that were used in passport-sized separate photographs. **c**. Baron-Cohen's Reading the Mind in the Eyes test was the third test administered. This shows three examples of eye expressions together with the 'four choice' description of emotions for each expression from which subjects made their choice. **d**. Duchaine & Nakayama's Cambridge Face Memory Test was the fourth test administered at Phase 1. This shows example images used; the bottom row shows faces 'with noise' (i.e. made more difficult to discern through pixilation). After these tests, the standard free delayed recall component of the Buschke VSRT was administered. Further details of the tests are provided in Chapters 1 and 2.

Figure 2.1B: Supervised Testing: Phase 2

a

1	GREEN	22	YELLOW
2	BLUE	23	ORANGE
3	RED	24	RED
4	GREEN	25	GREEN
5	RED	26	RED
6	YELLOW	27	ORANGE
7	BLUE	28	BLUE
8	ORANGE	29	GREEN
9	GREEN	30	BLUE
10	BLUE	32	RED
11	YELLOW	34	ORANGE
12	ORANGE	35	GREEN
13	BLUE	36	BLUE
14	BLUE	37	GREEN
15	GREEN	38	YELLOW
16	RED	39	ORANGE
17	ORANGE	40	RED
18	RED	41	GREEN
19	YELLQW	42	GREEN
20	BLUE	43	YELLOW
21	RED	44	ORANGE

b

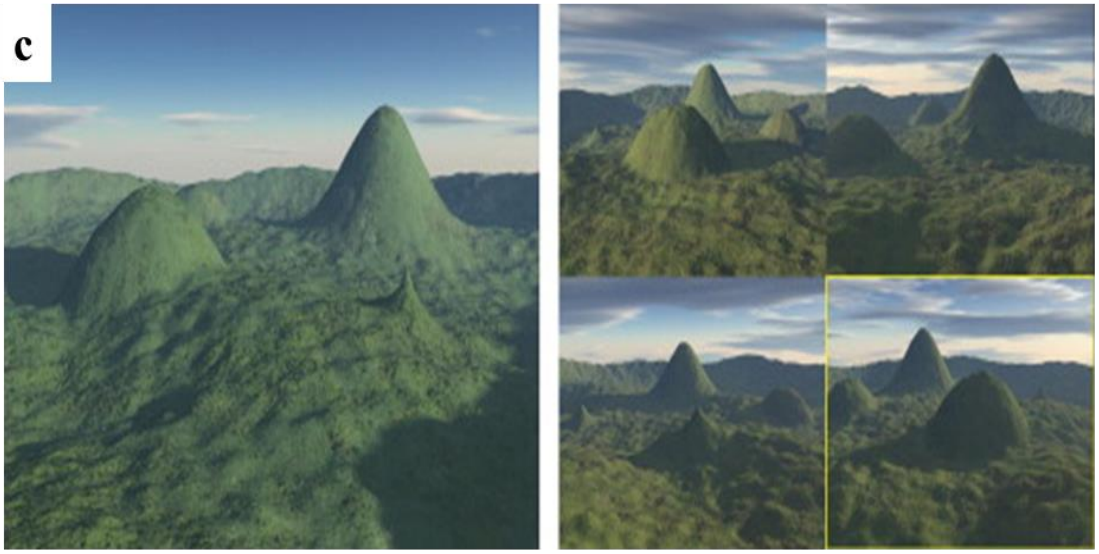
REY AUDITORY VERBAL LEARNING TEST (RAVLT) *Phase I*

Patient: _____

Age: _____

LIST A	1	2	3	4	5	LIST B	1	LIST A	6	7
DRUM						DESK		DRUM		
CURTAIN						RANGER		CURTAIN		
BELL						BIRD		BELL		
COFFEE						SHOE		COFFEE		
SCHOOL						STOVE		SCHOOL		
PARENT						MOUNTAIN		PARENT		
MOON						GLASSES		MOON		
GARDEN						TOWEL		GARDEN		
HAT						CLOUD		HAT		
FARMER						BOAT		FARMER		
NOSE						LAMB		NOSE		
TURKEY						GUN		TURKEY		
COLOR						PENCIL		COLOR		
HOUSE						CHURCH		HOUSE		
RIVER						FISH		RIVER		
SCORE										

c



d

Figure 2.1B shows examples of materials from the supervised testing of subjects at phase 2: Prior to phase 2 testing, subjects were re-tested without forewarning on free, cued recall and recognition components of Buschke's VSRT. **a.** The first full test administered at Phase 2 was the Stroop test. This shows the actual 5 colour version used (red, blue, green, yellow and orange). **b.** The RAVLT was the second test administered. This shows the scoresheet for the same version that was used in testing. **c**. The Four Mountains test was the third test administered. This shows an example of the full screen stimulus image and the four-choice screen, with a yellow border around the correct (rotated) choice. **d.** Burton's Glasgow Face Matching Test was the fourth test administered at Phase 2. In these examples, the female faces are a 'matching' pair and the male faces are a 'non-matching' pair. After these tests were administered, the RAVLT delayed recall and recognition components were tested. Further details of the tests are provided in Chapters 1 and 2.

2.1.6. Statistical Analysis, Methods & Assumptions used in the Present Study

Given the limitations on external testing imposed by the Covid 19 pandemic from March 2020, the sample population had to be severely restricted. Ideal sample sizes determined (e.g.) by power analysis could not be achieved and were made redundant. Detailed data and statistical analysis therefore began earlier than anticipated (in March 2020) with a smaller sample size than originally anticipated. At this point in the project, the statistical strategy adopted was to minimise the risk of Type I errors, albeit at the expense of failing to detect effects that might exist in a larger sample (i.e., a risk of Type II errors). The standard Fisher α-level value of 0.05 (Fisher & Bennett, 1990) was reduced so that in this project, *as a general rule*, findings are only *higlighted* as significant *and* subjected to further detailed analysis where the α-level value falls below 0.01 (i.e., 0.009 or lower). This is essentially a generalised Bonferroni correction that assumes 5 tests, although no *specific* corrections have been applied to simple correlations for multiple testing in the results reported independently in each of the chapters. In the majority of cases, group comparisons are confined to two groups; e.g., younger/older, good/poor sleepers, e.t.c. In a small number of cases which were supplemetary to the main two age group analyses, four age groups are considered (i.e., 6 comparisons). The revised α-level value of 0.01 is not sufficient here to reduce the risk of Type I familywise error probability below 0.05 (i.e., (1-0.01=) 0.99^6=0.941; 1-0.941=0.059). However, the detailed four age group comparisons are generally used to illustrate how the trend in age-related differences may develop in certain characteristics (e.g., for Sleep Debt and Social Jet Lag in Figure 4.7) and such results are not presented as major findings.

Sample size and the resulting restrictions on power is a limitation of the overall statistical approach necessitated by the Covid 19 pandemic restrictions on testing. Although detailed analysis of results has been restricted to the α-level value of 0.01, values of α-level between 0.01 and 0.05 may still be highlighted in some Tables as statistically significant results (in accordance with the convention for distinguishing between results at the <.05 and <.001 levels of significance, principally for ease of reading), but these statistical findings have generally not been examined in any great detail. It has been well-reported elsewhere how lowering the α-level value may lead to a corresponding increase in the risk of Type II errors (see, e.g., Field & Hole, 2002; Howell, 1992) but that is an inevitable consequence of minimising the risk of Type I errors. This project is primarily concerned with determining factors that may help to

preserve healthy cognitive ageing and the main focus has therefore been in avoiding the risk that factors are identified which may have no effect in a wider population (i.e., a Type I error).

The data analysis approach has generally been to proceed from correlation to regression (Miles & Shevlin, 2001). First, correlations are examined between the key variables identified in each chapter (e.g., 'age' in Chapter 2, 'sleep quality' in Chapter 3, and so on) and (better) performance in each of the four separate memory domain factors. Linear regression was then used to construct an overlapping model which combines the layered findings from each of the main chapters. The developing regression model is shown in the Summary section for each of the separate chapters (chapters 2 to 6 inclusive) and the final model for each of the four memory domains is shown in Figure 7.1 in Chapter 7 (Conclusions).

As shown in Supplementary Table 2.1, some of the key variables identified in the main chapters are not normally distributed; for example, age (Chapter 2) shows a distribution that is skewed towards the older end of the age range (18-91) due to the predominance of older subjects in the sample (W_{145}=.936, p=.001); additionally, PSQI score for sleep quality (Chapter 3) is concentrated towards the lower end of the PSQI scoring range of 0-21 (W_{140}=.942, p<.0001), which is consistent with findings elsewhere (e.g., Nebes 2009). As a result, Tables which contain key variables that are non normally distributed will also show non-parametric Spearman r_s correlations alongside standard Pearson r correlations. As a general rule, results have *not* been subjected to further detailed analyis where they show results below the α-level of 0.01 in *only one* of the two separate tests of correlation (i.e., Pearson *or* Spearman correlations), although again, in line with conventional reporting, tables may highlight significant findings at the <.05 and <.001 levels in either of the two tests, principally for ease of reading. Detailed analysis of results has mainly been confined to associations where both Pearson and Spearman tests meet the adjusted significance criteria of α-value <.01.

In regression analyses, results are predominantly reported only for linear models using the Enter method where variables make a statistically significant contribution to the overall model and where beta values (β) have been standardised. As a general rule, regression models have not been reported in any case where variables do not make a significant contribution to the model. For example, in this Chapter 2, it is explained how age is not correlated with VEM Long Term Forgetting (in an Enter regression model, age=standardised β=.088, p=.29) and in the next Chapter 3 it will be explained how PSQI sleep quality score is highly correlated with VEM Long Term Forgetting (in an Enter regression model, PSQI score=standardised β=.289,

p=.001). However, the Enter regression model that combines these two variables does not add any material explanatory interpretation (in an Enter regression model combining both variables, age: β=.020, p=.80, PSQI: β=.287, p=.001) and such non-significant results are not therefore reported.

The approach taken to regression modelling has been to base models upon preliminary findings for correlations between key variables identified in each chapter and their association with better or worse performance in one of the key memory domains. Where only a single variable is correlated with memory domain performance, a regression model may not be separately reported for the single variable on the basis that standardised β in the linear Enter model will generally be equivalent to the Pearson's r correlation. Where only two variables are separately correlated with performance in any memory domain, the Enter method has been used to determine which, if any, of the two variables makes a separate and independent contribution to a linear regression model. For example, in Chapter 2, age is shown to be strongly correlated with worse Face Memory & Perception (standardised β=-.327, p<.0001) and in Chapter 4, higher Social Jet Lag is shown to be strongly correlated with better Face Memory & Perception (standardised β=.285, p=.001). However, in combination, it is clear from using the Enter method that the variable Social Jet Lag reflects an underlying strong correlation between that variable and age (in an Enter regression model combining both variables, age: β=-.244, p=.012, Social Jet Lag: β=.147, p=.13). Such results in which only one of two variables contribute to a regression model are not generally reported. However, in some cases, the Enter Method may produce seemingly equivalent models for two different variables; this is shown for example in Figure 6.8 where, using the Enter method, two different psychological mood PCA factor scores help to predict VEM Long Term Forgetting. In these circumstances, the backwards Stepwise model has also been used to identify the best model which is then determined and reported using the Enter method (see, e.g., Figure 6.9).

Where multiple (i.e., more than two) significant correlations exist between key variables and performance in a memory domain, the backwards Stepwise model has been used to identify the best model combining significantly contributing variables. For example, in Chapter 4, there are multiple correlations between Working Memory and separately age, education level and a number of different areas of activity or inactivity. The end result from the Stepwise model has been verified using the Enter method and the result from using the Enter method is the one that

is reported (in these cases, variations between the best backwards Stepwise model and the reported Enter model are very slight and do not merit separate reporting).

Accordingly, the layered approach to determining which factors (measured in each of the relevant chapters) may affect performance in each of the four measured memory domains can be broadly summarised as follows:

Chapter 2: age and education correlations

Then age + education regression analysis

Chapter 3: objective and subjective sleep measure correlations

Then Age + education + objective and subjective sleep measure regression analyses

Chapter 4: chronotype, Social Jet Lag and Sleep Debt correlations

Then Age + education + objective and subjective sleep measure + chronotype, Social Jet Lag and Sleep Debt regression analyses

Chapter 5: physical activity level correlations

Then Age + education + objective and subjective sleep measure + chronotype, Social Jet Lag and Sleep Debt + physical activity level regression analyses

Chapter 6: psychological health measure correlations

Then Age + education + objective and subjective sleep measure + chronotype, Social Jet Lag and Sleep Debt + physical activity level + psychological health measure regression analyses

The results of this process are shown in the 'Summary' sections of each of the main Chapters (2 to 6). The final result of this process is shown in Figure 7.1 in Chapter 7 (Conclusions).

In addition to correlation and regression analyses, comparisons have also been made between groups based on age, gender, PSQ sleep quality ('good' versus 'poor') and Circadian preference ('owls' versus 'larks'). Further details on how these different groups are composed are given in this Chapter 2 (Age groups and gender differences), Chapter 3 (Sleep quality groups) and Chapter 4 (Circadian Behaviour groups or colloquially 'owls' and 'larks'). In general, independent t-tests are used to compare performance between the different groups and Cohen's d has been used to calculate effect sizes for all comparisons that reveal significant differences (effect sizes are not reported for non-significant differences). If Levene's test F statistic is significant in independent t tests, this is not separately reported, but the reported

degree of freedom will generally indicate where this is the case and where equal variances have not been assumed and thus where Levene's correction has been applied.

Comparison between groups has been made in order to compare and contrast the results in the present study with those reported elsewhere. For example, in the sleep literature, the performance of PSQ 'good' and 'poor' sleepers is frequently compared (see, e.g., Nebes, 2009; Rezaei, 2018); in Chapter 3, comparisons in memory domain performance have been made between 'good' and 'poor' sleepers and this has allowed the contrast with 'older' and 'younger' subjects. In addition, comparisons across multiple age groups may facilitate understanding of correlations; for example, by comparing the different profiles of how Social Jet Lag and Sleep Debt develops across four different age groups (Figure 4.7). Finally, group differences based on gender are revealed in VEM Long Term Forgetting (section 2.8.6) which are taken into account in the final overall regression model for VEM Long Term Forgetting (Figure 7.1 in Chapter 7). It should be noted however that age and gender groups, sleep quality groups and Circadian behaviour groups are not equally sized. Given this limitation, two-way ANOVA has been used in fairly limited areas; effect sizes for two-way ANOVA results show partial eta squared.

Finally, where Principal Component Analysis (exploratory factor analysis) has been undertaken, results are only reported for the best factor model as determined by the highest Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and highest cumulative variance explained by the factor model. Inferior models containing different variables are not reported; for example, no statistically acceptable model could be produced which included results from the Reading the Mind in the Eyes test and this 'failed' model is not therefore reported. Full results are provided for all factor models used in the analysis, including KMO, Bartlett's test of sphericity, determinant, eigenvalues, separate and cumulative factor variance, rotated component matrix scores, communalities, anti-image correlations and scree plots; in some cases, these have been shown in Supplementary Tables (e.g., for PCA factor analysis applied to certain psychological health questionnaire results). Reliability tests for PCA factor models show Cronbach's α and Cronbach's α based on standardised items. Items have not been deleted if to do so would not materially alter Cronbach's α (in practice by more than 0.05%) and provided Cronbach's α remains at a reasonable and high level if the item is retained.

2.2. Materials: Selection of Cognitive Tests and Key Scores from those Tests

In order to comply with ethical and practical considerations (principally, not over-burdening older community-dwelling subjects), it was necessary to be selective in the choice of supervised tests used in this project. Several overarching principles have been followed.

2.2.1. Principles Underlying Selection of Cognitive Tests: Straightforward, Well-established Tests were Chosen to Permit Reasonably Challenging Assessment of Different Memory Domains in a Sample of Predominantly Older Subjects

First, no more than four tests of memory and cognition would be undertaken in each phase of testing, with an approximate maximum duration of c.60-70 mins for each phase; see Table 2.1. Second, the selected neuropsychological tests should be established tests of memory and learning in three different domains; VEM, working memory and social cognition (comprising unfamiliar face memory and perception and mentalizing). This would permit the use of different tests to assess performance in each of these three domains. Third, as testing would take place in subjects' home and work environments, and subjects would include many older persons, tests had to be straightforward to administer. Finally, given the focus on older subjects in this project, and in order to minimise attrition in subject numbers between phases, the tests had to be challenging and engaging. Although a large number of persons declined to participate once the project was explained to them, no subjects withdrew from the project between phases.

2.2.2. Principles Underlying Selection of Representative Test Scores: Some Tests Generate a Large Number of Different Scores

Most of the working memory and social cognition tests generated a single overall score. However, neuropsychological tests of VEM potentially generate a large number of different scores. As explained in Chapter 1, it was originally intended to test a minimum of 200 subjects, but this had to be severely curtailed owing to the Covid 19 pandemic. It had always been the intention to undertake dimension reduction in order to categorise the memory domains represented by the scores in all the tests. A minimum of 200 subjects would have permitted 20 scores to be entered into exploratory Principal Component (PCA) factor analysis (adopting a case to variable ratio of 10:1). However, this had to be modified to a maximum of 14 scores for 145 subjects for PCA factor analysis to be valid. This in turn made it necessary to be selective about choosing the best representative test scores from the VEM tests, a task that was made more difficult by the computation of new test scores for long term forgetting in Buschke's VSRT (Buschke, 1973; see further below). There follows a summary of the cognitive tests used in this project in the chosen domains of VEM, working memory and social cognition. In

addition to describing the materials and procedures in all the tests, in the case of VEM tests, reasons will also be given for selection of particular scores from those tests as representative scores to be used in PCA factor analysis.

2.2.3. VEM: Buschke's Verbal Selective Reminding Test (or VSRT): One Important Addition was made to the Standard VSRT Test Measures

Buschke's VSRT (Buschke, 1973) measures VEM using multiple-trial list learning (Buschke, 1973; Buschke & Fuld, 1974). The standard adult version (Form 1) of the test was used (Hannay & Levin, 1985) and the procedure adopted is described in Larrabee et al. 1988 (Larrabee, 1988). In summary, a list of 12 words is read to a subject who then recalls as many of the words as possible. Each subsequent trial (12 in total) involves the selective presentation of only those words that were not recalled on the immediately preceding trial. The standard VSRT distinguishes between what it describes as short-term and long-term free recall (or STR and LTR) and includes components of cued recall and recognition, the latter component being assessed by way of multiple choice.

The VSRT free recall, cued recall and recognition were always administered as the first test in Phase 1; see Table 2.1. At the end of Phase 1, and after the intervening social cognition tests, subjects were again invited to recall the 12 words (i.e., standard delayed recall). The exact length of the delay depended on how long the subject took to complete the social cognition tests. Delayed recall was usually between 30 minutes and 45 minutes after completion of the main VSRT which is in line with usual practice, see, e.g. Larrabee, 1988; Ruff, 1989. In order to differentiate this standard delayed recall from the long-term recall after two weeks (described further below), this 30-45 mins delayed recall will be referred to as short-term delayed recall.

Importantly, one novel addition was made to the standard VSRT procedure (Larrabee, 1988). Phase 2 testing (after two weeks) began with a recap of the VSRT in which participants were first asked to freely recall as many of the Form 1 words as they could (i.e., 'delayed recall +14 days'). Immediately following this delayed free recall attempt, they were invited to repeat the cued recall and recognition components of the VSRT from phase 1 testing; see Table 2.1. Subjects were not informed at phase 1 testing that they would be re-tested on the 12 words at phase 2, to forestall any writing down of the words or deliberate rehearsal between phases 1 and 2.

The reason for introducing this new element to the VSRT is that phase 2 testing offered an opportunity to examine the durability of delayed recall over a much longer period than the

standard 30-45 minutes delay (i.e., assessment of new *long-term* delayed recall). As described below, new 'VEM Long Term Forgetting' scores were calculated for free recall and cued recall components after two weeks. There was so little variation in VSRT recognition scores (i.e., there were clear ceiling effects), at both phase 1 and phase 2, that a forgetting score for multiple choice/recognition was not separately calculated or included in factor analysis.

2.2.4. Calculation of VSRT Forgetting Rate included Measures for both Free and Cued Recall after Two Weeks

Two measures of long term forgetting were therefore calculated using the formula (A-B)/(A+B) where A is the score for free or cued recall at phase 1 and B is the score for free or cued recall at phase 2. This methodology takes into account relative change, as opposed to simple absolute differences, (as recommended by Loftus, 1985). For example, Person X may remember 10/12 words at phase 1 and 8/12 words at phase 2 whereas Person Y may remember 8/12 words at phase 1 and 6/12 words at phase 2. Both X and Y have a score of 2 using a simple A-B formula for forgetting, but as Loftus, 1985 notes, Person X has 'more to remember'. The A-B/A+B methodology reflects this additional burden on Person X so that their rate of forgetting is lower (10-8/10+8=0.111) than that of Person Y (8-6/8+6=0.143).

The two scores for free and cued long term forgetting were both included in PCA factor analysis (see further below). PCA exploratory factor analysis was also undertaken for two other methods of calculating long term forgetting. The first used a simpler (A-B) formula (with A and B as previously described) and the second used a slightly adjusted formula of (A-B)/A. When scores for free and cued long term forgetting using these different bases of calculation were entered into exploratory factor analysis alongside the ten other cognitive test scores (see below), the same four factor memory domain solution was returned as when using the (A-B)/(A+B) formula (see Supplementary Tables 2.2 and 2.3), and the two different factor solutions also explained very similar levels of variance. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy suggested that the strongest factor model was the one using the (A-B)/(A+B) formula (KMO=.747, compared with KMO of .639 for (A-B) and KMO of .704 for (A-B)/A). Accordingly, the PCA factor solution using the (A-B)/(A+B) methodology for calculating long-term forgetting is the one used and reported in this study.

2.2.5. Scoring system in the VSRT: the VSRT Generates a Number of Different Measures

Aside from the newly created long-term forgetting scores, the Buschke VSRT yields a number of different potential measures; (see Larrabee, 1988 at page 176). When a word is recalled

twice in a row, it enters long term storage (LTS) from the occasion of first recall. When a word in LTS is recalled, it enters long term recall (LTR). LTR may become consistent long term recall (CLTR) where it is recalled without fail in all subsequent trials. Any LTR occurring before CLTR is random long term recall (RLTR). Any isolated recall before a word moves into LTS is short term recall (STR). The number of reminders is also calculated, being the aggregate total number of times a subject fails to recall any of the 12 words in any of the trials. 'Intrusions' are words recalled that are not on the list. It follows that high scores for STR and Reminders are indicators or poorer VSRT performance whereas high scores for LTS, LTR and CLTR are indicators of better VSRT performance. Sum Recall is the sum of LTR and STR scores.

2.2.6. Selecting Representative Scores from the VSRT: Scores for Immediate Recall and Short Delayed Recall (after 30 minutes) are Frequently Reported

Although there are different versions of selective reminding test, the most frequently reported scores across all versions appear to be those for immediate or sum recall and delayed recall (Masur, 1994; Albert, 2001; Sliwinski & Buschke, 1997; Brickman, 2011). In the VSRT, immediate recall comprises both STR and LTR and is therefore a composite score of good and poor performance. Those persons who score highest on LTR score lower on STR, and vice versa (Larrabee, 1988). However, immediate recall remains one of the core scores of selective reminding tests and, for example, has been shown to predict both conversion to, and diagnosis of, AD (Tabert, 2006; Didic, 2013; Lemos, 2015; Jacobs, 1995).

Buschke's VSRT scores selected as variables to be included in factor analysis were VSRT sum recall, immediate cued recall and delayed free recall after 30 minutes (Larrabee, 1988). In addition, the two new measures of VSRT long term forgetting for both free and cued recall (described above) were also included.

2.2.7. VEM: the RAVLT is the Second Test of Verbal Learning and Memory used in the Present Study

The RAVLT (Rey, 1964) also assesses VEM using a test of verbal learning and memory and, like Buschke's VSRT, includes measures of immediate and delayed recall (Woodard, 1999; Bleecker, 1988).

2.2.8. The Present Study used the Standard RAVLT Procedure

The procedure followed in this study is described in detail elsewhere (e.g. Moradi, 2017 at page 417 and Sundermann, 2016 at page 1369). Briefly, in the RAVLT, the subject freely recalls 15 words for 5 trials. After trial 5, an interference list of 15 words (List B) is freely recalled,

followed by delayed recall of the first list (List A, trial 6) without further presentation. After a 30 minute delay, the subject is again tested on free recall of List A (trial 7). Recognition is also then tested with 50 words from which the subject must identify the 15 List A and 15 List B words.

In order to avoid interference between Buschke's VSRT and the RAVLT lists of words, the RAVLT was administered to subjects in phase 2 of the supervised testing (see Table 2.1) after they had completed the Stroop test. In the event, no subject suffered any intrusions of words from Buschke's VSRT when recalling RAVLT words. As seen from Table 2.1, the Four Mountains Test and Glasgow Face Matching Test were administered in the approximate 30 minutes period between the last free recall trial (trial 6) and the delayed recall (trial 7) of the RAVLT.

RAVLT scores include 'acquisition' (the number of List A words recalled across the first 5 trials), 'learning' (the difference between 'acquisition' and the number of words recalled on the first trial, A1, multiplied by 5) and total percentage correct (or percentage immediate recall of the List A words across the first five trials); intrusions (i.e. words 'recalled' that were not on the list) affect the percentage RAVLT scores. Other scores for (e.g.) the interference effect of List B, 'forgetting' and 'recognition' are also calculated. The 'delayed recall' score is the percentage achieved at Trial A7 (with any intrusions reducing the percentage delayed recall score).

2.2.9. Selecting Representative Scores from the RAVLT: Immediate and Short Delayed Recall (after 30 minutes) have been shown to Predict Cognitive Functioning

As with VSRT scores, previous research shows that the RAVLT scores for immediate and delayed recall appear to have the highest predictive power for cognitive functioning. In some cases, immediate recall is computed as the simple sum of all recalled words across the first five trials (e.g., Estevez-Gonzalez, 2003) and immediate and delayed recall are often therefore scored in a range of 0-75 and 0-15 respectively (e.g., Sundermann, 2016). In this study, total percentage correct has been taken as the actual measure of immediate recall, i.e., adjusting the immediate recall score for any incorrect intrusions. However, owing to the low numbers of intrusions generally, the correlation between adjusted percentage correct and the unadjusted score is very high (Pearson's $r=.975$, $p<.0001$). Similarly, delayed recall has also been calculated as a percentage, again adjusting for intrusions, rather than as a score out of 15. Although other RAVLT scores have been the focus of specific studies (see e.g., Dunlosky &

Salthouse, 1996; Woodard, 1999; Loftus, 1985) in line with earlier research, the best representative scores from the RAVLT chosen to be included as variables in PCA factor analysis were those for immediate recall and delayed recall.

2.2.10. Working Memory Comprises Two Different Tests in the Present Study

Two tests of working memory (the Stroop test and the Four Mountains test) were undertaken. The two tests are very different but were in any event separated by the RAVLT so that there was no question of any interference arising between them.

2.2.11. The Stroop Test: Two Versions of the Classic Card Reading Stroop Test were Used

The Stroop test (MacLeod, 1991) is a well-known test of selective attentional control (MacLeod, 1991; 1992, Van der Elst, 2006) and is a useful test of working memory in older subjects because it is easy to administer and "the effect is large and always statistically reliable" (MacLeod, 1992 at page 12). Although there are different formats, including computerised versions, (see, e.g., Spieler, 1996; Perlstein, 1998), the classical card-reading version of the Stroop test (MacLeod, 1992) was used here, principally for the ease and comfort of older subjects. The version used requires the subject first to perform a baseline timed task, namely, reading a list of 50 words which are names of colours. A second timed task involves naming the incongruous colour of the ink for a displayed word, e.g., subjects must say 'blue' for the word 'red' appearing in blue ink. This second task takes longer because the subject must suppress the name of the word ('red') and name the colour of the ink ('blue'). The difference in time between the two tasks is known as the Stroop interference effect and represents two cognitive processes: enhancement of the salient ink colour and inhibition of the non-relevant word (Van der Elst, 2006).

Subjects undertook two versions of the Stroop Test. The first version involved three colours: red, green and blue. The second version involved the same procedure but used five colours: red, green, blue, yellow and orange. In each version, between the two timed trials, subjects were asked to name the colour of 50 plain blocks of colour (i.e. no words). This was a control measure to check for correct colour discernment by subjects. Two subjects self-reported some mild colour blindness but were able to complete the colour block control test without evident difficulty. The Stroop interference effect in each of the two versions was calculated for each subject and the average interference effect (in seconds) was calculated. The correlation between the interference effect in the two versions of the test for all subjects is Pearson's r=.829,

p<.0001. Subjects' performance was therefore highly consistent across both the 3 and 5 word versions of the test.

2.2.12. The Four Mountains test (4MT) was used to Assess Spatial Working Memory

The 4MT (Hartley, 2007) is a well-established test of spatial working memory in which the subject must identify a previously seen scene from a new viewpoint after a short delay of two seconds (Hartley, 2007; Hartley & Harlow, 2012). The 4MT has been shown to be a reliable differentiator between clinical and non-clinical levels of spatial memory impairment (Bird, 2010; Pengas, 2010; Moodley, 2015; Wood, 2016; Chan, 2016).

In the test, the subject is first shown a full-screen stimulus landscape of an array of four mountains for eight seconds. This is followed by a blank filler screen lasting 2 seconds (i.e., a very short delay) before a quartered screen presents a choice of four different arrays, each comprising four mountains, for a period of 20 seconds. The subject's task is to select from the four-choice slide the array that correctly matches the full-screen stimulus previously shown; see Figure 2.1B. However, this is not simply a visual matching test after a short delay because the correct target could be rotated by as much as 70^{o} to show the target array from a different perspective. The test therefore requires some manipulation of spatial working memory. Further details of the test are described in earlier research (Hartley, 2007). All subjects undertook the test on the same laptop computer and all subjects were first given a practice of several trials before completing the actual test.

Two working memory scores, for the 4MT total correct and average Stroop interference effect, were selected for inclusion as variables in PCA exploratory factor analysis.

2.2.13. Four Tests of Social Cognition were used in the Present Study

Four social cognition tests were used in total, comprising three tests of unfamiliar face processing and one test of interpreting emotion (or mentalizing).

2.2.14. Face Memory and Perception: the Jenkins & Burton Unfamiliar Face Learning test was used to Measure Subjects' Performance in Unfamiliar Face Processing

The Jenkins & Burton unfamiliar face learning task (Jenkins & Burton, 2011) is the least well-known of the 4 social cognition tests used. One of the main reasons for its inclusion early on in phase 1 testing was to relax and engage older subjects who might have been anxious about what to expect from cognitive testing, as well as their own performance. In the event, the test

proved to be a highly effective test of unfamiliar face processing, performance on which was strongly associated with the other two more well-established tests of face processing (see further below).

The test had two conditions. In the first 'free sort' condition, subjects were given a shuffled series of 40 passport-sized black and white photographs of faces comprising 20 pictures each of two unfamiliar young women. Subjects were asked to arrange the pictures into separate piles for the number of different identities (i.e., different persons) they perceived. There was no time restriction on this task. The materials used were identical to those used in earlier research (Jenkins & Burton, 2011; Andrews, 2017). The materials were identical for all subjects; see Figure 2.1A. The measure of interest in the 'free sort' condition was the number of identities chosen. This condition was essentially a familiarisation or learning condition, and the score has not been subjected to any detailed analysis in this study. The actual performance range in the first condition was 2-40 with a mean of 10.27 identities (SD=6.82). Both the range and the mean are higher than that reported elsewhere (Jenkins & Burton, 2011). Unlike the second condition, there was no age-related performance effect in the number of identities perceived; Pearson's r=.055, p=.51.

In the second 'forced choice' condition (which followed immediately after the 'free sort'), subjects were told there were in fact only two persons, and were then asked to sort the photos into the relevant two piles. Fifteen subjects identified 2 persons in the 'free sort' condition and were then simply given the option of making any changes to their original two piles. The measure of interest in the 'forced choice' condition is the overall number of unfamiliar learned face errors (maximum=20).

2.2.15. The Cambridge Face Memory Test (CFMT) was used to Assess Subjects' Memory for Unfamiliar Faces

The CFMT is a well-established memory test for unfamiliar faces in which subjects familiarise themselves on screen with six target faces (Duchaine & Nakayama, 2006). Subjects are tested for their memory of the introduced faces in a 'forced choice' design experiment where the test items may be (a) identical views of the target, (b) novel views of the target or (c) 'noisy' (i.e. visually indistinct) novel views of the target. The objective is for the participant to 'recognise' the target (learned) face in any of the relevant presentations (identical, novel or novel with noise), i.e., it is a test of memory for unfamiliar faces; see Figure 2.1A.

In the first introductory section, subjects are presented with a face shown from each side and straight on (i.e., from 3 perspectives) and are instructed to memorise the face. They must then select this target face from a choice of three different faces. There are 18 trials in the introduction section. The second and third sections increase in difficulty. In the second 'no noise' section, the subject is asked to memorise six faces presented together for a period of twenty seconds. The subject must select, in 30 trials, which of three presented faces is one of the six originally memorised. The third 'noise' section follows the same procedure as the second section through 24 further trials, but in these trials the faces are all pixilated.

The CFMT is available as a download programme and automatically records the subject's choice, providing a score for each of the three sections and an overall score out of 72. All subjects completed the test on the same laptop computer. The test is not time constrained and subjects were permitted to take as long as they needed to make their selection.

2.2.16. The Glasgow Face Matching Test (GMFT) was used to Measure Subjects' Perceptual Processing of Unfamiliar Faces

The GMFT is a test of unfamiliar face matching (Burton, 2010), i.e., *not* face memory. Subjects are shown pairs of unfamiliar faces on a laptop and must judge whether the pair of faces is the same identity or not. This is a test of perceptual processing rather than memory. In the example stimuli shown in Figure 2.1B, the female faces are a 'matching' pair and the male faces are a 'non-matching' pair. A short form of the test comprising 40 trials was used, so that GFMT scores have an absolute range of 0-40.

In a recent study (Verhallen, 2017), scores on the CFMT and GFMT were found to be highly correlated (Pearson's r=0.48). In order to avoid any potential interference effects between the two tests, the CFMT was carried out in phase 1 testing and the GFMT in phase 2.

2.2.17. Mentalizing: The Reading the Mind in the Eyes Test was used as a Measure of Subjects' Mentalizing Abilities

In this test, subjects examine a pair of eyes and make a judgement from 4 available choices, about what that person is thinking or feeling (Baron-Cohen, 1997; 2001); see Figure 2.1A. This test of emotion recognition is a key element of cognitive empathy or mentalizing (Vellante, 2013; Gregory, 2019). For subjects who may have been unfamiliar with any of the descriptions of emotion, a glossary defining the word and giving a contextual example was provided. There were 36 trials in total and subjects undertook the test on a laptop computer at their own speed.

2.2.18. Face Memory and Perception--Summary

As described, when undertaking PCA exploratory factor analysis, the Reading the Mind in the Eyes test score did not load onto any of the factors to a statistically acceptable level and its inclusion would have prevented generation of a statistically strong PCA model. Accordingly, the reported PCA factor solution only therefore includes the results from the three face memory and perception tests. The Reading the Mind in the Eyes test is very different from the other three tests of social cognition because those all involve complete faces and do not require the subject to 'take the perspective' of the viewed person (i.e., there is no element of mentalizing in the three tests of unfamiliar face memory and perception). As described later, scores on the Reading the Mind in the Eyes test correlate significantly with the three tests of face memory and perception, but not as strongly as those other three tests correlate with each other.

2.3. Materials: Questionnaires

2.3.1. Subjects Completed 15 Questionnaires, including 11 on Psychological Health

Subjects completed 15 questionnaires, a full list of which is given in Appendix 4. Full details of 11 psychological health questionnaires are given in Chapter 6. The four remaining questionnaires comprised a questionnaire on educational level attainment, the Pittsburgh Sleep Questionnaire (see Chapter 3), the General Practice Physical Activity questionnaire (see Chapter 5) and the Spatial Abilities questionnaire (see Chapter 6).

Scores from the 11 psychological health questionnaires were arranged into two separate, slightly overlapping groups for the purposes of exploratory PCA factor analysis, again due to the limitations imposed by case to variable ratios. PCA factor analysis produced a total of five social psychological factors derived from the two sets of scores that were taken from the 11 separate questionnaires. However, due to a clear relationship between some factors in the two different sets, the five factors have been further reduced to three social psychological measures or domains, as further described below.

2.4. Materials: Actigraphy Assessment

2.4.1. Subjects' PA levels and Sleep over Two Weeks were Measured using a Research-grade Accelerometer

Subjects (N=145) wore a "GENEActiv Original" wrist triaxial accelerometer device ('the device'; see Figure 2.2) continuously for a two week period. Triaxial, put simply, means that

the device measures acceleration in three planes: backwards/forwards, up/down and side to side.

Figure 2.2: Methods of Sleep, Circadian and Physical Activity Measurement

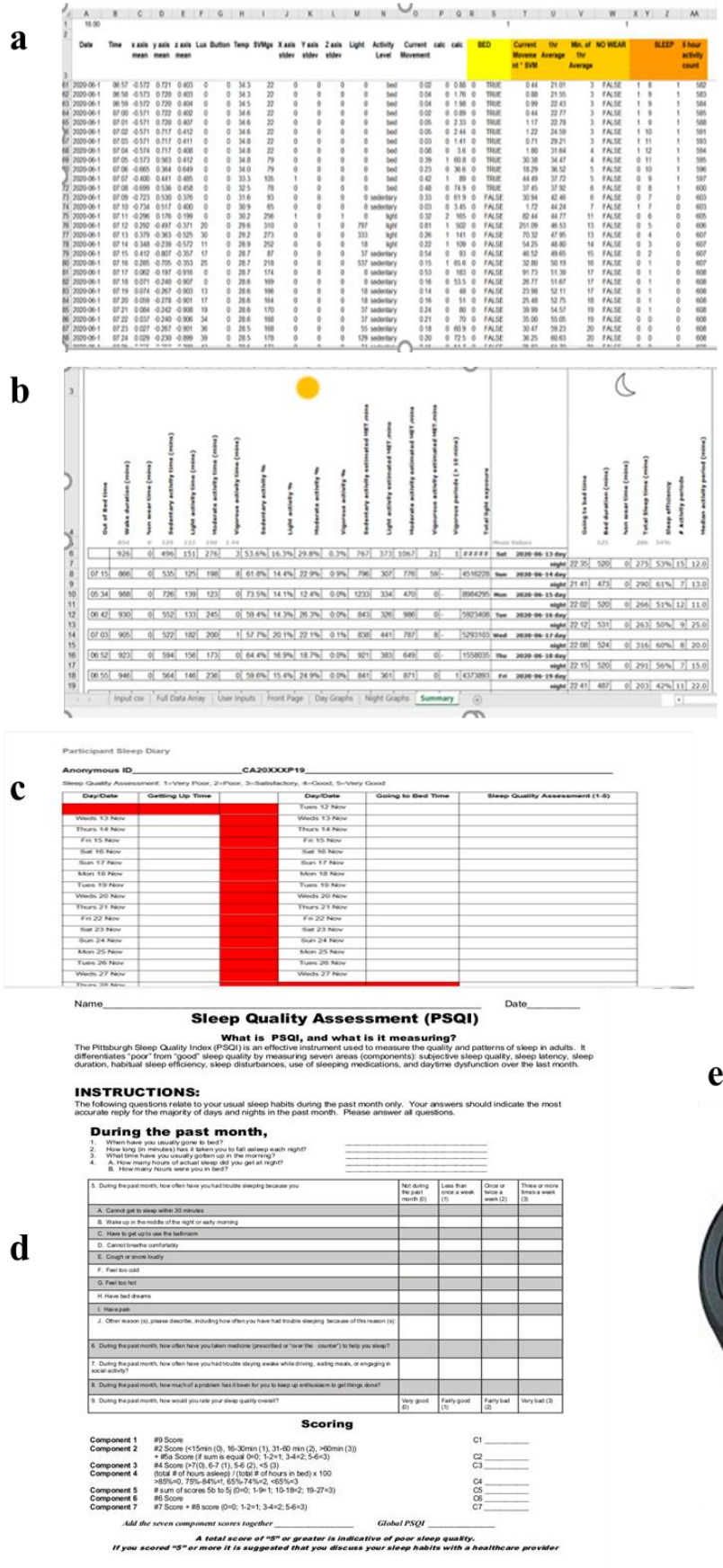


Figure 2.2. Methods of Sleep, Circadian and Physical Activity Measurement. **a.** Example data printout showing recordings of activity and sleep (coded 1) made by the accelerometers worn by subjects. Detailed analysis of activity levels (see central column) in 60 second intervals. **b.** Example of a summary report produced by GeneActiv software, showing daily summaries of wake and sleep periods and different activity levels. **c.** Example Sleep Diary for completion by subjects. **d.** The Pittsburgh Sleep Quality Questionnaire measures aspects of sleep quality to produce a score on the Pittsburgh Sleep Quality Index (or PSQI score). The questionnaire formed part of an online questionnaire completed by the majority of subjects (N=140). **e.** GeneActiv Original wrist-worn accelerometer used by **all subjects.**

Wrist-worn devices were chosen for the better comfort of subjects, especially older subjects. The devices are small, lightweight and waterproof (Phillips, 2013) and allow good age-group comparability of raw accelerometer data (Hildebrand, 2014). GENEActiv devices are produced by ActivInsights Ltd. The GENEActiv Original device was chosen because it provides access to raw acceleration data up to 100 Hz and, when calibrated at 50Hz (as here) records sleep and PA for each minute for a consecutive period of 15 days; see Figure 2.2 for representations of data output. The GENEActiv Original device has been used in sleep-only, PA-only and 'mixed' sleep and PA studies (e.g. Kuula & Pesonen, 2019).

GENEA ('Gravity Estimator of Normal Everyday Activity') devices are reliable instruments which accurately classify PA levels (sedentary, light, moderate and vigorous) and PA intensity (Esliger, 2011). The devices' cut-off points for different activity levels have been verified against oxygen consumption (VO2) (Hildebrand, 2014). Validation of the device's performance in the analysis of PA levels has been undertaken in different populations in free living conditions, including (e.g.) children, wheelchair users, adults with depression, adolescent girls, pregnant women and adult recreational marathon runners (Montoye, 2015; Welch, 2013; Schaefer, 2014; Nightingale, 2015; Pentecost, 2015; Hamlyn-Williams, 2014; Morgan, 2014; Hernando, 2018).

Twenty (20) GENEActiv Original devices were acquired and used in the project together with cradles for charging, configuring and downloading data from the devices. Freely available GENEActiv software was used to extract the data from the devices and convert it into csv. files. Subsequently, data was converted into 60 second Epoch csv. files which were imported into Excel Macro schedules. This schedule provides an 'easy-read' summary of the daily physical activity and sleep data (see Figure 2.2) together with a 'minute by minute' analysis of activity levels and sleep in the accompanying full data array schedule (see Figure 2.2). Data collection and interpretation is based on the full data array, and not the summary information.

2.4.2. Subjects only Wore the Devices over a Fairly Typical Two Week Period (e.g. not including any Personal Holiday)

Subjects in the main study wore the devices at some point during the year from March 2019 to March 2020. To assist configuration of devices, subjects provided certain personal details in advance, namely height, weight, date of birth, sex, handedness (left/right) and whether the device would be worn on the left or right wrist. Generally, subjects were provided with the device at the time of Phase 1 cognitive testing and the device was collected from them two

weeks later at Phase 2 testing; see above for details of testing phases. Subjects were asked to wear the devices only during a fairly typical two week period. Subjects did not wear the devices (and did not wish to wear the devices) during extended holiday periods. Subjects were asked to keep a note of, and report, any significant non-wear time. No subject reported any significant non-wear time; when non-wear was reported, it was generally *de minimis* (e.g. 10 minutes in the shower). Any reports of non-wear time were corroborated against the data array.

The main reason for requiring 15 days wear was in order to examine subjects' sleeping patterns over a two week period that included two weekends, so that chronotype and certain Circadian measures, such as Sleep Debt and Social Jet Lag, could be objectively calculated (see further in Chapters 3 and 4 below). In other cases, (e.g., Menai, 2017) the same devices have been calibrated at higher levels (e.g. 85.7 Hz in that case) allowing finer analysis (e.g. 5 second epochs) albeit over a shorter period (e.g. 7 days). This allows for more rigorous appraisal of whether any given minute should (e.g.) be characterised as 'light' rather than 'moderate' PA, but close analysis of one particular level of activity was not a major focus of this study; the main interest was in collecting both sleep and PA data over an extended two week period.

A small number of subjects wore the devices for slightly under 15 days, where, for example, Phase 2 testing was scheduled exactly two weeks from Phase 1. However, subjects always wore the devices over two full weekends and, in some cases, over Bank Holiday Weekends. All PA data for partial days of wear (e.g. the days on which the devices began and ceased to be worn) has been entirely excluded from the analysis of PA. Data collection effectively commenced with 'going to bed time' on the first day of device wear and terminated with 'getting up time' on the last day of device wear.

2.4.3. The Aggregate of Bed Duration and Four Different Activity Levels Comprise the Data collected for each Full Day of Accelerometer Wear

In the data summary provided in the GENEActiv software (see Figure 2.2), a full day of device wear comprises 'bed duration' plus 'wake duration'. Bed duration is the duration between the time at which the device records the person going to bed and getting up, which itself includes both 'sleep' and 'non sleep' time. This is considered in more detail in Chapters 3 and 4 below. Wake duration is the sum of the 4 different activity levels (sedentary, light, moderate and vigorous).

A standard full day comprises 1440 minutes (24x60) meaning that each participant should, in principle, have a total of 1440 minutes comprising bed duration, aggregate PA and sedentary

time when the devices are set at 50Hz. However, in practice, average 'total day' wear time differs from day to day. This is most obviously the case where, for example, a subject's behaviour for the first day of wear/recorded data is (say) 7 hours of sleep from (say) 1:00am following first wear and 16 hours of waking time (from say 8:00am until midnight) on the first full day of wear (giving a total of 23 hours of data for the first full day). Similar patterns may arise on the last day of full wear. Over a two week measurement period, the average total day for subjects tends to converge towards 1440 minutes. The average total day for all participants is 1428.27 minutes (SD=33.6 minutes). No adjustments have been made to accommodate this small difference (11.73 minutes) between 'standard' daily minutes and average recorded daily minutes.

Finally, no attempt has been made to validate, standardise or manipulate physical activity (or sleep) data measurements made by the GENEActiv Original devices in this study to bring them into line with any measurements made or taken in any other study. In particular, no attempt has been made to examine or modify the standard device cut-off points between light, moderate and vigorous activity levels. Other studies may use different more specialised methods for accelerometer raw data extraction and analysis.

Further details of the accelerometer devices worn by subjects and actigraphy data assessment are provided in Chapter 3 (Sleep), Chapter 4 (Circadian behaviour) and Chapter 5 (Physical Activity).

2.5. Age Groups

2.5.1. Procedure for Analysing by Age Groups--Age 50 has been selected as the point for dividing Subjects into Main Age Groups

For the purposes of comparing the performance of younger and older persons, subjects in this project have been divided into two main age groups. The younger age group is aged below 50 and the older age group is aged 50 or above. The age range of all subjects is 21-91 (i.e., a very wide range of 70 years). Average age in the younger group (N=52) is 36.06 years (SD=8.94) and in the older group (N=93) is 66 years (SD=9.51); i.e., there is a mean difference of approximately 30 years between the younger and older groups; see Table 2.3. The population sample in this study comprises almost twice as many older subjects as younger subjects and accordingly age is not normally distributed (Shapiro-Wilk's test: W_{145}=.936, p=.001). This was a deliberate sampling bias in the first year of the present study in which the priority was to recruit older subjects; it had been hoped that the number of younger subjects might be increased

at a later point, but extending the sample numbers in this way was undermined by the restrictions imposed on subject testing by the Covid 19 pandemic throughout 2020 and 2021.

Table 2.3 Age Groups

Age Group	Number (N)	Mean Age	SD
Younger (18-49)	52	36.06	8.94
Older (50+)	93	66	9.51
All	145	55.26	17.14

Age Group	Number (N)	Mean Age	SD
18-35	26	28.35	4.36
36-50	28	44.21	4.64
51-65	40	57.65	4.38
66+	51	73.18	5.73

Table 2.3 shows the division of subjects into age groups. The top half of Table 2.3 shows the main division used in this study between younger and older age groups. The younger group comprises 52 subjects who were aged 18-49 at the time of testing and the older group comprises 93 subjects who were aged 50 or above at the time of testing. The average age of the younger group is 36.06 and the average age of the older group is 66. There is therefore a 30 year gap in the average age of subjects in the two groups. The age range of all subjects is 21-91 (70 years). For the purposes of certain detailed exploratory analysis, subjects were also divided into four separate age groups (shown in the bottom half of Table 2.3). Group 1 comprises subjects aged 18-35 (M=28.35). Group 2 comprises subjects aged 36-50 (M=44.21). Group 3 comprises subjects aged 51-65 (M=57.65). Group 4 comprises subjects aged 66 or older (M=73.18). The groups were selected to represent (broadly) 15 year age gaps, although no subject was aged under 21 and the age range in the oldest group is 66-91. The differences in mean ages of the Groups is reasonably consistent: Group1-Group 2=15.86 years; Group 2-Group 3=13.44 years and Group 3-Group 4=15.53 years. Group 2 (36-50) contains 2 subjects who were aged 50 at the time of testing. These subjects fall into the second youngest of the four age groups but into the older group (50+) in the main age groups. Accordingly, there are 54 subjects in Group 1 and Group 2 but 52 subjects in the younger of the two main age groups so that the two main age groups, younger and older, do not precisely correspond with Groups 1 & 2 and Groups 3 & 4.

For the purposes of undertaking some detailed exploratory analysis, and because of the wide 70 year age range and 30 year gap in average age in the two main age groups, subjects have also been categorised into four smaller age groups with, very broadly, 15 year age ranges, i.e., 18-35 years, 36-50 years, 51-65 years and 66 years or over; see Table 2.3 for details.

2.5.2. Brief Summary of Reasons for Selecting Age 50 as Cut-off between Younger and Older Groups

There are several reasons why the cut-off between younger and older groups in this project has been selected as age 50. First, the decline in cognitive performance in some of the neuropsychological tests used in this project (in particular, in VEM) has been shown to accelerate from approximately age 50 (Larrabee, 1988; Van der Elst, 2005). Second, there is evidence to suggest that the brain changes that occur in cognitive impairment may already be underway by middle age (see, e.g., Price & Morris, 1999). Third, physical performance (although not activity level) tends to decline from late middle age (Hall, 2017) and normal

sleep patterns may also be starting to deteriorate around this age (Scullin, 2017). Age 50 has also been identified as the point for Circadian behavioural change towards greater morningness-type behaviour (Ishihara, 1992; Tankova, 1994); the precise timing of this change is considered in detail in Chapter 4. Finally, evidence suggests that deliberate pruning of social friendship networks may also begin to occur around late middle age (Carstensen, 1992; Wrzus, 2013; English & Carstensen, 2014).

In summary, a cut-off at age 50 has therefore been taken for the purposes of dividing subjects into younger and older groups because age 50 may be the latest point at which memory and cognitive performance, PA and sleep behaviour can be safely assumed not to have appreciably changed, and it should also be before any substantial selective pruning of social networks has taken place. In some areas, exploratory analysis using the four smaller age groups has also been helpful, although being mindful that this is a cross-sectional study only. For example, in Chapter 4, results from the more detailed groups suggest that Circadian behavioural change may occur substantially before age 50 and in Chapter 5 a more nuanced picture of physical activity changes seems to emerge when examining the more detailed age groups.

2.5.3. Gender Profile

There were a higher number of female subjects in the study, and they outnumber males overall and in the two age groups by a little over 2:1. Older males in particular were much more reluctant to participate; see Table 2.4A. No answer is offered here as to why that was the case; it might reflect some greater resistance by older males to any perceived health testing, even though it was made clear to all potential subjects that this was not a personal, clinical assessment of their cognitive health.

Table 2.4A: Gender Representation in the Main Age Groups

Gender	Number (N)	Mean Age	SD	Younger (N)	Age (M)	Older (N)	Age (M)
Male	46	54.46	16.07	16	35.94	30	64.33
Female	99	55.64	17.68	36	36.11	63	66.79

Table 2.4A shows gender representation in the two main age groups. Female subjects outnumber male subjects by approximately 2:1. There is no age difference between male (M=54.46) and female (M=55.64) subjects (t_{143}=-.385, p=.70).

2.5.4. Education Level

Table 2.4B shows education level by age group. Education is scored at 16 for highest level (post-graduate degree) to 1 for lowest. There is a significant reduction in educational attainment level with age; (N=139), Pearson's r=-0.267, p=.001. The younger group is more highly educated than the older group; $t_{133.195}$=2.905, p=.004, Cohen's d=0.50.

Table 2.4B: Education Level in the Main Age Groups

Age Group	Education Level (1-16)	SD
Younger (18-49)	14.18 (N=49)	3.17
Older (50+)	12.18 (N=90)	4.94
All	12.88 (N=139)	4.49

Table 2.4B shows education level in the main age groups. Education is measured on a scale of 1-16 where 16 represents the highest level of educational attainment (by reference to qualifications achieved rather than years in education, although there is likely to be some relationship between the two). Younger subjects have a higher level of educational attainment than older subjects ($t_{133.195}$=2.905, p=.004).

2.5.5. BMI and Handedness

When accelerometer devices were configured for subjects, they provided details of their handedness and their BMI was also automatically calculated from their height and weight information; see Table 2.5A.

Subjects' BMI averages were somewhat lower than the national averages for England in 2018; see Table 2.5B. National averages for 2018 are the best available comparator to the BMI of subjects in this study at the commencement of testing (it is possible that more recently published BMI statistics may be influenced by Covid 19 lockdowns during 2020 and 2021). Average national figures would suggest a BMI of 28.8-29 for male subjects and a BMI of 28.3-28.4 for female subjects in this study. Normality plots suggest that BMI is skewed towards lower scores in the range (Shapiro Wilk's: W_{145}=.969, p=.002). Both males and females have BMI figures that are approximately 10-15% lower than these national averages. This probably reflects the socio-economic profile of this sample and the fact that participation has generally been limited to more active persons.

Table 2.5A: BMI by Age Group and Gender

Age group	N	BMI Mean	SD
Younger	52	24.54	3.73
Older	93	24.88	3.72
Total	145	24.76	3.72
Gender	**N**	**BMI Mean**	**SD**
Male	46	25.72	3.28
Female	99	24.31	3.83

Table 2.5B: National Averages for BMI in England, 2018; source: Statista.com

Age Group	Men	Women
16-24	24.4	24.5
25-34	26.2	26.9
35-44	27.4	27.7
45-54	28.8	28.4
55-64	29	28.3
65-74	28.6	28.5
75+	27.8	27.7

Tables 2.5A and 2.5B show Body Mass Index (BMI) scores for all subjects derived from weight and height information they provided for the purposes of personally configuring their accelerometer. Table 2.3 above showed that the average age in the younger group was 36.06 years and in the older group was 66 years. Based on externally sourced data (Table 2.5B) it can be seen that national average BMI for someone aged 36 is approximately 27.4-27.7. The average BMI of subjects in the younger group in this study approximates to the national average for 16-24 year olds. In the older group, BMI of 24.88 is not different from BMI of the younger group (t_{143}=-.521, p=.60) and is some way below the national average of 28.6-28.5 for the 65-74 age group. These figures suggest that both younger and older subjects in this study represent a population that is probably more physically active and comparatively healthier than the wider population.

2.6. Methodological Issues

2.6.1. The Cross-Sectional Nature of the Present Study is a Limitation

One of the major methodological limitations of this study is its cross-sectional design. Cognitive performance, sleep and physical activity have not been measured longitudinally and so it is not possible to determine how these factors may have changed, and how any such changes may be associated with one another, over the lifespan. At best, inferences might be drawn from associations between different variables and age, but this is also subject to the major limitation in a study such as this, namely, the practical problem of correcting or controlling for a multiplicity of potentially contributory variables. To give some very simple examples, some subjects may have very different diet behaviours which may affect physical activity and exercise levels; importantly also, alcohol consumption, which might (say) affect sleep patterns and behaviour, has not been quantified. Some older subjects may take supplements or over-the-counter medicines that may affect their sleep, activity levels or even psychological mood. These matters may have a bearing on simple correlations which should therefore be approached with a measure of caution, particularly where p values are only moderate and/or effect sizes are low.

2.6.2. Self-selection Bias

Self-selection bias may arise if older subjects are either too busy or too incapacitated (e.g., in poor health) to participate (Harada, 2013). This may limit the participant pool to subjects who may over-represent a particular socio-economic sub-group of healthy and willing volunteers.

As testing in this project was extensive, subjects also self-selected according to their willingness and ability to undertake testing over two separate supervised phases. This has probably skewed the studied population towards more active, confident and socially engaged persons who were willing to make a reasonably large time commitment to the project, and in particular, this may not be fully representative of persons in any similar older age group in the wider population.

2.6.3. Cohort Differences

There may be cohort differences in any cross-sectional study. For example, matters such as diet, education and exercise may vary substantially between different age groups. In this sample, this can probably be seen most clearly in education levels. Based on an educational attainment scale of 1-16, the younger group (M=14.18) has a significantly higher level of attainment than the older group (M=12.18); (p=.004). Comparisons in some memory domains between the two age groups may be affected by the different levels of education between younger and older groups.

2.6.4. Age-group Comparisons

Aside from age-group cohort differences, age-group comparisons can be inherently problematic. In this project, as explained, two main age groups have been compared, with the cut off at age 50. However, as an illustration of potential difficulties, two different subjects, one aged 48 and one aged 51, are only 3 years apart but fall into different age groups. However, the age ranges within their respective age groups (in this study) is 32 years (younger group) and 41 years (older group). One possible way of dealing with this is to use a larger number of age groups and this is a further reason why some exploratory analysis has been carried out in four smaller age groups, although approximately 35% of all subjects (N=51) are included in the oldest of the four detailed age groups (66 plus), so there is still some imbalance when more than two groups are used to cover the 70 year age span of subjects in the present study (21-71). In addition, a larger number of age groups makes straightforward comparison between ‘younger’ and ‘older’ subjects more difficult. As noted above, the interruption to project testing from the Covid 19 pandemic made it impossible to equalise numbers in the two main age groups so that numbers are disproportionately skewed towards older subjects.

2.6.5. Undiagnosed Cognitive Impairment

Perhaps the most significant difficulty for any study of normal cognitive ageing is the possibility that any large sample of older persons may inadvertently include those who have pre-clinical, undiagnosed cognitive impairment (Hassentab, 2016). The effect of having such undiagnosed impairment in the sample may be to contaminate the results, so that the level of cognitive functioning may be under-estimated, and the effect of normal ageing on performance may be over-estimated (Sliwinski, 1996). In a cognitively healthy, screened sample, a minimum of 20% of older subjects (M=79 years old) were ultimately diagnosed with dementia within 4 years (Sliwinski, 1996; 2003a; 2003b). (The average age in the oldest age group of subjects who are 66 or older in the present study is 73). Other studies have produced results that are consistent (e.g., Balota, 2010). It is therefore reasonable to conclude that any large sample of cognitively healthy older adults (such as in this study) may well include a minority of persons with preclinical cognitive impairment.

2.6.6. Task Artefact and Engagement

It is possible that adults of different ages may have had different levels of engagement with study tasks. Differential age-related results may arise because older adults are less motivated by certain types of cognitive tasks or find it harder to focus on the task (Moran, 2012; McVay & Kane, 2009; Hess, 2009). Arousal may also be a feature of any experimental testing, particularly where older subjects may feel motivated to perform well or be nervous/anxious about performing poorly in tests of memory (Lee, 2018). Testing conditions and briefing of subjects was carefully undertaken to minimise these issues. Differences in arousal arising from possible Circadian preference over time of day of testing is dealt with in detail in Chapter 4.

2.7. Data Reduction

2.7.1. Cognitive Scores: Exploratory Factor Analysis Using Principal Component Analysis (PCA) revealed a Four Factor Solution, each Factor representing a Different Memory Domain

Exploratory factor analysis was carried out on the 12 selected cognitive test scores using Principal Component Analysis (PCA) as the Extraction Method and Varimax with Kaiser Normalization as the Rotation Method. Coefficients below 0.512 were suppressed in line with recommended limits for a minimum sample of 100 subjects (Stevens, 1992). PCA arranged the test scores into a four factor memory domain solution (Table 2.6) which together explains 74.52% of the variance. Each factor has a mean score of zero (and a standard deviation of 1)

within a range of negative and positive factor scores. The four memory-related cognitive factors have a correlation with each other of zero (and a 'p' value of 1). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy is 0.747 and Bartlett's test of sphericity is significant (p<.0001). For PCA Factors 1, 2 and 4, higher (positive) factor scores denote higher memory performance, whereas for PCA Factor 3, a higher positive score denotes higher long-term forgetting (i.e. worse long term memory performance). It should be noted that the factor labels shown in Table 2.6 (and used throughout this study) are umbrella terms of convenience, rather than strict or exact descriptions of the underlying cognitive attributes of the component tests, selected scores from which are comprised in those factors.

Table 2.6: Principal Component Analysis (PCA) Cognitive Factors

PCA Factor 1 Verbal Episodic Memory Short Term Recall		PCA Factor 2 Face Memory and Perception		PCA Factor 3 Verbal Episodic Memory Long Term Forgetting		PCA Factor 4 Working Memory	
VSRT Free Delayed Recall Baseline	.844	Cambridge Face Memory	.842	VSRT Cued Recall Forgetting	.901	Stroop Test	-0.815
VSRT Cued Recall Baseline	.783	Glasgow Face Matching	.819			Four Mountains	.745
VSRT Sum Recall	.765	Jenkins & Burton	.748	VSRT Free Recall	.899		
RAVLT Delay	.706	Face Learning		Forgetting			
RAVLT Immediate	.543						
Eigenvalue	**5.089**		**1.634**		**1.155**		**1.064**
% of Variance	**42.41**		**13.62**		**9.63**		**8.86**
Cumulative Variance %	**42.41**		**56.03**		**65.65**		**74.52**

Table 2.6 shows the four factor memory domain solution produced by factor analysis using Principal Component Analysis (PCA) as the extraction method and Varimax with Kaiser Normalization as the rotation method. Table 2.6 shows the rotated component matrix. The PCA solution resulted in four independent, clearly interpretable memory domain factors. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy is 0.747 indicating a strong factor solution. For PCA factors 1, 2 and 4, higher positive scores denote higher/better memory performance, whereas for PCA factor 3, a higher positive score denotes higher long-term forgetting (i.e. lower/worse long term memory performance). The five immediate and short delay measures taken from two different parent verbal episodic memory tests all loaded onto the first PCA factor. Accordingly, factor 1 was labelled 'Verbal Episodic Memory Short Term Recall' (or VEM Short Term Recall). Scores on two face matching and perception tasks along with the Cambridge Face Memory Test loaded onto the second PCA factor which was labelled 'Face Memory and Perception'. Both of the long term measures of forgetting that were developed based on free and cued recall in Buschke's VSRT loaded onto the third PCA factor which was labelled as VEM Long Term Forgetting. Two tests of working memory, the Stroop test and the Four Mountains test loaded onto the fourth PCA factor which was labelled as Working Memory. In the Stroop test itself, a lower score (measured in seconds of interference) denotes better performance; this is reflected in the negative loading. Overall however, a higher factor score on PCA factor 4 denotes better working memory performance.

Table 2.6 shows the rotated component matrix scores for each of the underlying test scores together with the eigenvalues (all greater than 1) and variance explained for each of the four PCA memory domain factors. Table 2.7 shows the (high) communalities and anti-image correlations for each of the underlying variable scores and Figure 2.3 shows the scree plot which supports a four factor PCA solution. Basic reliability analysis of the PCA four factor

memory domain solution has been carried out using Cronbach's α (and standardized Cronbach's α) to determine the reliability of each factor and this is shown in Table 2.8. Jenkins & Burton Face Learning scores and Stroop test scores were reverse scored for the purposes of this calculation. Table 2.8 shows 'corrected item-total correlations' (CITC) and 'alpha if item deleted' (AIID) statistics. AIID is not produced where the PCA factor only comprises two underlying scores (i.e. for VEM Long Term Forgetting and Working Memory). As a general principle, item deletion (applying AIID) is only used where deletion of the underlying score would produce a substantial improvement in Cronbach's α (here taken to be 0.05 or higher). As Table 2.8 shows, Cronbach's α might be improved for PCA Factor 1 if the score for VSRT cued recall at baseline were to be excluded. However, the improvement would be minimal (.024), and Cronbach's α for PCA Factor 1 is strong before improvement. The inclusion of the VSRT cued recall baseline score is also merited on the basis that it provides a useful counterpart to the long-term cued recall component of PCA Factor 3. Cronbach's α would not therefore be improved substantially by deletion of any of the variables in the two factors (VEM Short Term Recall and Face Memory & Perception) which each comprise more than two underlying variable scores.

Table 2.7: Cognitive Factors: Communalities & Anti-image Correlations

Cognitive Test Measure	Communalities	Anti-Image Correlations
VSRT Free Delayed Recall Baseline	.801	.695
VSRT Cued Recall Baseline	.686	.768
VSRT Sum Recall	.727	.839
RAVLT Delay	.690	.806
RAVLT Immediate	.673	.832
Cambridge Face Memory	.785	.741
Glasgow Face Matching	.782	.713
Jenkins & Burton Face Learning	.735	.829
VSRT Cued Recall Forgetting	.866	.599
VSRT Free Recall Forgetting	.857	.606
Stroop Test	.716	.765
Four Mountains	.625	.837

Table 2.7 shows communalities and anti-image correlations for the 12 underlying cognitive test measures comprised in the PCA Four Memory Domain Factor Solution shown in Table 2.6 above.

Figure 2.3: Cognitive Factors Scree Plot

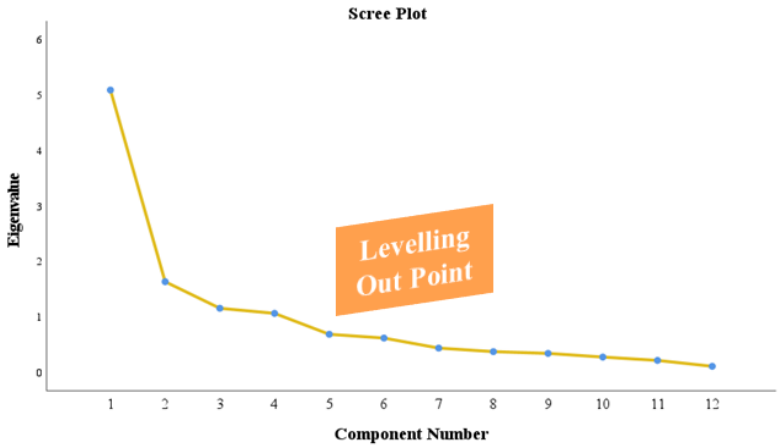


Figure 2.3: Scree plot for PCA Four Memory Domain Factor Solution. The scree plot suggests the plot levels out at component 5, suggesting a four factor solution

Table 2.8: Reliability Analysis for the PCA Four Factor Memory Domain Solution

PCA Factor 1 Verbal Episodic Memory Short Term Recall			PCA Factor 2 Face Memory and Perception			PCA Factor 3 Verbal Episodic Memory Long Term Forgetting		PCA Factor 4 Working Memory	
	CITC	CAIID		CITC	CAIID		CITC		CITC
VSRT Free Delayed Recall Baseline	.716	.750	Cambridge Face Memory	.685	.651	VSRT Cued Recall Forgetting	.797	Stroop Test	.417
VSRT Cued Recall Baseline	.575	.764	Glasgow Face Matching	.694	.559			Four Mountains	.417
VSRT Sum Recall	.684	.614	Jenkins & Burton Face Learning	.552	.604	VSRT Free Recall Forgetting	.797		
RAVLT Delay	.761	.600							
RAVLT Immediate	.747	.652							
Cronbach's α	**.740**			**.683**			**.874**		**.318**
Standardized Cronbach's α	**.879**			**.795**			**.887**		**.589**

Table 2.8 shows reliability analysis for the PCA four factor memory domain solution shown in Table 2.6. Table 2.8 shows Cronbach's a and Cronbach's a based on standardized items (Standardized Cronbach's a) for each of the four separate factors together with Corrected Item-Total Correlation (CITC) and Cronbach's Alpha If Item Deleted (CAIID). Jenkins & Burton Face Learning scores and Stroop test scores have been reverse scored in determining factor reliability. Factors containing only 2 items cannot generate CAIID. As Table 2.8 shows, Cronbach's a might be improved for PCA Factor 1 if the scores for VSRT free recall and/or VSRT cued recall at baseline were to be excluded. However, the improvements would be minimal in each case (.010 and.024), Cronbach's a for PCA Factor 1 is reasonable before improvement (.740) and the inclusion of the VSRT free and cued recall baseline scores is merited on the basis that it provides a useful counterpart comparator to the long-term free and cued recall components of PCA Factor 3 (Verbal Episodic Memory Long Term Forgetting). Although results on the Stroop test and Four Mountains test are strongly correlated (Pearson's r=.417, p<.0001), Cronbach's a is at the lowest value for Working Memory out of all PCA Factors. In the present study, the underlying test scores of PCA factor 4 (Working Memory) are occasionally analysed separately, where it appears necessary or appropriate to do so.

Although results on the Stroop test and Four Mountains test are strongly correlated (Pearson's r=.417, p<.0001), reliability results suggest that the PCA Working Memory factor is the least reliable of the memory domain factors (see Table 2.8). Accordingly, separate analysis of the underlying 4MT and Stroop test scores has been undertaken in the present study where the Working Memory results indicate that it would be appropriate to do so (see, e.g., Chapter 5 on physical activity).

2.7.2. The Four Independent Memory Domain Factors Explain 74.5% of the Variance

Table 2.6 shows that PCA Factor 1 explains 42.41% of the variance and comprises the neuropsychological test measures of immediate free and cued recall and short (30-60 minute) delayed recall measures from the VSRT as well as the immediate and delayed recall measures from the RAVLT (i.e. 5 separate underlying test scores in total). PCA Factor 1 was labelled as "Verbal Episodic Memory, Short Term Recall" (or "VEM Short Term Recall"). Notably, the new VSRT Long Term Forgetting scores for free and cued recall after two weeks specifically did not load onto this factor but did load onto a separate factor (see further below).

PCA Factor 2 explains 13.62% of the variance and comprises all 3 of the tests used to assess full face processing (both face memory and face matching) in social cognition. PCA Factor 2 was labelled as "Face Memory and Perception". This factor loading is consistent with findings elsewhere (Verhallen, 2017), where a common factor underlying face processing was identified and which there comprised measures for both unfamiliar face memory and face perception. Notably, the Reading the Mind in the Eyes test score did not load onto this factor (or any other factor).

PCA Factor 3 explains 9.63% of the variance and comprises the two new measures of VSRT Long Term Forgetting which were developed and based on delayed free and cued VSRT recall after two weeks. PCA Factor 3 was labelled as "Verbal Episodic Memory, Long Term Forgetting" (or "VEM Long Term Forgetting").

PCA Factor 4 explains 8.86% of the variance and combines the test scores for the Four Mountains test and the Stroop test. PCA Factor 4 was labelled as "Working Memory".

2.7.3. Questionnaire Scores: Exploratory PCA Factor Analysis of Questionnaire Scores Revealed Different Composite Psychological Factors

Exploratory factor analysis using PCA was also applied to categorise the scores from the questionnaires relating to psychological health into independent psychological factors. As the

total number of questionnaire scores exceeded a valid case:variable ratio for factor analysis, some of the main questionnaire scores were first arranged into two main sets. The first set of questionnaire scores dealt with aspects of sociability, social networks and social functioning. These were predominantly measures of positive social or psychological experience. The second set of questionnaires was concerned with psychological mood, including components of social fear and anxiety, but also including some clinical-level measures such as anxiety, stress and depression. These were predominantly questionnaires where high scores denote negative social or psychological experience. There was some overlap in the first and second set of questionnaires. For example, the UCLA Loneliness Scale (Russell, 1980) and the Liebowitz Social Anxiety Scale (Heimberg, 1999) were used in both sets. This overlap was undertaken deliberately to see whether, despite the limitations of case:variable ratios, some common constructs might be identified by PCA factor analysis, and this proved to be the case. Finally, as will be explained in Chapter 6 below, the SF36 Short Form General Health Assessment (Ware Jr & Shelbourne, 1992) provides scores in 8 separate health domains. PCA factor analysis of these 8 domains revealed that they divided reliably into two factors which were labelled as "SF36 psychological" and "SF36 physical" in Chapter 6. Four scores comprised in the SF36 psychological factor were also included as variables in the exploratory PCA factor analysis for the questionnaire scores; see Table 2.9.

PCA analyses for each of the two main sets of questionnaires (i.e. for sociability and psychological mood) returned the factor results shown in Table 2.9. Table 2.9 shows the rotated component matrix scores for each set of underlying variables together with the eigenvalues (all greater than 1) and variance explained for each of the two sets of psychological factors. Factor analysis was again carried out on both sets of psychological scores using Principal Component Analysis (PCA) as the Extraction Method and Varimax with Kaiser Normalization as the Rotation Method. Coefficients below 0.512 were again suppressed in line with recommended limits for a minimum sample of 100 subjects (Stevens, 1992).

Table 2.9: Principal Component Analysis (PCA): Psychological Health Factors in Two Sets of Factors

PCA Factor 1A Positive Social Experience		PCA Factor 2A Social Confidence		PCA Factor 3 Social Connectedness			PCA Factor 1B Negative Social Experience		PCA Factor 2B Social Fearfulness	
Diener SPANE (Positive)	.844	Liebowitz Fear Scale	-.869	Lubben Social Networks Family Sub-scale	.786		Diener SPANE (Positive)	-.847	Liebowitz Fear Scale	.904
Diener Satisfaction With Life	.785	Liebowitz Avoidance	-.850	Lubben Social Networks Friendship Sub-scale	.707		DASS 21 Score	.810	Liebowitz Avoidance	.835
Diener Flourishing Scale	.780	Social Situation Score	.643				Diener SPANE (Negative)	.745	Brief Fear of Negative Evaluation	.666
SF36 Emotional Well-Being	.765	Social Situation Trend	.548				Zung Anxiety Scale	.736		
SF36 Social Functioning	.692						SF36 Energy & Fatigue	-.720		
UCLA Loneliness Scale	-.577						UCLA Loneliness Scale	.673		
							SF36 Emotional Limits	-.594		
Eigenvalue	**5.180**		**1.748**		**1.106**			**5.04**		**1.36**
% of Variance	**43.17**		**14.56**		**9.21**			**50.4**		**13.61**
Cumulative Variance %	**43.17**		**57.73**		**66.94**			**50.4**		**64.01**

Table 2.9. PCA Factor Analysis was conducted on two separate sets of questionnaire scores due to the limitations of case to variable ratios. PCA was used as the extraction method and Varimax with Kaiser Normalization as the rotation method. Table 2.9 shows both rotated component matrices for the two separate sets. There is some overlap in questionnaire scores between the two factor sets. PCA Factor scores for factors in each of the two sets (i.e. PCA Factors 1A-3 and 2A&2B) have a correlation with each other of 0 and a p value of 1. However, strong associations exist between some of the factors in the two separate sets of factors. This underpins the labelling of the separate factor scores for Positive and Negative Social Experience as PCA Factor 1A and 2A respectively and the separate factor scores for Social Confidence and Social Fearfulness as PCA Factor 2A and 2B respectively. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy for PCA Factors 1A-3 is .855 and for PCA Factors 2A-2B is .847. These indicate strong factor solutions for each of the two sets.

2.7.4. Exploratory PCA Factor Analysis Revealed that the First Set of Questionnaire Scores Comprised 3 Separate Psychological Health Factors and the Second Set of Questionnaire Scores Comprised 2 Separate Psychological Health Factors

PCA categorised the 'positive experience' set of questionnaire scores into three independent factors (KMO=.855), and categorised the 'negative experience' set of questionnaire scores into two independent factors (KMO=.847), as shown in Table 2.9. The high KMO measures of sampling adequacy indicate strong factor solutions for both sets. Within each set, factors have a correlation with each other of 0 and a p value of 1.

PCA psychological factors 1A, 2A and 3 together explain 66.94% of the variance in the first set of questionnaire scores. These three independent factors have been labelled as 'Positive Social Experience', 'Social Confidence' and 'Social Connectedness'. Higher scores in each of these three factors denote higher Positive Social Experience, higher Social Confidence and higher Social Connectedness respectively. Again, factor labels are umbrella terms of convenience rather than exact descriptions of specific constructs.

PCA psychological factors 1B and 2B together explain 64.01% of the variance in the second set of questionnaire scores. The two independent factors have been labelled as 'Negative Social Experience' and 'Social Fearfulness'. Higher scores in each of the two factors denote higher levels of Negative Social Experience and Social Fearfulness respectively.

Associations between the two different sets of psychological factors are shown in Table 2.10. Table 2.10 explains the rationale for the labelling of the psychological factors in Table 2.9 by showing Pearson's r and Spearman (r_s) correlations between factors in the two different sets of factor solutions (PCA Factors 1A-3 and PCA Factors 2A&2B) shown in Table 2.9. As noted in Table 2.9, PCA Factors 1A, 2A and 3 (Positive Social Experience, Social Confidence and Social Connectedness) have a correlation with each other of 0 and a p value of 1. The same applies to PCA Factors 2A and 2B (Negative Social Experience and Social Fearfulness). Table 2.10 shows that Positive Social Experience (PCA Factor 1A in the first set) is highly negatively associated with Negative Social Experience (PCA Factor 1B in the second set) ($p<.0001$). Also, Social Confidence (PCA Factor 2A in the first set) is highly negatively associated with Social Fearfulness (PCA Factor 2B in the second set) ($p<.0001$). This suggests that PCA Factors 1A & 1B (Positive and Negative Social Experience) and PCA Factors 2A & 2B (Social Confidence and Social Fearfulness) are, to some extent, mirror-image positive/negative versions of similar psychological constructs. As such, they have not been treated as separate, unrelated factors but instead have been grouped together both in the numbering of the labels (1A & 1B, 2A & 2B and 3) as well as in the descriptive labels applied to them (i.e. Positive and/or Negative Social Experience and Social Confidence and/or Fearfulness). Social Connectedness (which, in the same PCA factor solution, has a 0 correlation with Positive Social Experience) has a reasonable negative association with PCA Factor 1B, Negative Social Experience (Pearson's $r=-.267$, $p=.002$). There is though no association between Social Connectedness and Social Fearfulness (2B). There is also no association between Social Confidence (2A) and Negative Social Experience (1B) or between Social Fearfulness (2B) and Positive Social Experience (1A).

Table 2.10: Associations between Psychological Health Factors in Different Factor Analysis Sets

PCA Factors for Social Experience	Negative Social Experience				Social Fearfulness			
	r	p	r_s	p	r	p	r_s	p
Positive Social Experience	-.826	<.0001	-.780	<.0001	-.011	.9	.026	.77
Social Confidence	-.156	.07	-.153	.07	-.880	<.0001	-.819	<.0001
Social Connectedness	-.267	.002	-.261	.002	.152	.08	.137	.11

Table 2.10 describes the rationale for the labelling of psychological factors in Table 2.9 by showing associations between factors in the two different sets of factor solutions (PCA Factors 1A-3 and PCA Factors 2A&2B) shown in Table 2.9. Associations are shown for both Pearson (r) and Spearman (r_s) correlations. As noted in Table 2.9, PCA Factors 1A-3 (Positive Social Experience, Social Confidence and Social Connectedness) have a correlation with each other of 0 and a p value of 1. The same applies to PCA Factors 2A&2B (Negative Social Experience and Social Fearfulness). Table 2.10 shows that Positive Social Experience (PCA Factor 1A in the first set) is highly negatively associated with Negative Social Experience (PCA Factor 1B in the second set) ($p<.0001$). Also, Social Confidence (PCA Factor 2A in the first set) is highly negatively associated with Social Fearfulness (PCA Factor 2B in the second set) ($p<.0001$). This suggests that PCA Factors 1A & 1B (Positive and Negative Social Experience) and PCA Factors 2A & 2B (Social Confidence and Social Fearfulness) appear to be, to some extent, 'mirror-image' positive/negative versions of similar psychological constructs. PCA Factor 3, Social Connectedness (which of course has a 0 correlation with Positive Social Experience) has a reasonable negative association with PCA Factor 1B, Negative Social Experience ($p=.002$). There is no association between Social Connectedness and Social Fearfulness (2B). There is also no association between Social Confidence (2A) and Negative Social Experience (1B) or between Social Fearfulness (2B) and Positive Social Experience (1A). Orange shading denotes significant associations across the two sets of psychological health factors.

2.7.5. The 5 Psychological Factors Revealed by Factor Analysis show Strong Reliability; There are Two Pairs of Factors that Correspond to Positive/Negative Measures of Similar Psychological Constructs

Table 2.11 shows communalities and anti-image correlations for the 12 separate scores from psychological questionnaires comprised in the first set of PCA psychological factors 1A, 2A and 3 in Table 2.9 above. Figure 2.4 shows the scree plot for PCA factors 1A, 2A and 3 which suggests a 3 factor solution (shown in Table 2.9 above).

Table 2.11: Psychological Health Factors 1A, 2A & 3A: Communalities & Anti-image Correlations

Psychological Test Measure	Communalities	Anti-Image Correlations
Diener SPANE (Positive)	.808	.839
Diener Satisfaction With Life	.655	.901
Diener Flourishing	.731	.909
SF36 Emotional Wellbeing	.688	.891
SF36 Social Functioning	.504	.913
UCLA Loneliness Scale	.706	.903
Liebowitz Fear	.771	.731
Liebowitz Avoidance	.748	.743
Social Situation	.694	.850
Social Situation Trend	.413	.844
Lubben Family	.668	.779
Lubben Friendship	.647	.843

Table 2.11 shows communalities and anti-image correlations for the 12 separate scores from psychological questionnaires comprised in the first set of psychological health measures under Principal Component Analysis (PCA). These underlying scores are comprised in psychological PCA factors 1A, 2A and 3; see Table 2.9.

Figure 2.4: Psychological Health Factors 1A, 2A & 3A: Scree Plot

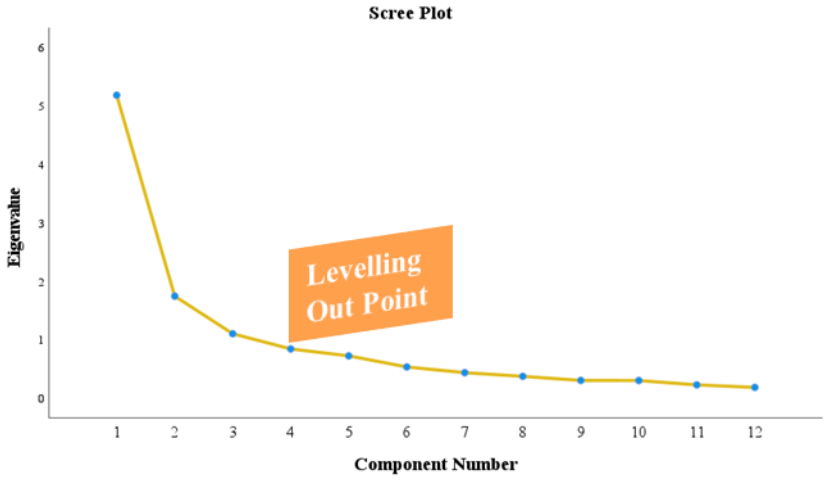


Figure 2.4 shows the scree plot for PCA factors 1A, 2A and 3 which suggests a 3 factor solution (shown in Table 2.9).

Table 2.12 shows basic reliability analysis for the PCA psychological factors 1A to 3 using Cronbach's α and standardized Cronbach's α for each of the three separate factors together with Corrected Item-Total Correlation (CITC) and Alpha If Item Deleted (AIID). UCLA Loneliness and both Liebowitz scale scores were reverse scored for this analysis. The Social Connectedness factor contains only 2 items and cannot generate AIID. As Table 2.12 shows, Cronbach's α might be improved for PCA Factor 1A if the score for SF36 Social Functioning were to be excluded. However, the improvement would be minimal (.009) and Cronbach's α for PCA Factor 1A is strong before improvement. Similarly, Cronbach's α might be improved for PCA Factor 2A by excluding the Social Situation Trend score but the improvement would be minimal (.001). Cronbach's α is least strong for the two Lubben scores, although the family and friendship subscale scores are themselves reasonably strongly correlated (Pearson's r=.319 p=.0001). Nevertheless, the approach taken in the present study will be to use PCA psychological factor 3 as an indicative guide in results, but to analyse any significant Social Connectedness results for family and friendship networks separately, where it appears necessary or appropriate to do so.

Table 2.12: Reliability Analysis for PCA Psychological Health Factors 1A, 2A & 3

PCA Factor 1A Positive Social Experience			PCA Factor 2A Social Confidence			PCA Factor 3 Social Connectedness	
	CITC	CAIID		CITC	CAIID		CITC
Diener SPANE (Positive)	.781	.791	Liebowitz Fear Scale	.627	.693	Lubben Social Networks Family Sub-scale	.319
Diener Satisfaction With Life	.485	.786	Liebowitz Avoidance	.643	.686	Lubben Social Networks Friendship Sub-scale	.319
Diener Flourishing Scale	.622	.768	Social Situation Score	.584	.723		
SF36 Emotional Well-Being	.566	.759	Social Situation Trend	.485	.775		
SF36 Social Functioning	.300	.821					
UCLA Loneliness Scale	.498	.769					
Cronbach's α	**.812**			**.774**			**.480**
Standardized Cronbach's α	**.885**			**.781**			**.483**

Table 2.12 shows reliability analysis for the PCA psychological health factors 1A to 3. The table shows Cronbach's a and Cronbach's a based on standardized items (Standardized Cronbach's a) for each of the three separate factors together with Corrected Item-Total Correlation (CITC) and Cronbach's Alpha If Item Deleted (CAIID). UCLA Loneliness and both Liebowitz scale scores have been reverse scored in determining reliability. The Social Connectedness factor contains only 2 items and cannot generate CAIID. As Table 2.12. shows, Cronbach's a might be improved for PCA Factor 1A if the score for SF36 Social Functioning were to be excluded. However, the improvement would be minimal (.009) and Cronbach's a for PCA Factor 1A is strong before improvement. Similarly, Cronbach's a might be improved for PCA Factor 2A by excluding the Social Situation Trend score but the improvement would be minimal (.001). Cronbach's a is least strong for the two Lubben scores. The approach taken in this study will be to analyse the underlying test scores for family and friendship networks separately, where it appears necessary or appropriate to do so.

Table 2.13 shows communalities and anti-image correlations for the 10 separate scores from psychological questionnaires comprised in the second set of psychological PCA factors 1B and 2B; see Table 2.9 above. Figure 2.5 shows the scree plot for PCA factors 1B and 2B which suggests a 2 factor solution (shown in Table 2.9 above).

Table 2.13: Communalities and Anti-Image Correlations for PCA Psychological Factors 1B & 2B

Psychological Test Measure	Communalities	Anti-Image Correlations
Diener SPANE (Positive)	.720	.816
Diener SPANE (Negative)	.673	.886
DASS 21	.722	.890
Zung Anxiety	.635	.930
SF36 Energy & Fatigue	.582	.884
SF36 Emotional Limits	.395	.943
UCLA Loneliness	.537	.886
Brief Fear of Negative Evaluation	.561	.797
Liebowitz Fear	.840	.710
Liebowitz Avoidance	.734	.725

Table 2.13 shows communalities and anti-image correlations for the 10 separate scores from psychological health questionnaires comprised in the second set of psychological measures under Principal Component Analysis (PCA). These underlying scores are comprised in psychological PCA factors 1B and 2B; see Table 2.9 above.

Figure 2.5: Psychological Health Factors 1B & 2B: Scree Plot

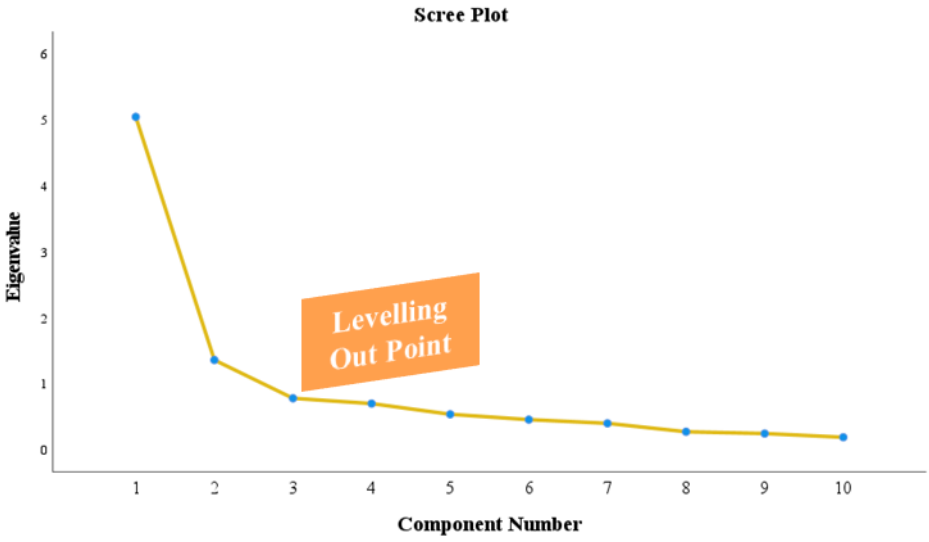


Figure 2.5 shows the scree plot for PCA factors 1B and 2B which suggests a 2 factor solution (shown in Table 2.9 above).

Table 2.14 shows reliability analysis for the PCA psychological factors 1B & 2B using Cronbach's α and standardized Cronbach's α for each of the two separate factors together with Corrected Item-Total Correlation (CITC) and Alpha If Item Deleted (AIID). For PCA Factor 1B, Diener SPANE (Positive), SF36 Energy & Fatigue and SF36 Emotional Limits, scores have all been reverse scored for the purposes of this analysis. As Table 2.14 shows, Cronbach's α might be improved for PCA Factor 1B if the score for SF36 Emotional Limits were to be excluded. However, the improvement would be small (.044) and Cronbach's α for PCA Factor 1B is strong before improvement. Similarly, Cronbach's α might be improved for PCA Factor 2B by excluding the Brief Fear of Negative Evaluation (BFNE) score but the improvement would be small (.044). In addition, including the BFNE questionnaire score in PCA Factor 2B helps to differentiate this factor 2B from PCA Factor 2A (Social Confidence).

Table 2.14: Reliability Analysis for PCA Psychological Factors 1B & 2B

PCA Factor 1B Negative Social Experience			PCA Factor 2B Social Fearfulness		
	CITC	CAIID		CITC	CAIID
Diener SPANE (Positive)	.630	.756	Liebowitz Fear Scale	.760	.563
DASS 21 Score	.683	.691	Liebowitz Avoidance	.625	.723
Diener SPANE (Negative)	.683	.751	Brief Fear of Negative Evaluation	.525	.833
Zung Anxiety Scale	.691	.712			
SF36 Energy & Fatigue	.647	.691			
UCLA Loneliness Scale	.583	.732			
SF36 Emotional Limits	.534	.806			
Cronbach's α	**.762**			**.789**	
Standardized Cronbach's α	**.884**			**.793**	

Table 2.14 shows reliability analysis for the PCA psychological factors 1B & 2B. The table shows Cronbach's a and Cronbach's a based on standardized items (Standardized Cronbach's a) for each of the two separate factors together with Corrected Item-Total Correlation (CITC) and Cronbach's Alpha If Item Deleted (CAIID). For PCA Factor 1B, Diener SPANE (Positive), SF36 Energy & Fatigue and SF36 Emotional Limits, scores have all been reverse scored in determining reliability. As the table shows, Cronbach's a might be improved for PCA Factor 1B if the score for SF36 Emotional Limits were to be excluded. However, the improvement would be small (.044) and Cronbach's a for PCA Factor 1B is strong before improvement (.762). Similarly, Cronbach's a might be improved for PCA Factor 2B by excluding the Brief Fear of Negative Evaluation score but the improvement would be small (.044) and Cronbach's a for PCA Factor 2B is strong before improvement (.789). In addition, including the BFNE questionnaire score in PCA Factor 2B helps to differentiate this factor 2B from PCA Factor 2A (Social Confidence).

In summary, examining the five social psychological factors delivered by the two separate sets of PCA analysis suggests that there are three main, reliable psychological health domains represented by PCA analysis and by the scores in the psychological questionnaires. These are first, Positive and Negative Social Experience, second, Social Confidence and Social Fearfulness, and third, Social Connectedness. The results for these social psychological factors will be examined in more detail in Chapter 6.

2.8. General Age-related Results

2.8.1. Memory Domain Factors: Three Memory Domain Factors show strong Correlations with Age-related Performance Decline

Figure 2.6 shows the basic correlations between older age and lower performance in three of the memory domain factors; VEM Short Term Recall (Pearson's r=-.263, p=.001), Face Memory & Perception (Pearson's r=-.327, p<.0001) and Working Memory (Pearson's r=-.475, p<.0001). The exception is VEM Long Term Forgetting where there is no correlation between older age and worse performance (Pearson's r=.088, p=0.29; Spearman's r=.038, p=0.65). There is only a weak, marginal association between older age and lower mentalizing or Reading the Mind in the Eyes test score (Pearson's r=-0.161, p=.053).

Figure 2.6: Associations with Age in the Four Memory Domain Factors

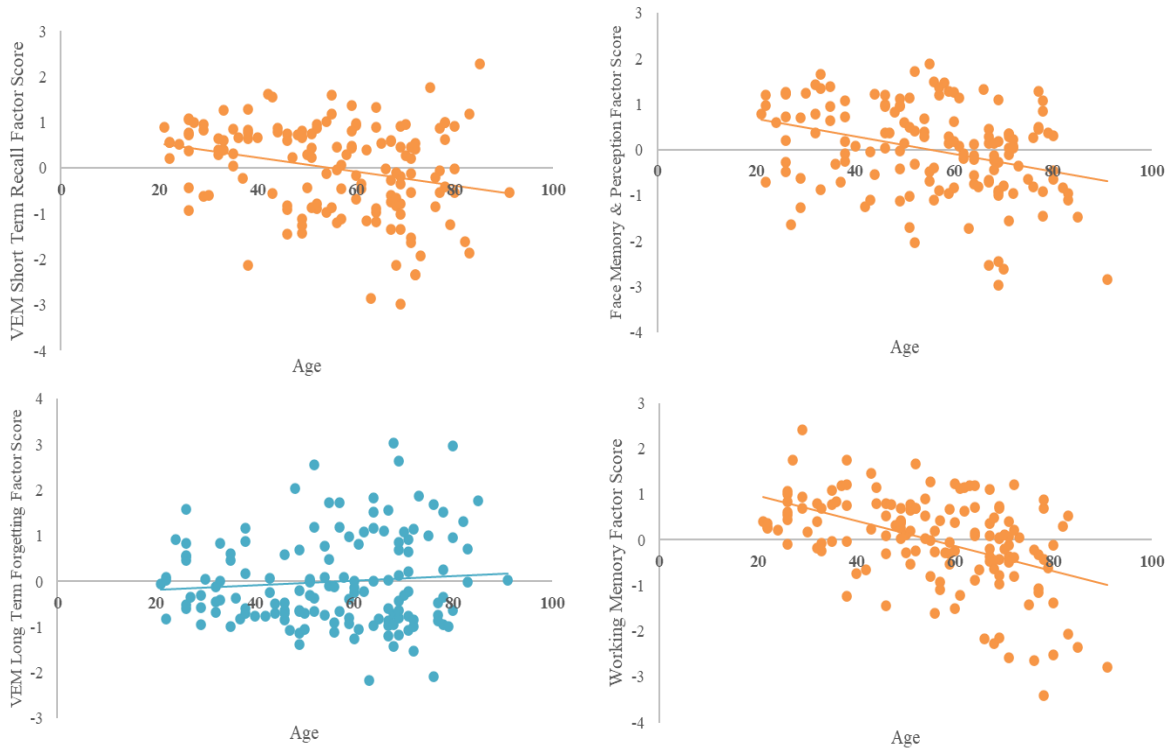


Figure 2.6 shows Pearson associations between age and the Four Memory Domain Factors. Older age is associated with worse performance in all of the memory domain factors *except* VEM Long Term Forgetting. Higher factor scores denote higher performance except for VEM Long Term Forgetting where higher factor scores denote worse performance (higher long term forgetting). VEM Short Term Recall : Pearson's r=-.263, p=.001. Face Memory and Perception : Pearson's r=-.327, p<.0001. VEM Long Term Forgetting : Pearson's r=.088, p=.29. Working memory : Pearson's r=-.475, p<.0001.

2.8.2. Memory Domain Factors: Age-related Decline in Three Memory Domains is also Shown in Performance Differences between the Main Younger and Older Age Groups

Figure 2.7 compares performance in the four memory domains between the main younger and older age groups. The younger group performs better in three of the memory domain factors; VEM Short Term Recall (t_{143}=2.888, p=.004, Cohen's d=0.48), Face Memory & Perception (t_{143}=3.229, p=.002, Cohen's d=0.54) and Working Memory ($t_{138.930}$=5.123, p<.0001, Cohen's d=0.87). The exception, where there is no difference between the younger and older age groups, is VEM Long Term Forgetting ($t_{139.315}$=-1.420, p=.16). For completeness (not shown in Figure 2.7), there is no difference in mentalizing (Reading the Mind in the Eyes test score) between younger and older groups (t_{143}=.380, p=.70).

Figure 2.7: Comparisons between Younger and Older Age Groups in the Four Memory Domain Factors

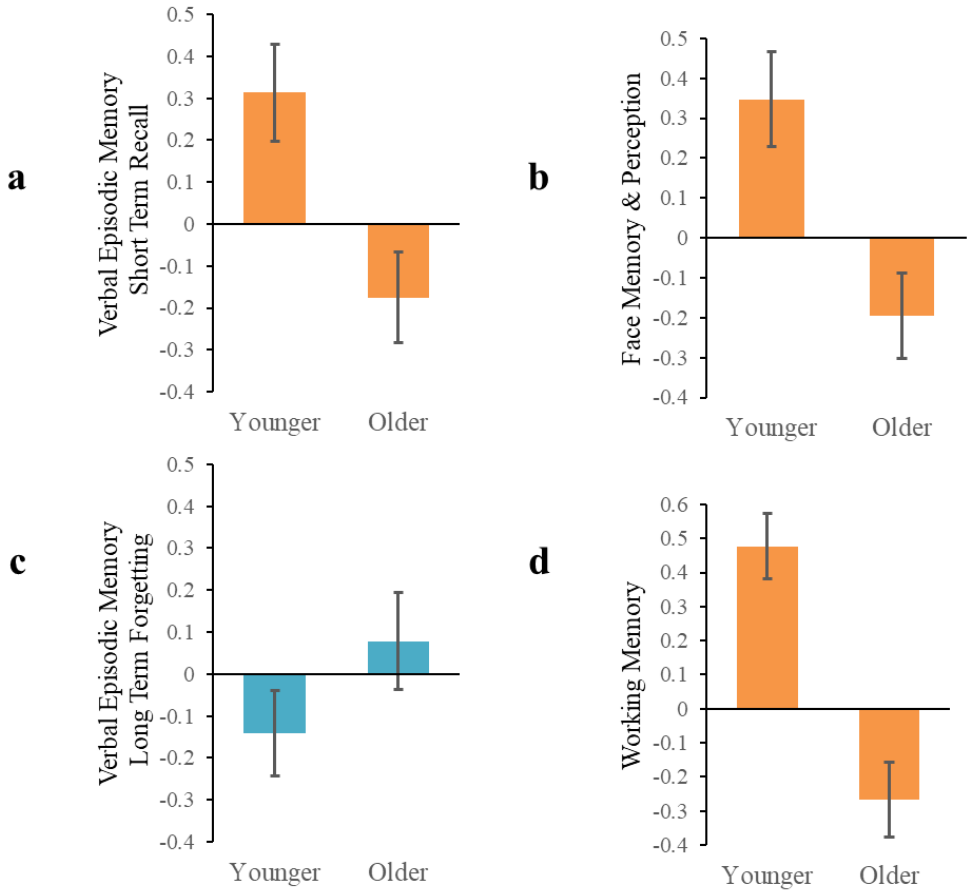


Figure 2.7 compares performance by the two main Age Groups in each of the Four Memory Domain Factors. The older group performs worse than the younger group in all memory factors domains *except* VEM Long Term Forgetting. **a**. VEM Short Term Recall: t_{143}=2.888, p=.004, Cohen's d=0.48. **b**. Face Memory & Perception: t_{143}=3.229, p=.002, Cohen's d=0.54. **c**. VEM Long Term Forgetting: $t_{139.315}$=-1.420, p=0.16. **d**. Working Memory: $t_{138.930}$=5.123, p<.0001, Cohen's d=0.87. Error bars show +/- one s.e.m.

2.8.3. Memory Domain Factors: Differences in Performance are also Evident in More Detailed Age Groups, except for VEM Long Term Forgetting, where there are No Differences between any of the Four Detailed Age Groups

Figure 2.8 and Table 2.15 summarise performance in the four memory domain factors across four more detailed age groups. Full statistical details for the summary provided in Table 2.15 are set out in Supplementary Table 2.4.

Figure 2.8: Memory Domain Performance in Four Age Groups

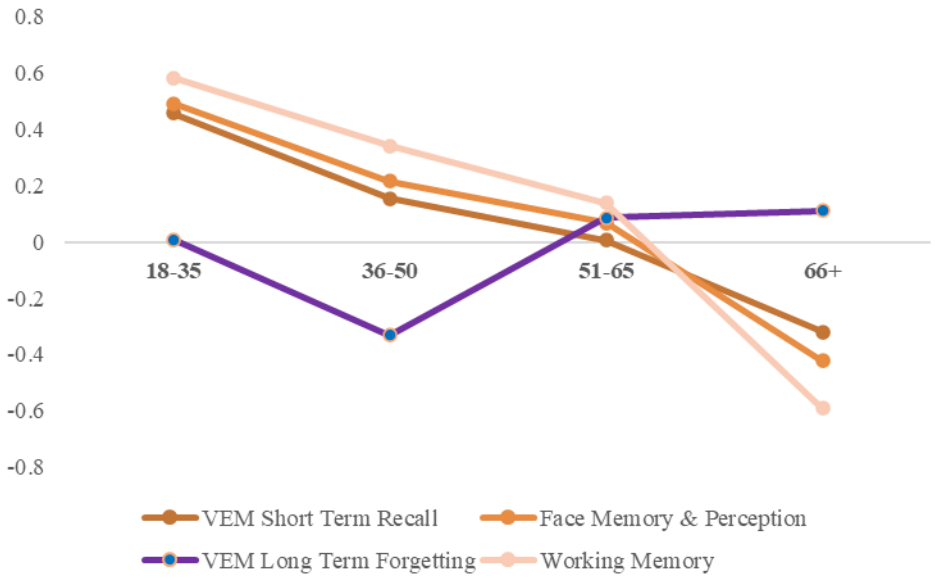


Figure 2.8: Lower factor scores for VEM Short Term Recall, Face Memory and Perception and Working Memory indicate worse performance. Higher factor scores on VEM Long Term Forgetting indicate worse performance. There is a steep decline in performance (to negative factor scores) for VEM Short Term Recall, Face Memory & Perception and Working Memory between the youngest (18-35) and oldest (66+) age groups. By comparison, there is no apparent trend towards higher forgetting rates between the youngest and oldest age groups. In contrast with the other three factor domains, although there appears to be some improvement in forgetting rates around early middle age (36-50), overall performance is relatively flat. Performance in the other three factors shows a relatively steady decline across the different age groups. Note: as described in the text, there appears to be some justification here for a substantial decline in some memory domain performance between middle and older age (i.e. between groups 3 and 4, particularly in Working Memory)

Table 2.15: Comparison of Memory Domain Performance in Four Different Age Group

Compared Groups	VEM Short Term Recall	Face Memory & Perception	VEM Long Term Forgetting	Working Memory
Group 1 (18-35) & Group 2 (36-50)	N/A	N/A	N/A	N/A
Group 2 (36-50) & Group 3 (51-65)	N/A	N/A	N/A	N/A
Group 3 (51-65) & Group 4 (66+)	N/A	.02	N/A	.001
Group 1 (18-35) & Group 3 (51-65)	.02	N/A	N/A	.01
Group 1 (18-35) & Group 4 (66+)	.0001	.0003	N/A	<.0001
Group 2 (36-50) & Group 4 (66+)	N/A	.005	N/A	<.0001

Table 2.15: Differences in performance between four age groups: Significant differences emerge between more detailed age groups in all cognitive factors except VEM Long Term Forgetting. Differences are strongest between the youngest (Group 1) and oldest (Group 4) groups where, by contrast, the p value in VEM Long Term Forgetting between the youngest and oldest group is p=.63. Orange shading shows significant differences and p values.

It is noticeable that in no case is there any significant difference between groups 1 and 2 (ages 18-35 and 36-50 respectively) or between groups 2 and 3 (ages 36-50 and 51-65 respectively) in any memory domain. There is a significant fall in performance between groups 3 and 4 (ages 51-65 and 66 plus) in both Face Memory & Perception (p=.02) and Working Memory (p=.001). Larger differences emerge when comparing group 4 (the oldest group, ages 66 plus) to either of group 1 or 2 (the two youngest groups, ages 18-35 and 36-50 respectively) in Face Memory & Perception and Working Memory. There are significant differences between age groups 1 and 3 in both VEM Short Term Recall and Working Memory, suggesting that some appreciable age-related decline may occur in the 51-65 age groups in each of these domains (but acknowledging that this is not a result of longitudinal testing). For Face Memory & Perception, it is only possible to discern any appreciable age-related decline by comparing performance in the oldest group (66+) to each of the other three younger age groups, suggesting that decline in this memory domain may be relatively more attenuated in comparison with VEM Short Term Recall and Working Memory.

It should be noted that there are no differences between any of the four age groups in VEM Long Term Forgetting. Notably, the marked difference between groups 1 and 4 which appears in all other memory domains does not exist in VEM Long Term Forgetting (p=.63). The comparison which is nearest to reaching statistical significance is between groups 2 and 4 (p=.052). The long term forgetting in group 2 (ages 36-50) is lower than the other 3 age groups, both younger and older, (although not statistically so) so that the performance line for VEM Long Term Forgetting in Figure 2.8 is quite different from the other 3 memory domains and,

but for the non-linear performance of group 2, would be essentially flat (see Figure 2.6c and 2.8).

2.8.4. VEM Long Term Forgetting is a composite measure (derived by PCA) of two relative measures for differences over 2 weeks in free and cued recall

As described above (2.8.1), there is no correlation between age and VEM Long Term Forgetting, but VEM Long Term Forgetting is a composite factor score derived from PCA factor analysis and comprises two measures (free and cued recall forgetting) based on the relative performance at phase 1 and then two weeks later at phase 2 in both delayed free and cued recall. In other words, there are 'four' absolute scores for immediate cued recall, cued recall at 14 days, free delayed recall after 30 minutes and free delayed recall after 14 days. The four absolute scores generate two separate forgetting scores (for free and cued recall) which PCA factor analysis groups into a single, separate memory domain factor, VEM Long Term Forgetting; see also section 2.2.4 above.

2.8.5. Age Differences Exist in Underlying Absolute Measures of Long-Delayed Free and Cued Recall

Examining the two underlying absolute scores for free and cued recall at 14 days shows that better underlying scores in both are strongly correlated with younger age; free recall at 14 days: Pearson's r=-.225, p=.007, Spearman's r_s=-.220, p=.008; cued recall at 14 days: Pearson's r=-.329, p<.0001, Spearman's r_s=-.311, p=.0001. Younger persons perform better than older persons in free recall at 14 days ($t_{122.633}$=2.918, p=.004, Cohen's d=0.53) and in cued recall at 14 days ($t_{129.123}$=3.700, p=.0003, Cohen's d=0.65). Moreover, using the A-B/A+B formula for forgetting, age remains correlated with cued recall forgetting (Pearson's r=.238, p=.004, Spearman's r_s=.191, p=.021), although not with delayed free recall forgetting (Pearson's r=.161, p=.053, Spearman's r_s=.110, p=.187). Younger subjects outperform older subjects in both free recall forgetting ($t_{140.937}$=-2.492, p=.014, Cohen's d=0.42) and cued recall forgetting ($t_{140.141}$=-2.794, p=.006, Cohen's d=0.47).

It is not therefore correct to say that older age is unrelated to higher ordinary forgetting and, in this respect, the results in the present study replicate those seen elsewhere (e.g. Mary, 2013). On the basis of the underlying results in the present study, there is a relationship between older age and lower long term free and cued recall. However, there is an important qualification to this. As described at section 2.2.4 above, absolute scores do not take account of relative performance differences in forgetting (Loftus, 1985). For example, Person X may have

absolute scores of 10/12 words at phase 1 and 8/12 words at phase 2, whereas Person Y (who may be older) may have absolute scores of 8/12 words at phase 1 and 7/12 words at phase 2. Person X has higher absolute scores than Person Y at both phases 1 and 2. Such a scoring pattern across an entire sample may produce a strong age-related correlation for absolute scores at each phase. However, using the A-B/A+B formula, Person Y has lower forgetting (0.067) than Person X (0.111) reflecting a better percentage recall of the words originally recalled (Person X=80% and Person Y=87.5%).

Accordingly, the composite PCA factor measure of forgetting, VEM Long Term Forgetting is *unrelated* to age. It is intriguing that cued recall forgetting shows a stronger negative association with older age than free recall forgetting (in no measure of calculating forgetting, A-B/A+B, A-B or A-B/A, is free recall forgetting correlated with age). Cued recall might be a simpler test than free recall as it is more akin to recognition. One possibility is that older subjects do not work as hard at cued recall after 14 days than they do with free recall. Another possibility is that cued recall may generate more interference for older subjects, with the cueing letters perhaps strongly suggesting different possible words from the original learned word. Finally, as will be seen in the next chapter, it should be noted that age correlations with all of the underlying measures comprised in VEM Long Term Forgetting are *secondary* to those for sleep quality (i.e. sleep quality is shown to be more important than age to long-term forgetting). This secondary effect (of age compared to sleep quality) also extends to the absolute scores for free and cued recall at two weeks.

2.8.6. Effects of Gender: Females tend to Perform Better in VEM Long Term Forgetting and in the Underlying Measures of the RAVLT

Females also perform better than males on VEM Long Term Forgetting (t_{143}=2.089, p=.04, Cohen's d=0.35) but there are no apparent differences between males and females in VEM Short Term Recall (p=.12), Face Memory & Perception (p=.58), Working Memory (p=.48) or mentalizing (p=.80).

Examining the cognitive test scores underlying the four separate memory domains reveals a more nuanced gender and age picture in VEM Short Term Recall, as well as VEM Long Term Forgetting. There are no gender differences in any of the component cognitive test scores in either Face Memory & Perception (i.e. the CFMT, the GFMT or the Jenkins & Burton test of unfamiliar face matching) or in Working Memory (i.e. the 4MT and the Stroop test). However,

gender differences do arise in the RAVLT scores and in the score for long term forgetting free recall (but not cued recall).

For RAVLT immediate recall, females (N=99) score higher than males (N=46); females=82.16%, SD=10.55, males=76.96%, SD=11.09; t_{143}=2.716, p=.007, Cohen's d=0.45. Similarly, females score higher than males on RAVLT delayed recall; females=83.79%, SD=18.5, males=73.48%, SD=21.78; t_{143}=-2.949, p=.004, Cohen's d=0.49. However, despite their superiority in VEM Long Term Forgetting (which is based only on Buschke VSRT measures) females do not score higher than males on any of the Buschke VSRT components of VEM Short Term Recall, although females do score lower/better than males on the free recall score for long term forgetting (calculated on the (A-B)/(A+B) basis); females=.253, SD=.260, males=.363, SD=.320; $t_{73.957}$=2.039, p=.045, Cohen's d=0.34. There is no difference between males and females in cued recall in long term forgetting (p=.11).

2.8.7 Female Advantages in the RAVLT and Forgetting are also apparent in the Older Age Group

These gender differences do not appear in the younger group alone (males N=16 and females N=36), but they do appear in the older age group alone (males N=30 and females N=63) with moderately larger effect sizes. So for RAVLT immediate recall, older females score higher than older males; females=79.49%, SD=10.87, males=73.6%, SD=11.37; t_{91}=2.403, p=.018, Cohen's d=0.5. Again, similarly, older females score higher than older males on RAVLT delayed recall; females=81.68%, SD=19.59, males=65.88%, SD=20.64; t_{91}=-3.573, p=.001, Cohen's d=0.75. Older female subjects do not score higher than older male subjects on any of the Buschke VSRT components of VEM Short Term Recall but older females do score lower/better than older males on the free recall score for long term forgetting (calculated on the (A-B)/(A+B) basis); females=.282, SD=.293, males=.420, SD=.345; t_{91}=2.003, p=.048, Cohen's d=0.42. There is no difference between older males and older females in cued recall in long term forgetting (p=.11).

Accordingly, in summary, in both the whole group and the older group, some female-gender performance superiority is apparent in components of both short and long-term verbal episodic memory (in line with e.g., Pauls, 2013). These differences appear to be strongest in the RAVLT, and in particular in RAVLT delayed recall. Differences in long-term forgetting free recall are moderate but there are no gender differences in Buschke's VSRT, in long-term forgetting cued recall or in any other memory domain.

2.8.8. Higher Education is associated with Better Working Memory but not with Better Performance in the other 3 Memory Domains

Higher education is not associated with better performance on VEM Short Term Recall (p=.20), Face Memory & Perception (p=.53) or VEM Long Term Forgetting (p=.92). However, higher education is associated with better Working Memory (Pearson's r=.424, p<.0001) and with better mentalizing (Pearson's r=.203, p=.017). The strong association between higher education and better Working Memory is reflected in the underlying associations between higher education and better performance in both the Stroop test (Pearson's r=-.390, p<.0001) and the 4MT (Pearson's r=.355, p<.0001). Using the Enter method for linear regression, both younger age (β=-.402, p<.0001) and higher education (β=.316, p<.0001) help to predict better Working Memory (R=.574, R Sq=.329).

There are no gender differences in education level which might help to explain gender differences in verbal episodic memory (see above); t_{137}=.732, p=.46. Finally, there are no associations between BMI and any of the memory domain factors (or with mentalizing). There are too few subjects who are left handed (12) or of mixed handedness to make valid comparisons of performance based on handedness.

2.8.9. Face Memory & Perception: support for 'f' characteristic

In this study, there is an even stronger correlation between results on the CFMT and GFMT (Pearson's r=.68, p<.0001; Spearman's r=.69, p<.0001) than was reported in earlier research (Verhallen, 2017) (Pearson's r=.48). The results on these two tests also correlate strongly in the present study with the Jenkins & Burton, 2011 test of unfamiliar face processing, and all three tests loaded onto a single factor in PCA factor analysis. This suggests that the resulting factor (which has been labelled here 'Face Memory & Perception') may be a reasonable approximation for an individual subject's 'f' cognitive ability, as suggested in that earlier research (Verhallen, 2017). The 'f' measure may not be a purely mnemonic domain, although as it contains memory components, scores for the Face Memory & Perception PCA factor will continue to be referred to as a separate memory domain in this study.

2.9. Summary of Chapter 2

This Chapter has explained how 145 subjects undertook two separate phases of cognitive testing. The tests provided many results and Principal Component Analysis (PCA) was used to categorise results into four independent memory-domain factors.

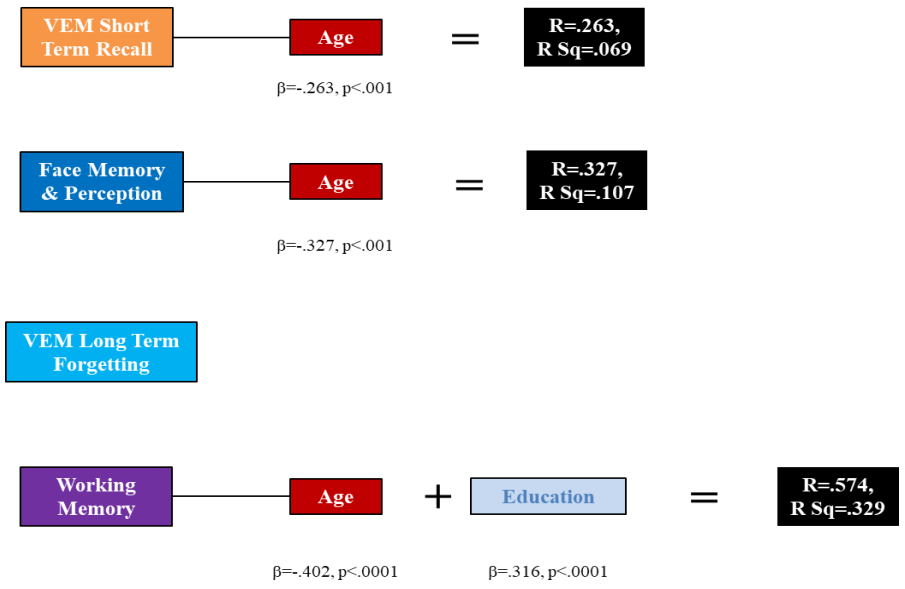
A similar approach was used to categorise subjects' responses in a collection of questionnaires into five independent social psychology factors, representing three main psychological domains or constructs.

This Chapter also described some general age-related results for the four memory-domain factors. It is clear that performance in Verbal Episodic Memory (VEM) Short Term Recall, Face Memory & Perception and Working Memory all decline with older age. There are large differences in these memory-domains between younger and older groups. Exploratory analysis in more detailed age groups suggests that decline accelerates appreciably with more advanced age (66 plus).

VEM Long Term Forgetting is a notable exception. There is no apparent age-related decline, no difference between younger and older subjects and subjects in the youngest age group (18-35) perform at broadly the same level as subjects in the oldest age group (66 plus). Females tend to perform somewhat better than males, but the main differentiator in performance (good sleep) is a main topic of the next chapter (Chapter 3).

The regression model derived from the results in this Chapter 2 is shown in Figure 2.9 below.

Figure 2.9: Regression Models for Chapter 2 Variables



Note: the Stepwise model for VEM Long Term Forgetting did not enter any of the 3 variables (age, education or gender) into the model.

CHAPTER 3: SLEEP

3.1. Introduction

In the last chapter, older age was associated with lower performance in three of the four measured memory domains, VEM Short Term Recall, Face Memory & Perception and Working Memory. Age was not though a determinant of performance in VEM Long Term Forgetting. This chapter examines the effects of sleep on memory, taking into account the age-related changes in memory already seen in Chapter 2. The next chapter (Chapter 4) will extend the analysis to Circadian behavioural measures associated with sleep, such as chronotype, Sleep Debt and Social Jet Lag.

3.1.1. Healthy Sleep plays an important role in Good Cognitive Health but may be Difficult to Define with precision

Despite much research into the relationship between sleep and cognition, the role that sleep plays in healthy cognitive ageing is still not well understood. Unlike physical activity, (where very broadly, the more you do, the better), there are no such simple messages that can be delivered for sleep. Recent research (Mohlenhoff, 2018; Ding, 2020; Lucey, 2021) has, for example, even suggested that too much sleep may be as unhelpful to healthy cognition as too little, building on earlier research showing a nuanced relationship between sleep duration and cognitive functioning (see e.g. Tworoger, 2006; Kronholm, 2009). However, the direction of causation remains unclear; it is possible that impaired cognition may require longer sleep to facilitate enhanced repair, rather than longer sleep itself causing cognitive under-performance. In May 2019, the World Health Organisation (WHO) published Guidelines on 'Risk Reduction of Cognitive Decline and Dementia' (Organisation, 2019), making twelve recommendations, covering areas such as physical activity, social activity, nutrition, weight management, smoking and alcohol, but specifically, excluding sleep. Recommendations to 'sleep well', let alone 'get enough sleep, but maybe not too much', are not simple to formulate.

Examining the relationship between sleep, memory and ageing is highly complex. Each separate element, 'sleep', 'ageing' and 'memory performance', is itself layered in complexity. Taking sleep alone, there are many different sleep measures and attributes, ranging from relatively straightforward concepts such as 'sleep duration' to less well-known sleep behavioural constructs such as 'Sleep Debt'. Most people, if asked, might be able to estimate their sleep duration with reasonable accuracy, but very few may have much idea of what their weekly 'Sleep Debt' is like. Yet Sleep Debt is becoming established as an important measure

of sleep adequacy, or colloquially, 'getting the right amount of sleep' (see, e.g., Fox, 2018). Research has found that many different sleep measures can affect cognitive function. For example, quite separate from the amount of sleep, some suggest that minimising sleep disturbance is the key to cognitive health (e.g., Blackwell, 2006; Oosterman, 2009; Mary, 2013). Others claim that regular Circadian behaviour is a major factor (e.g., Buysse, 2005; Kondratova & Kondratov, 2012; Gao, 2019; Taillard, 2021). All of these different sleep measures and attributes may change in ageing and may have quite distinct effects on different memory domains. The purpose of this Chapter, and the next Chapter (Chapter 4), is to investigate the meaning and effect of 'good sleep' in a healthy ageing population.

3.1.2. Sleep Changes occur in both Normal Ageing and Abnormal Cognitive Development

Sleep changes tend to coincide with changes in cognition over the lifespan, although the exact relationship between the two remains unclear (Ohayon, 2004; Mander, 2017; Helfrich, 2018; Dzierzewski, 2018). Age-related changes in sleep patterns across the normal adult lifespan include an increase in certain types of sleep disturbance, like sleep apnea, and insomnia (Zisberg, 2010; Ling, 2016). Sleep disturbances are common in adults over 60, i.e., in normal ageing (Walker, 2017; Bliwise, 1993; Redline, 2004). Older age is also associated with shorter durations of certain types of sleep, such as 'slow wave' sleep and REM sleep (Lichstein & Morin, 2000; Scullin & Bliwise, 2015; Mander, 2017). These various sleep attributes may differently affect the memory performance of younger and older persons (Hokett, 2021).

Sleep plays a critical role in learning and memory, social and emotional functioning and cognitive health generally (Diekelmann & Born, 2010; Goldstein & Walker, 2014; Walker & Stickgold, 2010; Walker, 2017). Sleep disruption is associated with medial PFC atrophy in older adults, leading to loss of hippocampal-dependent memory function (Mander, 2014). Sleep disturbances, such as reduced time asleep, Circadian rhythm disruption and increased nocturnal awakenings, are common in individuals with AD and MCI (McCurry, 1999; Coogan, 2013; Lucey & Bateman, 2014; Peter-Derex, 2015; Lucey & Holtzman, 2015, Ju, 2013; 2014; Guarnieri, 2012). Disturbed sleep can be characteristic of MCI long before AD diagnosis (Hita-Yañez, 2012) and Aβ protein accumulation in the brain disrupts sleep consolidation of memory (Mander, 2015; Spira, 2013). Greater sleep fragmentation is associated with increased risk of AD (A.S. Lim, 2013) and self-reported sleep disturbance in cognitively healthy men has been associated with a significantly higher risk of dementia (Benedict, 2015).

3.1.3. The Characteristics of 'Good Sleep' include Two Main Components: Sleep Duration and Sleep Quality

The major characteristics of 'good sleep' are wide-ranging and include reasonable sleep duration and high sleep efficiency (i.e., time asleep as a proportion of time in bed), low sleep latency (time taken to fall asleep) and a low number and/or duration of sleep disturbances or nocturnal awakenings (Nebes, 2009; Walker, 2017). These characteristics are all captured in the Pittsburgh Sleep Questionnaire (the PSQ; Buysse, 1989); see further below. The structure and content of the PSQ arguably suggests that 'good sleep' comprises two fundamental components; first, getting enough sleep (i.e., adequate sleep duration) relative to time spent in bed, including time spent trying to get to sleep, and second, enjoying good sleep quality (i.e., sleep that is subjectively regarded as restful and refreshing). The PSQ does not however measure Circadian regularity (or sleep timing).

3.1.4. Getting Good Sleep: Sleep Duration: Too Much Sleep may be as Harmful as Too Little

The research linking sleep duration to cognitive functioning or impairment shows some varying results (Kronholm, 2009; Xu, 2011; Ferrie, 2011; Genzel, 2013; Krause, 2017). For example, both excessively *short* and *long* sleep have been associated with lower verbal memory performance (Kronholm, 2009), and more recently, both types of abnormal sleep duration have been associated with lower performance in attention-based tasks across different age groups (Mohlenhoff, 2018). In a recent cross-sectional Chinese study, both short and long sleep duration was associated with worse cognitive performance in community-living older subjects (Ding, 2020); and in a study of pre-clinical AD, cognitive functioning was only stable in a mid-range of sleep duration, and not at the extremes, i.e., with too little or too much sleep (Lucey, 2021). The emerging evidence therefore appears to suggest, so far as 'good sleep' is concerned, that healthy sleep duration exists in a 'Goldilocks zone' between too little and too much. Excessively low sleep duration (5 hours or less) has been associated with cognitive impairment (Tworoger, 2006; Krause, 2017) but so too has excessively long sleep duration (Faubel, 2009; Loerbroks, 2010; Yaffe, 2014).

Recent research has also begun to question the long-held assumption of a clear relationship between shorter sleep time of older persons and their declining cognitive performance (see e.g., Fox, 2018), i.e., decline in cognitive performance may be age-related but it may also be the case that older persons simply need less sleep (Fox, 2018). The fact that problematic sleep duration is not merely a case of getting too little sleep has been emphasised by a recent

longitudinal study where a decline in cognitive performance across a composite range of tests (including free and cued selective reminding) was found in both short and long sleepers (Lucey, 2021). Longer sleep duration has previously been associated with increased dementia risk (Benito-León, 2009), although in another case sleep quantity did not differ significantly between cognitively normal individuals and those with preclinical AD (Ju, 2013).

Some evidence suggests that mild sleep deprivation may even promote (beneficial) attentional alertness or arousal (Dzierzewski, 2018). However, against this, the evidence for the detrimental effect of too little sleep (i.e., sleep deprivation as opposed to short sleep) is very strong. Partial sleep deprivation for one night in older adults can trigger the DNA damage molecular response associated with biological ageing (Carroll, 2016). Self-reported shorter sleep has also been associated with greater Aβ brain burden (Spira, 2013). In addition, just one night of sleep deprivation can lead to Aβ accumulation in the right hippocampus and thalamus, unrelated to APOE genotype (Shokri-Kojori, 2018).

3.1.5. Getting Good Sleep: Sleep Quality: Good Sleep Quality goes Beyond Sleep Duration

Sleep quality is something of an umbrella term that captures objective criteria such as sleep disturbances (e.g. the number and duration of nightly awakenings), sleep latency, i.e., the time taken to fall asleep after going to bed (e.g., Blackwell, 2006) and the necessity and regularity of sleep medication use. Sleep quality might be assessed subjectively (e.g., 'how well do you sleep on average?') in questionnaires and sleep diaries. The PSQ is the most well-known and reliable sleep quality questionnaire (reliability score: Cronbach's α=0.83; Buysse, 1989; 1991; Backhaus, 2002). The Pittsburgh Sleep Quality Index (PSQI) generates a score from 7 different sleep components, both objective and subjective, and allocates a rating as a 'good sleeper' or 'poor sleeper' based on the PSQI score. Higher PSQI scores denote worse sleep quality, with a score of 5 or below indicating good sleep and 6 or above (maximum 21) indicating poor sleep. The PSQ has been used before in sleep studies with elderly subjects (see, e.g., Zisberg, 2010) and PSQ poor sleep has previously been shown to predict lower performance in some cognitive domains in older persons (Nebes, 2009).

One component of the PSQ is sleep disturbances (PSQ component 5). It has been suggested that undisturbed sleep, rather than sleep duration, is more important for avoiding cognitive deficits (Oosterman, 2009; Mary, 2013). Higher levels of sleep disturbance inevitably mean a lower sleep to time-in-bed ratio (or lower sleep efficiency); poor sleep quality generally,

including low sleep efficiency, has been associated with cognitive impairment (Keage, 2012; Potvin, 2012; Ling, 2016). Individuals with preclinical AD (as determined by Aβ 42 levels) have worse sleep efficiency than cognitively normal individuals (Ju, 2013). Aβ 42 levels also fluctuate during the sleep/wake cycle, being higher during wakefulness and lower during sleep (Roh, 2012) so that a relationship exists between disrupted Circadian rhythm and the aggregation of Aβ that would normally be removed during sleep (Hastings & Goedirt, 2013). In short, disruption of the sleep/wake cycle has been shown to impede clearance of Aβ deposition in the brain (Cedernaes, 2016; Mander, 2016) which reinforces cognitive deterioration.

Good sleep quality also requires consistent and regular sleep behaviours (see, e.g., Zisberg, 2010). Poor or irregular Circadian management may be seen in wide discrepancies in sleep patterns, for example, large differences in the times of 'going to bed' and 'getting up' from day to day and, typically, between weekdays and weekends (Gao, 2019). Not getting enough sleep during the working week can lead to the build up of 'Sleep Debt' (Fox, 2018). Sleep Debt must be 'repaid' before a normal sleep pattern can be resumed. These Circadian behaviours of sleep timing are considered further in Chapter 4.

3.1.6. Good Memory Performance is Underpinned by Good Sleep Quality

It has been suggested that, without good sleep, long-term memory consolidation cannot take place (Stickgold & Walker, 2005). Sleep affords relief from interfering or competing sensory input during the process of memory consolidation (Gui, 2017; Olafsdottir, 2018) and is important to the process of memory dialogue or transfer between hippocampal regions and neocortex (Axmacher, 2009; Takashima, 2006; Gais, 2007; Mander, 2014; Lambert, 2020). Commonly, the benefit of sleep for memory consolidation has been shown in experiments where memory performance after a period of wakefulness is compared with performance after a similar period of sleep (Backhaus, 2007; Aly & Moscovitch, 2010; Wilson, 2012; Scullin, 2013; Cherdieu, 2014). These experiments have consistently shown sleep to be the clear winner for consolidation benefits (Backhaus, 2007; Cherdieu, 2014; Talamini, 2008; Genzel, 2013; Mazza, 2016).

However, memory consolidation occurs in multiple brain areas in *both* sleep and waking states, potentially over very long periods (Dudai, 2004; 2015; Squire & Alvarez, 1995). Although the benefit to consolidation of sleep over wakefulness is uncontroversial, some uncertainty

surrounds the timeframe required to maximise long-term memory consolidation. The consolidation process may require different lengths of time, asleep and awake, for different types of memory, such as, for example, declarative, procedural and spatial memory (Plihal & Born, 1997; Moscovitch & Nadel, 1998; Ficca, 2000; Walker, 2002; Gais & Born, 2004; Feld, 2014; Barry, 2016; Scullin, 2019). Measuring sleep consolidation benefits over longer periods than a week remains relatively unexplored, perhaps due in part to the predominance of 'sleep versus waking' comparisons in memory consolidation research to date. However, examining sleep benefits to memory consolidation over an extended longer-term period is necessary, if only to allow for the possible inconsistency of sleep patterns and behaviour over shorter to medium periods of measurement (i.e., one or two nights of poorer sleep than normal in a sleep lab could adversely affect potential memory consolidation benefits).

As well as helping longer term memory consolidation, it has also been suggested that good sleep quality may also enhance early-stage memory performance functions (such as encoding) by 'freeing up' neural space (Tononi & Cirelli, 2006; Yoo, 2007; Axmacher, 2009), effectively 'rebooting' the learning system. In this respect, it might be expected that 'good sleepers' should out-perform 'poor sleepers' in any memory-based task, not simply long-term memory.

3.1.7. Accelerated Long-term Forgetting is an Abnormal, Clinical Condition: But Not All Long-term Forgetting is indicative of Clinical Impairment

Any study examining the effects of sleep on memory consolidation should be careful to differentiate between two separate areas of research, *normal* sleep memory consolidation and *abnormal* accelerated long-term forgetting (ALF). Although they have adopted some common terminology, the two research areas have quite different backgrounds and should not be conflated. Broadly, sleep memory consolidation is a *normal* process, some of the benefits of which may be discernible overnight (e.g., Stickgold & Walker, 2005; Diekelmann & Born, 2010), although, in the case of long-term consolidation, such benefits may require days, weeks or even months to become evident (Squire, 1986; 2009; Gold, 2006). By contrast, ALF was first identified as an *abnormal* phenotype (Blake, 2000) in transient epileptic amnesia (TEA) (Muhlert, 2010) and is a clinical condition of abnormal forgetting in which initial learning and encoding may appear to be normal (Zeman, 1998; Mendes, 2002), but where clinical-level impairment is revealed in accelerated forgetting over a longer period of hours, days or weeks (Butler, 2007), i.e., long-term memory consolidation fails. In standard, neuropsychological tests of memory, delayed recall is typically tested after 30 minutes (see Chapter 2 above), and ALF patients may perform at unimpaired levels in these tests (Walsh, 2014). However, ALF

patients may, for example, fail to remember the content of conversations or books over the longer term, which then reveals the clinical impairment (Manes, 2008).

ALF has also been identified as a predictor of other forms of clinical memory impairment, such as amnestic mild cognitive impairment (aMCI) and AD (Martin, 1991; De Renzi & Lucchelli, 1993; Wearn, 2020; Weston, 2018), although more recently it has been suggested that ALF is not a feature of AD after all (Stamate, 2020). It is perhaps difficult to see how ALF may predict clinical-level cognitive decline in healthy adults over the following year (Wearn, 2020) if ALF is not actually a characteristic of AD (Stamate, 2020). This may illustrate one difficulty of applying a specific clinical concept like ALF beyond the clinical condition in which it was originally identified (TEA) and to which it specifically relates.

3.1.8. The Present Study includes a Test of Ordinary Long-term Forgetting over 2 weeks

The present study only concerns ordinary long-term forgetting (and to avoid any confusion, this will not be abbreviated to ALF). Taking a straightforward approach to the terminology, *accelerated* long-term forgetting strongly implies some form of impairment (i.e., that forgetting is accelerated in comparison with a *normal* rate of long-term forgetting that is not). This begs the question what is an ordinary, expected level of (unaccelerated) long-term forgetting and how is this 'normal' level of long-term forgetting measured. The simple fact that one group (e.g. older subjects) might show different performance in long-term forgetting from another group (e.g. younger subjects) does not characterise that lower performance level by older persons as abnormal, clinical-level ALF (see e.g., Mary, 2013) and does not help to define the boundary between ordinary and accelerated long-term forgetting. This should be borne in mind when considering the results of the present study, and specifically those between good and poor sleepers in rates of long-term forgetting. In short, it is not suggested that any group of subjects (such as poor sleepers) who may be shown to have higher rates of long-term forgetting have preclinical or undiagnosed ALF.

Although, as described, care should be taken not to conflate ordinary long-term forgetting with the clinical condition of ALF, current evidence suggests that *some* increased longer-term forgetting may normally occur with older age (Elliot, 2014; Davis, 2003; MacDonald, 2006). However, long-term forgetting in a healthy population may be quite subtle (Davis, 2003). The relationship between such subtle effects in a normal healthy population and sleep memory consolidation may be particularly difficult to detect over short to medium term timescales, if at all (Aly & Moscovitch, 2010). Analysing the contribution of sleep quality to forgetting in

any population that includes older subjects is also complicated by the fact that such individuals may already be experiencing sleep problems (Hita-Yanez, 2012), which might in turn be expected to have an impact on any consolidation benefits they could ordinarily achieve from sleep.

3.1.9. Sleep has been Measured in the Present Study using Actigraphy and Self-report

In this study, sleep quality was measured by self-report (the PSQ and sleep diaries) and actigraphy, with data collected over a two week period. There are two main methods of practical sleep measurement. Polysomnography (PSG) is recognised as the 'gold standard' of sleep measurement and usually involves subjects attending a 'sleep lab' overnight where brain state readings are taken to measure different phases and attributes of sleep (see, e.g., Cherdieu, 2014). PSG can detect different sleep phases, such as 'slow wave' and 'REM' sleep (e.g., Mander, 2017) and determine which phases are most helpful to memory consolidation (e.g., Wamsley, 2011). There are two main drawbacks with PSG. First, observations are not generally made in natural surroundings, which may affect their validity as being properly representative of a subject's normal sleep patterns (i.e., subjects may find it more difficult to sleep normally in a lab). Second, it is not practicable to undertake PSG over extended periods (e.g., for weeks at a time). Sleep patterns can however change from week to week, and as will be seen in Chapter 4, do change substantially over the course of the week, with large changes in sleep behaviour between weekdays and weekends.

The second main method of objective sleep measurement, and the method used in the present study, is actigraphy (see, e.g., Santisteban, 2018). Wrist-worn accelerometer devices, that are relatively unobtrusive, have the advantage of providing for sleep measurement over extended periods of time, including weeks. The major disadvantage with actigraphy is that it does not measure sleep per se, but normally the absence of movement (or strictly acceleration) as an algorithm-based proxy for sleep. Actigraphy devices are becoming increasingly sophisticated, incorporating, for example, light monitors and temperature readers, making the algorithms used to discern sleep from waking more refined. However, such advances cannot (yet) make the devices easily capable of detecting sleep phases, and the main problem remains that absence of nocturnal body movement is not a reliable predictor of actual sleep, as anyone who has lain awake but motionless for hours can attest (see, e.g., Leschziner, 2019). Whilst acknowledging these clear limitations, actigraphy has been used in this study for the purposes of objective sleep measurement and cross-corroboration with the PSQ.

Although some studies have found limited support from actigraphy for self-reported sleep behaviour (Grandner, 2006; Landry, 2015), as described in Results below, data from the devices used here shows a reasonable relationship with self-reports of sleep and bed behaviours by subjects in both their PSQ and sleep journals. As will be seen in Chapter 4, actigraphy strongly corroborates self-reported Circadian data (such as bed duration) and has enabled a detailed analysis of differences in Circadian behaviour across different age groups.

3.1.10. The Main Focus in the Present Study is the Effect of Sleep on Memory Domain Performance in Different Age Groups

This study is mainly concerned with the effects of sleep quality in the memory domains identified by factor analysis (see Chapter 2). In particular, two of the memory domains, VEM Long Term Forgetting and VEM Short Term Recall, represent tests of verbal episodic memory with and without the benefit of intervening periods of sleep. VEM Long Term Forgetting measures subjects' long-term recall and consolidation in VEM after two weeks (i.e. including two weeks' sleep), whereas VEM Short Term Recall is an aggregate measure of subjects' encoding and early-stage storage and (pre-sleep) consolidation in verbal episodic memory. In line with previous research, good sleep might be expected to be reflected in better long-term memory consolidation (or lower long-term forgetting). Most importantly, a long-term timeframe of two weeks, including two full weekends, was used here to examine the effects of sleep consolidation on forgetting over an extended period. There are no identified studies in sleep memory consolidation that have examined ordinary long-term forgetting over a period of two weeks. Separately, the 'learning re-boot' hypothesis might be expected to result in better performance in VEM Short Term Recall or other memory domains for good sleepers, even where there is no intervening period of sleep. If this hypothesis were correct, good sleep may not make any discernible difference between VEM Short Term Recall and VEM Long Term Forgetting.

3.1.11. Sleep-related Hypotheses: Summary

It is expected that PSQ grading as a good or poor sleeper *may* be reflected in actigraphy device-recorded measures, such as bed and sleep duration (but see Landry, 2015). It is also expected that older subjects may show poorer self-reported sleep quality than younger persons (Nebes, 2009).

In line with earlier findings (e.g., Nebes, 2009), it is expected that poor sleep in older persons may be associated with worse performance in some of the tested memory domain factors.

Specifically, performance in those memory domains such as VEM and Working Memory, which have previously been associated with poorer sleep quality (e.g., Bastien, 2003; Kronholm, 2009) may show a stronger relationship with sleep quality than, say, Face Memory & Perception. Good sleep quality in younger or middle-aged subjects may be associated with higher cognitive functioning (Scullin & Bliwise, 2015).

It is expected that VEM Long Term Forgetting may show a pattern of age-related decline, with higher levels of long-term forgetting in the older group (Mary, 2013). It is possible that good and poor sleepers may have different levels of performance in VEM Long Term Forgetting, possibly reflecting the benefits of good sleep to long-term memory consolidation.

3.2. METHODS

3.2.1. Measuring Sleep: Objective and Subjective Measures Used

GENEActiv Original^{R} accelerometers (the devices) were used to measure subjects' sleep over a two week period (see Chapter 2, General Methods and Results, for further details of how devices are configured and data is extracted from them); see also Figure 2.2. Specifically in relation to measuring sleep, the devices provide daily results for bed duration (showing both 'going to bed' and 'getting up' time), sleep duration, sleep efficiency and activity periods (or the number of non-sleep periods during a bed duration period). Bed duration is divided into sleep and non-sleep periods. This allows certain other measures to be calculated such as sleep latency (or the time in minutes from going to bed to the first minute of device-recorded sleep) and assumed sleep duration (or ASD) which is calculated as the total time in minutes between the first and last minutes of recorded sleep (see, e.g., Lin, 2020). ASD is different from actual sleep duration because it will not take into account any periods of activity (or sleep disturbances during sleep). The mid-point of sleep is relevant to the calculation of certain Circadian measures; see Chapter 4. ASD has been used to determine the mid-point of sleep without regard to any nightime periods of temporary waking or activity, i.e., there has been no differentiation between nightly disturbances that are 'movement while awake' as opposed to 'movement while asleep' because the devices are unable to make this distinction.

The majority of subjects (N=107) completed sleep diaries. These diary records provide corroboration of device data for 'going to bed' and 'getting up' times. Subjects also assessed their quality of sleep in the diaries on a scale of 1 to 5 (1= very poor, 5= very good) for each of the 15 days. An example of a Sleep Diary is shown in Figure 2.2. Subjects also completed the Pittsburgh Sleep Questionnaire (PSQ); see Figure 2.2. As described above, the Pittsburgh Sleep Quality Index (PSQI) scores sleep on seven different sleep components in a range of 0-21, with higher scores denoting worse sleep. The PSQ assigns subjects to one of two categories, a 'good sleeper' or a 'poor sleeper' with the cut-off point being 5 or below ('good') and 6 or above ('poor'). All references below to 'good sleepers' and 'poor sleepers' are to the PSQ categorisations calculated for subjects. Where actual PSQI scores are used, this is expressly stated. Sleep diary scores for sleep quality are highly negatively correlated with PSQI scores (Pearson's $r=-.529$, $p<.0001$) showing that sleep quality during the two week device measurement period accurately reflects the PSQI assessment of sleep quality (made for a four week period), at least for those subjects who completed sleep diaries. The non-parametric

correlation between PSQI and diary sleep quality score is Spearman's r_s=-.498, p<.0001. PSQI scores are not normally distributed (W_{140}=.942, p<.0001) because the majority of PSQI scores are at the low end (3-8) of the full PSQI range (0-21). This is a common occurrence (see, e.g., Nebes, 2009).

3.3. RESULTS

3.3.1. Consistent Finding: Bed and Sleep Data from Accelerometers shows reasonably good accord with comparable PSQ Self-reported Measures

Table 3.1 shows differences in age, education and BMI between younger and older subjects, males and females and between PSQI good and poor sleepers.

Table 3.1: Age, Education Level and BMI Comparisons by Age Group, Gender and PSQ Sleep Quality

	All	Age Group		Difference	Gender		Difference	PSQ Sleepers		Difference
	M/(SD)	Younger	Older		Male	Female		Good	Poor	
Number (N)	145	52	93		46	99		79	61	
Age	55.26 (17.14)	36.06 (8.94)	66 (9.51)	t_{143}=-18.575, p<.0001	54.46 (16.07)	55.64 (17.64)	t_{143}=-.385, p=.70	52.91[3] (16.74)	59.03[3] (17.07)	t_{138}=-2.127, p=.035
Education Level (16=high)	12.88 (4.49)	14.18[1] (3.17)	12.18[1] (4.94)	$t_{133.395}$=-2.905, p=.004	13.3 (4.3)	12.69 (4.49)	t_{137}=.732, p=.46	13.14 (4.42)	12.55 (4.6)	t_{137}=.765, p=.45
BMI	24.76 (3.72)	24.54 (3.73)	24.88 (3.72)	t_{143}=-.521, p=.60	25.72[2] (3.28)	24.31[2] (3.83)	t_{143}=2.153, p=.033	24.86 (3.42)	24.83 (3.96)	t_{138}=.060, p=.95

Table 3.1 shows descriptive statistics for all subjects, separated by main age group (younger=18-50 and older =50+), gender and Pittsburgh Sleep Questionnaire (PSQ) rating as a good or poor sleeper. Orange shading highlights significant differences between groups. Note 1: Younger subjects have higher education levels than older persons; $t_{133.195}$=2.905, p=.004. Note 2: Males have higher BMI than females; t_{143}=2.153, p=.033. Note 3: Good sleepers are younger than poor sleepers; t_{138}=-2.127, p=.035. Otherwise, there are no differences in BMI between younger and older groups, no differences in age or education level between males and females and no differences in education level or BMI between good and poor sleepers.

Comparison of actigraphy bed and sleep measurements showed reasonably strong correlations in most areas with corresponding measures calculated from subjects' PSQ self-report; see Table 3.2. For example, there are strong positive associations between higher device-recorded bed duration and higher PSQ self-reported bed duration; Pearson's r=.483, p<.0001; Spearman's r_s=.483, p<.0001. There is also a strong positive association between device-recorded ASD and PSQ self-reported sleep duration; Pearson's r=.374, p<.0001; Spearman's r_s=.416, p<.0001.

Table 3.2: Correlations between Accelerometer device-based Sleep Measures and Pittsburgh Sleep Questionnaire self-reported Sleep Measures

	Device Bed Duration		Pittsburgh Bed Duration		Pittsburgh Sleep Duration		Pittsburgh Sleep Effic.		Device ASD		Device Sleep Latency	
	r	p	r	p	r	p	r	p	r	p	r	p
Pittsburgh Bed Duration	.483	<.0001										
Pittsburgh Sleep Duration	.338	<.0001	.366	<.0001								
Pittsburgh Sleep Efficiency	-.021	.81	-.376	<.0001	.709	<.0001						
Device Assumed Sleep Duration	.750	<.0001	.374	<.0001	.374	<.0001	.012	.89				
Device Sleep Latency	.292	.0004	.183	.031	.155	.07	.024	.78	-.081	.33		
Device Awakenings	.222	.007	.047	.58	-.010	.91	-.051	.55	.201	.015	.002	.98

Table 3.2 shows Pearson's r correlations between actigraphy device-based sleep measures and PSQ self-reported sleep measures. Device-based measures are generally highly correlated with each other (apart from device-based ASD and device based sleep latency; p=.33) and PSQ self-reported sleep measures are also highly correlated with each other. The orange shading in Table 3.2 shows only significant 'crossover' correlations between actigraphy device-based measures and PSQ self-reported sleep measures (i.e. it does not show where accelerometer based measures are correlated with each other and mutatis mutandis for the Pittsburgh Sleep Questionnaire measures). In particular, device based and PSQ self-reported bed and sleep durations are highly correlated. The exception is that PSQ self-reported PSQ sleep efficiency is not associated with any device based sleep measure.

3.3.2. Consistent Finding: PSQI scores appear to be Reasonably Consistent with those seen in Previous Research Studies

Table 3.3 shows actigraphy, sleep diary and PSQ self-report sleep measures analysed by age group, gender and PSQ categorisation as a good or poor sleeper.

Although good sleepers tend to be younger than poor sleepers (see Table 3.1), younger and older subjects do not score differently on the PSQI, and neither do males and females (see Table 3.3). In the older group, good and poor sleepers are equally numerous (46/45) whereas in the younger group, good sleepers outnumber poor sleepers by a ratio of 2:1 (33/16). In earlier research, the division between good and poor sleepers varies; e.g. 69% good/31% poor in Nebes, 2009 and the opposite profile, 40% good/60% poor, is given in Rezaei, 2018. Average PSQI score in the present study (M=5.53) straddles the category boundary between good and poor sleep and is consistent with that found elsewhere, as are the average PSQI scores overall for good (3.56) and poor (8.08) sleepers respectively (e.g. Nebes, 2009, poor sleepers=8.4; Rezaei, 2018, PSQI M=6.32, SD=2.72). In this respect, the abnormal distribution of PSQI scores at the lower to middle end of the 0-21 score range is quite typical of findings in other research.

Table 3.3: Actigraphy, Sleep Diary and Pittsburgh self-reported Sleep Measures by age group, gender and PSQI categorisation

	All	Younger	Older	Difference Younger/Older	Male	Female	Difference Male/Female	Good Sleepers	Poor Sleepers	Difference Good/Poor Sleepers
PSQI Score	5.53 (2.83)	5.37 (2.51)	5.62 (3)	t_{138}=-.493 p=.62	5.57 (2.78)	5.51 (2.87)	t_{138}=.112 p=.091	3.56 (1.23)	8.08 (2.21)	$t_{88.176}$=-14.381 p<.0001
Sleep Diary Sleep Quality Assessment	3.48 (.56)	3.35 (.54)	3.53 (.57)	t_{105}=-1.469 p=.15	3.48 (.67)	3.48 (.52)	$t_{43.312}$=-.010 p=1	3.67 (.51)	3.25 (.52)	t_{103}=4.216 p=.0001
Device Bed Duration (mins)	500 (49)	506 (53)	497 46	t_{143}=1.148 p=.25	493 (40)	504 (52)	t_{143}=-1.211 p=0.23	497 (46)	506 (53)	t_{138}=-1.064 p=.29
Pittsburgh Bed Duration (mins)	502 (55)	487 (49)	510 (57)	t_{137}=-2.415 p=.017	492 (55)	506 (55)	t_{137}=-1.340 p=.18	492 (53)	515 (56)	t_{137}=-2.479 p=.014
Sleep Diary Bed Duration (mins)	496 (42)	505 (39)	492 (43)	t_{105}=1.412 p=.16	494 (42)	496 (42)	t_{105}=-.184 p=.85	493 (44)	500 (40)	t_{103}=-.910 p=.37
Device Assumed Sleep Duration (mins)	453 (42)	459 (38)	449 (44)	t_{143}=1.456 p=.15	443 (45)	457 (40)	t_{143}=-1.833 p=.07	451 (44)	456 (41)	t_{138}=-.645 p=.52
Pittsburgh Sleep Duration (mins)	418 (60)	425 (47)	414 (66)	$t_{126.590}$=1.168 p=.25	413 (52)	420 (63)	t_{137}=-.642 p=.52	444 (44)	382 (59)	$t_{104.747}$=6.818 p<.0001
Device Sleep Duration (mins)	328 (75)	337 (73)	323 (76)	t_{143}=1.089 p=.28	304 (73)	339 (74)	t_{143}=-.2.716 p=.007	324 (74)	333 (79)	t_{138}=-.671 p=.50
Pittsburgh Sleep Efficiency (%)	83.94 (11.99)	87.7 (8.84)	81.89 (12.99)	$t_{130.137}$=3.121 p=.002	84.6 (12.16)	83.63 (11.96)	t_{137}=.443 p=.66	90.95 (6.36)	74.7 (11.4)	$t_{86.508}$=9.932 p<.0001
Device Awakenings (N)	10.27 (2.4)	10.94 (2.2)	9.9 (2.44)	t_{143}=2.550 p=.012	10.5 (2)	10.17 (2.57)	$t_{110.126}$=.836 p=.41	10.43 (2.35)	10.05 (2.5)	t_{138}=.912 p=.36
Pittsburgh Disturbances (score 0-21)	6.82 (3.65)	6.69 (3.42)	6.89 (3.79)	t_{138}=-.302 p=.76	7.05 (3.69)	6.72 (3.65)	t_{138}=.490 p=.625	5.09 (2.79)	9.07 (3.42)	t_{138}=-7.578 p<.0001
Device Sleep Latency (mins)	24 (12)	24 (9)	25 (14)	t_{143}=-.438 p=.66	27 (15)	23 (11)	t_{143}=1.581 p=.12	25 (14)	23 (11)	t_{138}=.896 p=.37

Table 3.3 shows actigraphy (device-based), sleep diary and PSQ self-reported sleep measures. Circadian measures are considered in detail in Chapter 4. For sleep measures, younger subjects have lower PSQ bed duration than device-reported bed duration and (consequently) higher PSQ sleep efficiency, whereas older subjects have higher PSQ bed duration than device-reported bed duration and (consequently) lower PSQ sleep efficiency. A comparison between sleep diary bed duration, device bed duration and PSQ self-reported bed duration suggests that younger persons may be under-reporting their PSQ bed duration and consequently 'inflating' their PSQ sleep efficiency. Device bed duration and sleep diary bed duration are much closer than device bed duration and PSQ bed duration. The close agreement between sleep diaries and device records provides a strong basis for using device-based data to analyse Circadian behaviour in chapter 4. PSQ good and poor sleepers are (unsurprisingly) significantly different in most self-reported sleep measures, but are also different in their sleep diary assessments of sleep quality over the 2 week sleep measurement period.

3.3.3. A Comparison between Device-reported Bed Duration and PSQ Self-reported Bed Duration across Detailed Age Groups shows Some Differences: in self-report, the oldest group (66 plus) has a longer bed duration than any other age group

Figure 3.1 shows a comparison between device-based and PSQ self-report in bed duration and sleep duration across four detailed age groups.

Figure 3.1: Comparing Device-based and PSQ self-reported Bed and Sleep Duration in Detailed Age Groups

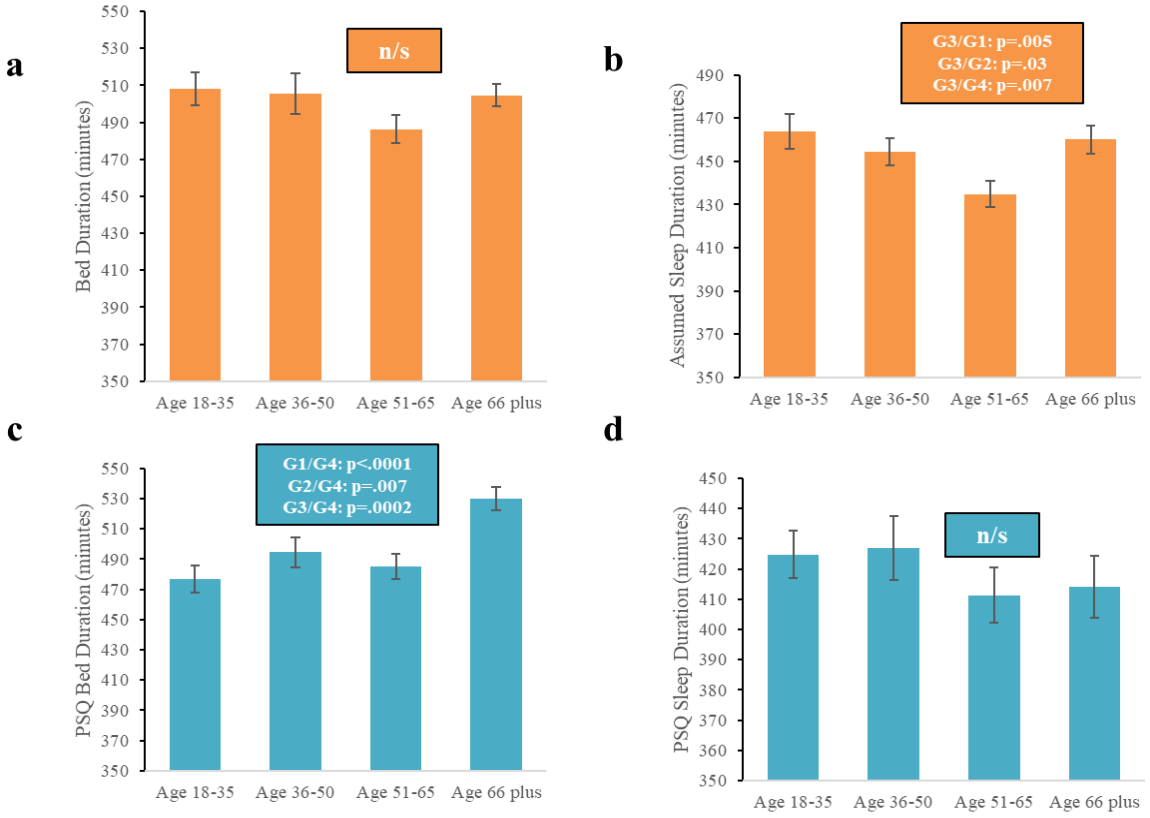


Figure 3.1: Device recorded bed duration and ASD and PSQ self-reported sleep duration, analysed by four age groups. **a**. Bed Duration: Group 3 (age 51-65) has marginally lower bed duration than the oldest and youngest age groups (p=.06 and p=.07 respectively) but not significantly. **b**. Assumed Sleep Duration or ASD: Group 3 (G3: age 51-65) has lower ASD than all three other age groups; Group 1 (G1): t_{64}=2.932, p=.005, Group 2 (G2): t_{66}=2.165, p=.034 and Group 4 (G4): t_{89}=-2.772, p=.007. **c**. Group 4 (66 plus) has longer PSQ self-reported bed duration than each of the 3 other age groups; Group 1: t_{73}=-4.205, p<.0001, Cohen's d=0.98 Group 2: t_{74}=-2.759, p=.007, Cohen's d=0.64 and Group 3: t_{86}=-3.919, p=.0002, Cohen's d=0.85. **d**. PSQ Self-reported sleep duration: There are no statistical differences between the age groups although Group 3 self-reports a lower sleep duration than all three other age groups, consistent with the position for both device recorded bed duration (a) and ASD (b). This tends to show some reasonable level of consistency between actigraphy-recorded and self-reported data. Error bars show +/- one s.e.m.

There is a strong correlation between device-recorded bed duration and self-reported bed duration (Pearson's r=.483, p<.0001) and the averages for both are nearly identical (M=500 mins and M=502 mins respectively). In addition, sleep diary records were used to cross-check accuracy of day by day device-recorded 'going to bed' and 'getting up' times; device-recorded bed duration and diary recorded bed duration are also very strongly correlated (Pearson's r=.750, p<.0001, Spearman's rs=.818, p<.0001).

However, while age is not correlated with device-recorded bed duration (Pearson's r=-.046, p=.58, Spearman's r_s=-.008, p=.92), older age is correlated with longer PSQ self-reported bed duration (Pearson's r=.324, p=.0001, Spearman's r_s=.354, p<.0001). This difference is illustrated in Figure 3.1 which shows both device based and self-reported bed duration across 4 detailed age groups. The key difference in self-reported bed duration is that the oldest age group (Group 4, 66 plus) has longer PSQ self-reported bed duration than each of the three younger age groups: Group 1 (18-35) and Group 4: t_{73}=-4.205, p<.0001, Cohen's d=0.98; Group 2 (36-50) and Group 4: t_{74}=-2.759, p=.007, Cohen's d=0.64; Group 3 (51-65) and Group 4: t_{86}=-3.919, p=.0002, Cohen's d=0.85. The effect size is more modest in a comparison of PSQ bed duration between the main younger and older groups (above and below 50); t_{137}=-2.415, p=.017, Cohen's d=0.41. There are no differences in self-reported bed duration between Group 3 (51-65) and either Group 1 (18-35, p=.51) or Group 2 (36-50, p=.47). This pin-points the major change in self-reported bed duration as occurring in the oldest age group (66 plus).

3.3.4. A Comparison between Device-reported ASD and PSQ Self-reported Sleep Duration across Detailed Age Groups also shows Some Differences: the 51-65 age group has lower ASD than any other age group

Table 3.3 shows time in bed characterised (by the devices) as sleep appears to be very short (M=328 mins). This is, on average, approximately 78% of the amount of sleep self-reported by subjects in the PSQ (M=418 minutes) and approximately 72% of device-based ASD (453 minutes). If this were correct, it would mean that, on average, between the first and last points of device-recorded sleep, subjects spend nearly 30% of the night awake (i.e. 2 hours difference of 'sleep disturbance'; the average number of nightly disturbances is 10 and average disturbance length is 12 minutes). This appears to be an excessive amount of time spent in sleep disturbance. This result is probably attributable to the fact that, as described above, some movement during sleep, or breaks in sleep, is being erroneously interpreted by the devices as 'non-sleep'. This means that actual sleep time may be substantially under-recorded by the devices and, in addition, some 'sleep disturbance' time may be substantially over-recorded. As a result, ASD has been used as the preferred measure of device-recorded sleep duration used in the present study (for comparison with PSQ self-reported sleep duration) albeit that some nightly awakenings might normally be expected to reduce actual sleep duration below the level of ASD.

Neither ASD nor PSQ self-reported sleep duration shows any correlation with age: Age/ASD: Pearson's r=-.020, p=.81, Spearman's r_s=.010, p-.90; Age/PSQ sleep duration: Pearson's r=-

.119, p=.16, Spearman's r_s=-.093, p=.28. There is also no difference in ASD between the two main age groups (p=.15). However, as Figure 3.1 shows, Group 3 (age 51-65) has lower ASD than each of the 3 other age groups: Group 3 and Group 1 (18-35): t_{64}=-2.932, p=.005, Cohen's d=0.73; Group 3 and Group 2 (36-50): t_{66}=-2.165, p=.034, Cohen's d=0.53; Group 3 and Group 4 (66 plus): t_{89}=-2.772, p=.007, Cohen's d=0.59. These results appear to suggest that lower assumed sleep duration occurs in the 51-65 age group. The comparable results for PSQ self-reported sleep duration do not show any differences between the detailed age groups, albeit that the profile of detailed age group changes appears comparable.

These results for bed duration and ASD will be re-considered in relation to certain Circadian behavioural differences discussed further in Chapter 4 below.

3.3.5. Younger Subjects and Older Subjects do not differ in Self-reported Sleep Quality

There is no difference between younger and older groups in self-assessment of sleep quality, as measured either by the PSQ or sleep diaries; see Table 3.3. There are also no differences in PSQI score or diary sleep-quality assessment between any of the four detailed age groups. As between the two main age groups, younger persons have an average PSQI score of 5.37 and older persons have an average PSQI score of 5.62 and there is no difference between the two (t_{138}=-.493, p=.62). However, applying normal roundings, younger persons would, on average, be good sleepers (score 5) and older subjects would tend to be poor sleepers (score 6). When age comparisons are made between good and poor sleepers, good sleepers (M=52.91 years, SD=16.74) tend to be younger than poor sleepers (M=59.03 years, SD=17.07); t_{138}=-2.127, p=.035, Cohen's d=0.36. However, there is no association between age and PSQI score (Pearson's r=.092, p=0.28; Spearman's r_s=.079, p=.35).

A higher sleep quality diary assessment is very moderately associated with shorter time in bed (Pearson's r=-.212, p=.028, Spearman's r_s=-.125, p=.20) and shorter ASD (Pearson's r=-.197, p=.042, Spearman's r_s=-.159, p=.10). There is some evidence that BMI may have an adverse effect on sleep. Higher BMI is moderately associated with lower ASD (Pearson's r and Spearman's r_s=-.172, p=.038). There is however no difference in BMI between good and poor sleepers; t_{138}=.060, p=.95.

*3.3.6. **Main New Finding:** A Better PSQI Sleep Score is strongly correlated with Better (lower) VEM Long Term Forgetting*

There are no significant associations between any memory domain factors and bed duration, ASD or most other device recorded sleep measures. Table 3.4 shows that a higher (worse) PSQI score is strongly associated with higher (worse) VEM Long Term Forgetting (Pearson's r=.283, p=.001; Spearman's r_s=.312, p=.0002). A better/lower PSQI score is not associated with improved performance in VEM Short Term Recall, Face Memory & Perception or Working Memory. The contrasting associations between age and PSQI score in VEM Short Term Recall and VEM Long Term Forgetting are illustrated in Figure 3.2.

Table 3.4: Correlations between PSQI Score, Actigraphy Sleep Measures and Memory Domain Factors

	VEM Short Term Recall		Face Memory & Perception		VEM Long Term Forgetting		Working Memory	
	r	p	r	p	r	p	r	p
PSQI Score	-.090	.29	.034	.69	.283	.001	-.075	.37
Bed Duration	.072	.39	.011	.90	-.104	.21	.070	.40
Assumed Sleep Duration	.022	.80	-.072	.39	-.026	.75	.112	.18
Sleep Latency	-.105	.21	.010	.90	-.147	.08	-.002	.98
Awakenings	.136	.10	-.035	.68	-.005	.95	.048	.57
	r_s	p	r_s	p	r_s	p	r_s	p
PSQI Score	-.046	.59	.119	.16	.312	.0002	.001	.99
Bed Duration	.078	.35	-.053	.53	-.101	.23	.044	.60
Assumed Sleep Duration	.057	.50	-.090	.28	-.013	.88	.092	.25
Sleep Latency	-.090	.28	-.016	.85	-.206	.013	-.002	.98
Awakenings	.143	.08	-.030	.72	.030	.72	.051	.54

Table 3.4 shows simple linear correlations between the four independent memory domain factors and certain sleep measures. Circadian measures are considered in detail in Chapter 4. These tests of association indicate that VEM Long Term Forgetting (PCA factor 3) has different determinants compared to the other three memory domains. Only VEM Long Term Forgetting was associated with PSQI score (where higher PSQI score and lower sleep quality was associated with higher/worse long-term forgetting). The other memory domain factors (PCA factors 1, 2 and 4) were not. All statistically significant results are shown in orange shading. All associations shown are for Pearson's r and Spearman's r_s correlations. No corrections are applied for multiple testing.

Although no differences were found between males and females in PSQI score (Table 3.3), females tend to have lower VEM Long Term Forgetting than males (t_{143}=2.089, p=.04, Cohen's d=0.35). Males and females do not differ in performance on any of the other memory domain factors.

Figure 3.2: Younger age is associated with better VEM Short Term Recall but not with better VEM Long Term Forgetting: Better VEM Long Term Forgetting is associated with better/lower PSQI score but better VEM Short Term Recall is not

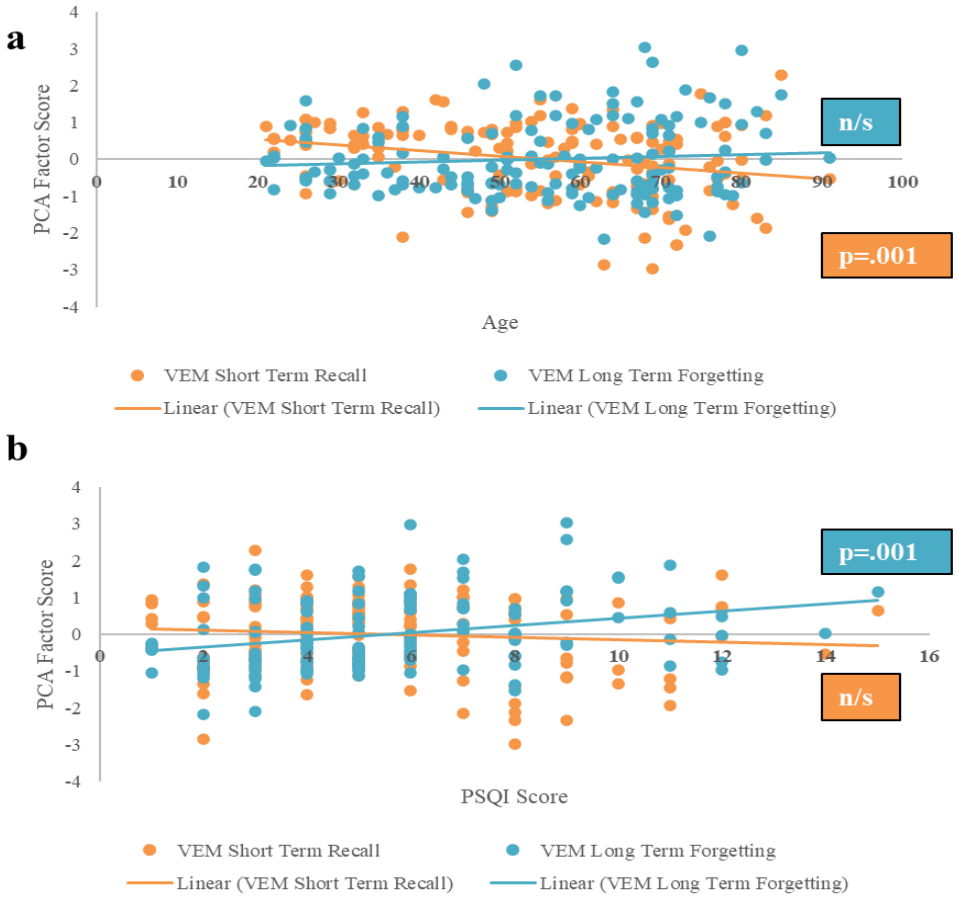


Figure 3.2 shows correlations between (a) age and (b) PSQI score with both VEM Short Term Recall and VEM Long Term Forgetting. **a**. Older age is associated with worse VEM Short Term Recall; Pearson's r=-.263, p=.001; Spearman's r_s=-.250, p=.002 but it is not associated with worse VEM Long term Forgetting; Pearson's r=.088, p=.29, Spearman's r_s=.038, p=.65. **b**. By contrast, higher (worse) PSQI score is associated with higher (worse) VEM Long Term Forgetting; Pearson's r=.283, p=.001, Spearman's r_s=.312, p=.0002 but it is not associated with lower (worse) VEM Short Term Recall; Pearson's r=-.090, p=.29, Spearman's r_s=-.046, p=.59.

As explained in Chapter 2, VEM Long Term Forgetting is a relative measure which compares scores at 2 weeks in both free and cued recall elements of Buschke's VSRT (Buschke, 1973) with the standard component scores for 30 minute delayed free call and immediate cued recall. VEM Short Term Recall comprises absolute measures (actual test scores). However, it should be noted that lower/better PSQ good sleep quality (but not gender) predicts higher/better new absolute scores for both free recall at two weeks (β=-.309, p=.0002) and cued recall at two weeks (β=-.347, p<.0001).

As described in Chapter 2, older age is not wholly unrelated to worse long term recall (after 2 weeks). When examining the actual FCSRT scores, as Figure 3.3 shows, at phase 1 testing, older age is strongly correlated with lower FCSRT free recall after 30 minutes (Pearson's r=-.379, p<.0001, Spearman's rs=-.392) and with lower immediate cued recall (Pearson's r=-.419, p<.0001, Spearman's rs=-.437, p<.0001). After 14 days, older age is still correlated with worse free recall (after two weeks), Pearson's r=-.225, p=.007, Spearman's rs=-.220, p=.008 and with worse cued recall after two weeks, Pearson's r=-.329, p<.0001, Spearman's rs=-.311, p=.0001. However, this consistent association with age contrasts with the relationship to PSQI score. In this case, there is no correlation between PSQI score and either FCSRT free recall after 30 mins (p=.16) or immediate cued recall (p=.29). There is a strong correlation between higher (worse) PSQI score and both lower free recall after 2 weeks (Pearson's r=-.248, p=.003, Spearman's rs=-.257, p=.002) and lower cued recall after 2 weeks (Pearson's r=-.276, p=.001, Spearman's rs=-.296, p=.0004).

*3.3.7. **Main New Finding:** Better Sleep Quality Selectively Predicts Better (lower) VEM Long Term Forgetting*

Regression models confirmed that lower VEM Short Term Recall, Face Memory and Perception and Working Memory are all predicted by older age but not by gender or PSQ scale rating; see Table 3.5. Conversely, PSQ scale rating as a poor sleeper predicts higher VEM Long Term Forgetting, but neither age nor gender contribute to the model. If age is removed from the regression model for VEM Long Term Forgetting shown in Table 3.5, two outliers emerge; both subjects scored 0/12 and 0/11 in free and cued recall respectively after two weeks. When these outliers are excluded, female gender also helps to co-predict lower VEM Long Term Forgetting. The model becomes R=.341, R Squared=.116; PSQ scale β=.277, p=.001 and gender β=-.180, p=.028 (see Figure 3.5 in the chapter summary below). Using two-way ANOVA (for PSQ scale and gender), and excluding the same two outliers, the results show that there is a main effect of both PSQ scale and gender on VEM Long Term Forgetting factor score but no significant interaction between PSQ scale and gender: main effect of PSQ scale: $F_{1,134}$=14.437, p=.0002, η_p^2=.097; main effect of gender: $F_{1,134}$=5.665, p=.02, η_p^2=.041; no interaction between PSQ scale and gender: $F_{1,134}$=2.758, p=.099, η_p^2=.020. There is no strong statistically significant difference between male and female good sleepers (p=.60) or between male and female poor sleepers (p=.054, marginal difference) in VEM Long Term Forgetting.

Figure 3.3. Dissociation between PSQI score and scores for free and cued recall at phase 1 and two weeks later at phase 2

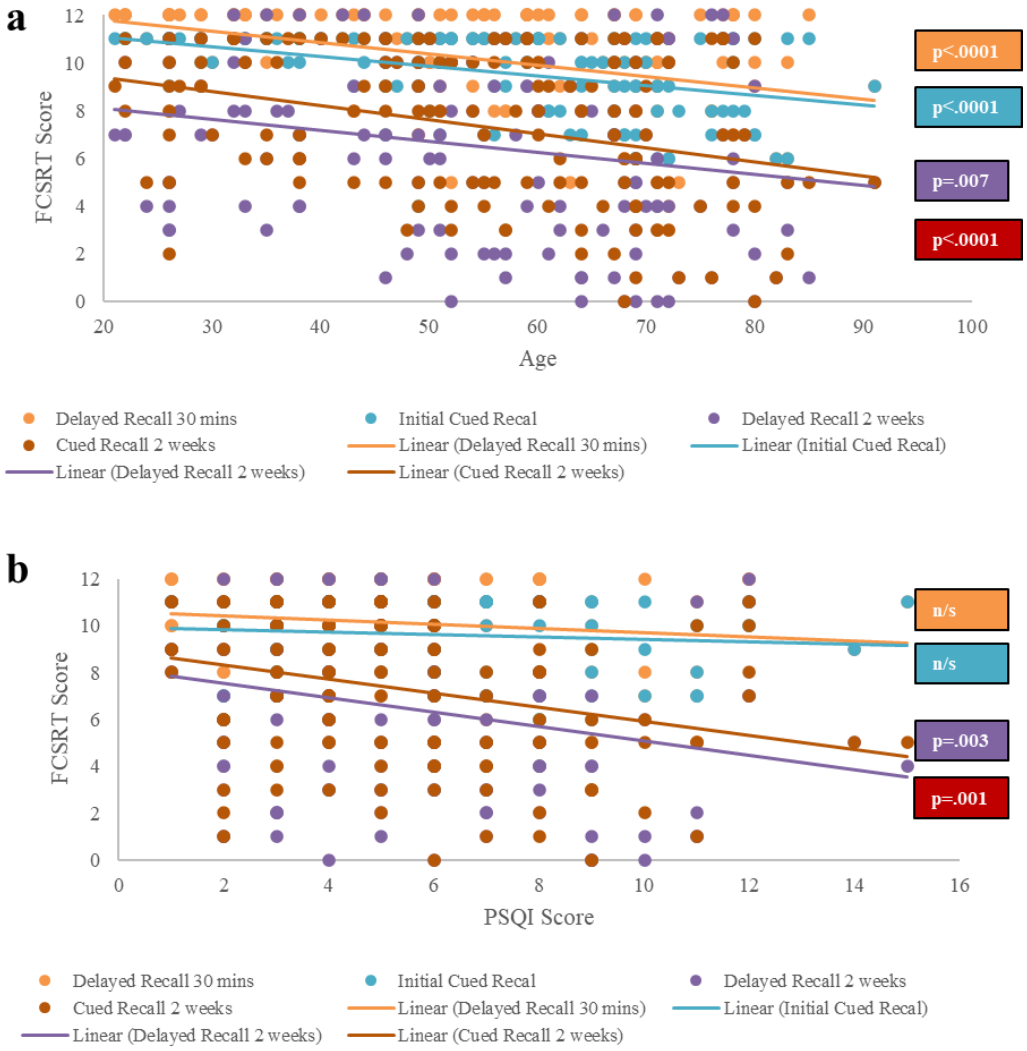


Figure 3.3 shows the dissociation in the relationship between PSQI score and underlying scores for Buschke's VSRT delayed free and cued recall at phase 1 and phase 2 (two weeks later) respectively. **a**. Older age is strongly correlated with lower delayed free recall after 30 mins (Pearson's r=-.379, p<.0001, Spearman's r_s=-.392, p<.0001) and with lower immediate cued recall (Pearson's r=-.419, p<.0001, Spearman's r_s=-.437, p<.0001). At phase 2 testing after 2 weeks, older age is still correlated with lower delayed free recall (after 2 weeks) (Pearson's r=-.225, p=.007, Spearman's r_s=-.220, p=.008) and with lower cued recall after two weeks (Pearson's r=-.329, p<.0001, Spearman's r_s=-.311, p=.0001). **b**. By contrast, PSQI score is not correlated with either free recall after 30 mins (p=.16) or immediate cued recall (p=.29). However, at phase 2 testing (after 2 weeks) a higher/worse PSQI score is associated with lower free delayed recall score (after 2 weeks) (Pearson's r-.248, p=.003, Spearman's r_s=-.257, p=.001) and lower cued recall after two weeks (Pearson's r=-.276, p=.001, Spearman's r_s=-.296, p=.0004). There is a clear dissociation between PSQI and Buschke's VSRT absolute scores at phase 1 and phase 2 testing (i.e. regardless of the position in the 'relative' measure of long term forgetting). FCSRT= Free and Cued Selective Reminding Test (or Buschke's VSRT).

Table 3.5: Regression Models for Memory Domain Factors using Age, Gender and PSQ Scale rating as Predictors

Measure	R	R Sq	Age		Gender		PSQ Scale	
			β	Sig.	β	Sig.	β	Sig.
VEM Short Term Recall	.322	.104	-.275	.001	.158	.055	-.045	.58
Face Memory & Perception	.359	.129	-.350	<.0001	.071	.382	.153	.06
VEM Long Term Forgetting	.346	.120	.028	.74	-.138	.09	.304	.0003
Working Memory	.479	.229	-.478	<.0001	-.033	.67	.011	.88

Table 3.5 shows linear regression models using the Enter method for the four independent memory domain factors using age, gender and PSQ scale rating (as a good or poor sleeper) as predictor variables. In line with simple correlations, younger age is the main predictor variable for PCA factors 1, 2 and 4. Gender and PSQ scale rating do not contribute to predicting scores on these three memory domain factors. PSQ scale rating (as a poor sleeper) does predict higher VEM Long Term Forgetting, but neither age nor gender does so. If instead of PSQ scale rating (as a good or poor sleeper), actual PSQI score is used as a predictor variable, two outliers emerge (both subjects scored very low on both free and cued recall after two weeks). Controlling for these outliers, both higher/worse PSQI score (β=.268, p=.001) and male gender (β=-.195, p=.018), but not age, then together predict higher/worse VEM Long Term Forgetting; see text for further details.

Analysing the two main age groups separately using two-way ANOVA reveals that in both older and younger age groups there is a main effect of good and poor sleep in VEM Long Term Forgetting score in both older and younger subjects, albeit somewhat weaker in the younger group alone. Female gender only makes a difference however to VEM Long Term Forgetting score in the older group. There is no interaction between PSQ scale and gender in either the younger or older age groups. In the older group, main effect of PSQ scale: $F_{1,85}$=9.620, p=.003, η_p^2=.102; main effect of gender: $F_{1,85}$=5.070, p=.03, η_p^2=.056; no interaction between PSQ scale and gender: $F_{1,85}$=1.389, p=0.24, η_p^2=.016. In the younger group, main effect of PSQ scale: $F_{1,45}$=4.316, p=0.04, η_p^2=.088; no main effect of gender: $F_{1,45}$=.812, p=0.37, η_p^2=.018; no interaction between PSQ scale and Gender: $F_{1,45}$=1.476, p=0.231, η_p^2=.032.

The main finding is therefore that PSQ status as a good sleeper selectively predicts lower VEM Long Term Forgetting but does not predict better VEM Short Term Recall. Female gender helps to co-predict lower VEM Long Term Forgetting. Additionally, good sleep does not predict better Face Memory & Perception or Working Memory.

*3.3.8. **Main New Finding:** There is a Double Dissociation between VEM Short Term Recall & Long Term Forgetting*

A double dissociation between VEM Short Term Recall and VEM Long Term Forgetting is illustrated in Figure 3.4. In summary, as seen in Chapter 2, younger subjects outperform older

subjects in VEM Short Term Recall (t_{143}=2.888, p=.004, Cohen's d=0.48), but the two age groups are no different in VEM Long Term Forgetting ($t_{139.315}$=1.420, p=.16). Good sleepers however outperform perform poor sleepers in VEM Long Term Forgetting (t_{138}=3.926, p=.0001, Cohen's d=0.67), but good and poor sleepers perform no differently in VEM Short Term Recall ($t_{113.470}$=1.181, p=.24).

Figure 3.4: There is a Double Dissociation in VEM Short Term Recall and VEM Long Term Forgetting

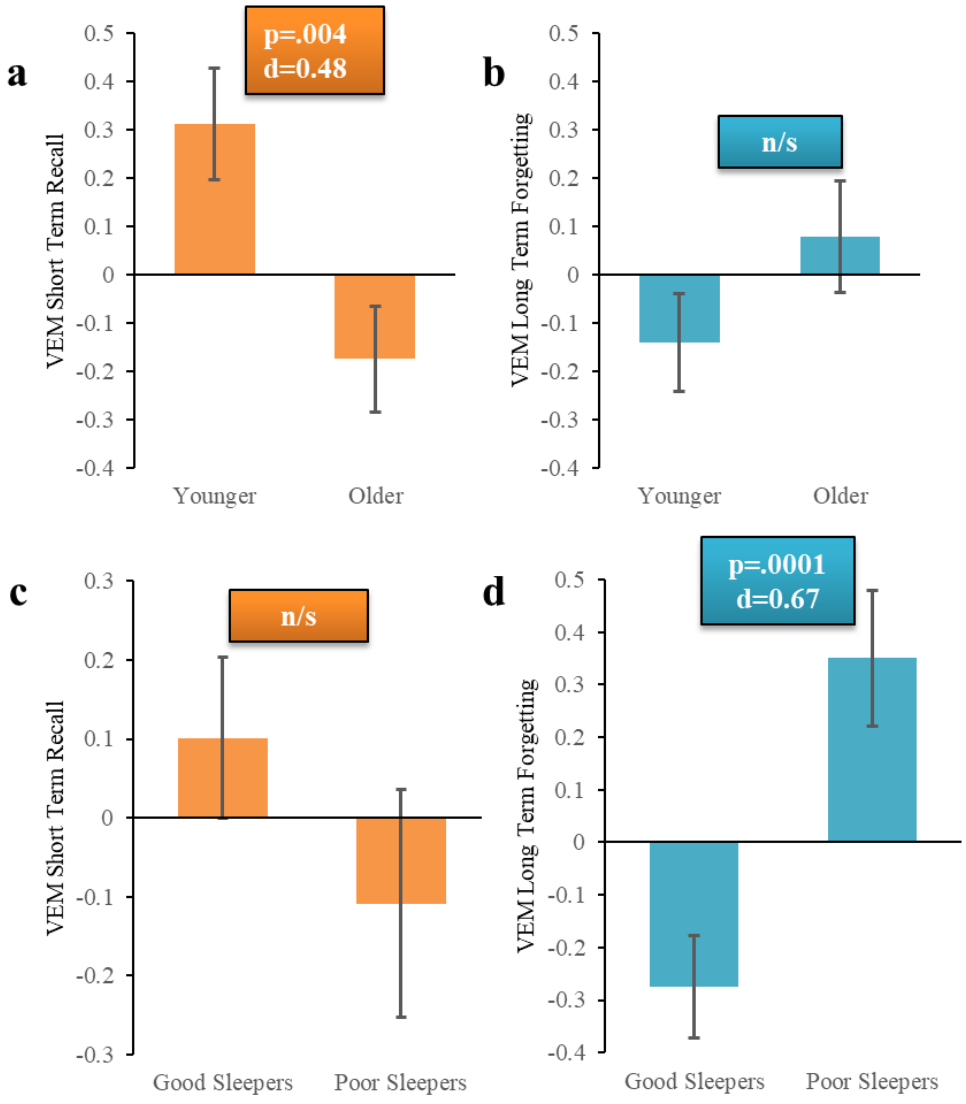


Figure 3.4: Double Dissociation between Younger and Older Age Groups and between Good and Poor Sleepers in both VEM Short Term Recall and VEM Long Term Forgetting: Older age predicts worse VEM Short Term Recall but not worse VEM Long Term Forgetting. Conversely, poor sleep quality predicts higher VEM Long Term Forgetting but not lower VEM Short Term Recall. **a**. In VEM Short Term Recall, younger subjects perform better than older subjects (t_{143}=2.888, p=.004, Cohen's d=0.48). **b**. In VEM Long Term Forgetting, younger and older subjects perform no differently ($t_{139.315}$=-1.420, p=.16). **c**. In VEM Short Term Recall, good sleepers and poor sleepers perform no differently ($t_{113.470}$=-1.189, p=.24). **d**. In VEM Long Term Forgetting, good sleepers have lower rates of forgetting than poor sleepers (t_{138}=3.926, p=.0001, Cohen's d=0.67). Error bars show +/- one s.e.m.

Again, it should be noted that age is not wholly unrelated to forgetting. If the underlying FCSRT scores for FCSRT free and immediate recall at 14 days are analysed, younger age makes an additional contribution, alongside good sleep quality, to better scores. The linear regression model for free recall at 14 days is R=.352, R Sq=.124; PSQ sleep quality: β=-.278, p=.001, age: β=-.172, p=.036. The linear regression model for cued recall at 14 days is R=.441, R Sq=.194; PSQ sleep quality: β=-.297, p=.0002, age: β=-.277, p=.001. As far as the two component forgetting scores of VEM Long Term Forgetting are concerned, age makes no contribution to the linear regression model for 'free recall forgetting' (R=.320, R Sq=.102; PSQ sleep quality: β=.285, p=.001, age: β=.104, p=.21. Age does continue to make a moderate contribution to the linear regression model for 'cued recall forgetting' (R=.364, R Sq=.132; PSQ sleep quality: β=.282, p=.001, age: β=.185, p=.024). None of the tested models for calculating forgetting (i.e. A-B/A+B, A-B or A-B/A) show significant correlations between 'free recall forgetting' and younger age.

These sleep results will be expanded in Chapters 4 and 6 below where, respectively, Circadian differences and psychological health will be considered, including their relationship to good sleep.

3.4. DISCUSSION

*3.4.1. **Main New Finding:** Better (lower) Long-term Forgetting is predicted by Good Sleep Quality in a Healthy Ageing Population*

In this sample of cognitively normal, healthy ageing subjects (M=55 years), age is not a significant predictor of VEM Long Term Forgetting after two weeks, whereas sleep quality is. This novel finding suggests that ordinary long-term forgetting is not primarily predicted by age, and may in fact be modulated by good sleep, facilitating better long-term memory consolidation.

The finding that higher performance on VEM Short Term Recall, which includes measures of immediate recall as well as standard short 30 minutes delayed recall, is predicted by lower age is in line with previous findings (Manoli, 2018), as is the finding that females perform better on verbal episodic memory, in this case, on VEM Long Term Forgetting (Sundermann, 2016; Manoli, 2018). However, good sleep does not appear to be associated with better VEM Short Term Recall and, as such, there is no evidence in this study to support the hypothesis that there is a relationship between good sleep and higher learning, encoding or early verbal episodic memory processes. In addition, the findings here of no relationship between good or poor sleep and performance in either VEM Short Term Recall or Working Memory are consistent with those of earlier research (Nebes, 2009) where 157 subjects aged 65-80 were divided between PSQ good and poor sleepers; no differences were found between good and poor sleepers in a standard test of verbal episodic memory—the Logical Memory Test from the Wechsler Memory Scale Revised (Wechsler, 1987)—or on the Stroop test. In that study, differences were however found between good and poor sleepers in attention shifting and non-verbal intelligence (Reitan & Wolfson, 1995; Brown, 1997), although there was no test of long-term memory/forgetting.

Higher VEM Long Term Forgetting in an ordinary, healthy population may represent a failure of long-term consolidation, rather than one of encoding or any early stage memory process. This is not based simply on the PCA factor analysis categorisation in this study of VEM Short Term Recall and VEM Long Term Forgetting as distinct memory domains. The dissociation in these results showing that good sleep is *not* associated with any improvement in VEM Short Term Recall but *is* strongly associated with lower VEM Long Term Forgetting strongly suggests that *ordinary* long-term forgetting is a late-stage process, occurring in the days, or possibly even weeks, after learning and represents a failure of long-term memory consolidation. In short, standard ‘short term’ delayed recall (after 30 minutes) does not show

any similar strong relationship with good sleep. In earlier studies, sleep-dependent memory consolidation benefits (i.e. lower forgetting) have been shown to be secured by overnight and medium-term periods of good sleep (Mary, 2013; Gui, 2017; Manoli, 2018). These findings extend this earlier research by showing that good sleep benefits to consolidation of VEM may be discerned over longer periods than a few days or a week, and the efficacy of this 'good sleep' dependent process may be more important than the simple fact of being younger.

The present study was not designed to investigate *accelerated* long-term forgetting in one group compared with another. Although therefore differences were found in ordinary long-term forgetting in subjects who were either good or poor sleepers, this does not imply that any subjects in any lower performing groups (e.g., poor sleepers) have levels of long-term forgetting that are *accelerated* to abnormal levels (e.g., comparable to those found in TEA or other clinical conditions). Also, in this study, memory consolidation effects have been examined over a longer two week period than has been seen in other studies, but it remains possible that the beneficial process of sleep-memory consolidation may still only be part-way through. Finally, only consolidation of *verbal episodic memory* has been examined over a two week period. The effects of extended periods of sleep consolidation for different forms of memory is an important area for further research.

3.4.2. ***Replicated Finding:*** *Age, but not Sleep Quality, predicts performance in VEM Short Term Recall, Face Memory & Perception and Working Memory*

In relation to the basic hypothesis that older age would be associated with worse sleep, there was no difference in sleep quality between younger and older subjects, either based on PSQI score, objectively recorded data or sleep diary self-assessment. This was also the case for the four more detailed age groups and was emphasised by an absence of any correlation between older age and either worse PSQI score or diary sleep quality assessment.

However, examining the differences between PSQ good and poor sleepers reveals that good sleepers tend to be younger ($p=.035$). Although age is a significant predictor in three of the four PCA memory domain factors (see Chapter 2), there is no evidence in the present study that good sleep quality makes any additional contribution alongside younger age to predicting better performance in these three memory domains, VEM Short Term Recall, Face Memory & Perception and Working Memory. This finding replicates some earlier research findings (Nebes, 2009), although the finding of no association between good sleep and Face Memory & Perception is arguably novel.

3.4.3. Limitations

The limitations concerning the use of actigraphy in sleep studies reported elsewhere (Leschziner, 2019) were most noticeable in the low device-recorded levels of sleep duration. As explained above, this may be due to the over-sensitivity of the devices to interpret movement as a period of waking. However, as will be seen further in Chapter 4, there is strong agreement between self-reported and device-recorded going to bed and getting up times and assumed sleep duration (ASD) has been used as a more reliable indicator of full, potential sleep duration. In addition, the main finding (on long-term memory consolidation) is unaffected by device-recorded sleep duration, or device measurements generally, although it should be borne in mind that some device measures show reasonably good associations with PSQ measures and, unlike the PSQ, devices do not provide any overall summary of sleep quality. Aside from these anticipated limitations with actigraphy data for sleep, there are several other limitations.

First, this sample of older persons comprises active individuals with fairly high levels of social engagement. Different results might arise with older groups of less active or socially-engaged individuals. In addition, the majority of volunteers were female. Second, the project was not designed around specific sleep hypotheses for the four memory-related domains ultimately revealed by factor analysis. This was necessarily the case since, before and during the cognitive testing, it was not known how PCA factor analysis would categorise the scores from the various tests. Third, in order to guard against rehearsal, subjects were not informed that they would be repeat tested on the VSRT (Buschke, 1973) after two weeks. This presents two potential confounds. First, some subjects may nevertheless have been motivated to rehearse in the intervening period; this was an unavoidable risk. Second, some subjects may have taken the reasonable view that that the words learned at phase 1 were irrelevant information that would not be needed in long-term memory. In this respect, having better ordinary long-term forgetting of non-salient information might arguably be regarded as a normal and efficient deployment of cognitive resource.

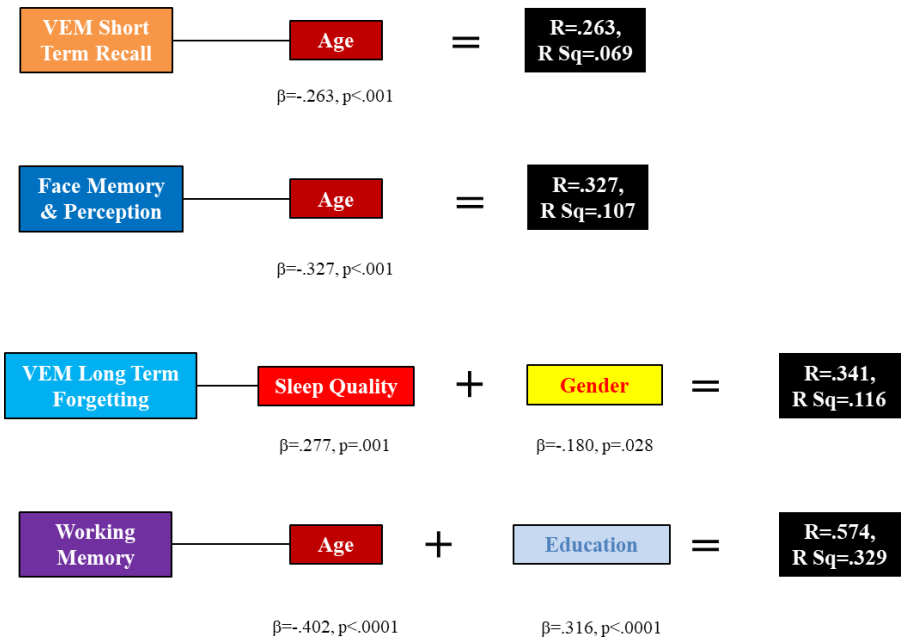
3.5. Summary of Chapter 3

The main new finding of this Chapter is a strong double dissociation whereby good sleepers (as characterised by PSQ) have lower VEM Long Term Forgetting than poor sleepers, although there is no difference between younger and older subjects. In contrast, while younger subjects outperform older subjects on VEM Short Term Recall, there is no difference between good and

poor sleepers. This is a major, new finding which points to the benefit of good sleep in the process of long-term memory consolidation.

The updated regression models are shown in Figure 3.5.

Figure 3.5: Updated Regression Models for Chapter 2 &3 Variables



Note: the regression model is updated from the Chapter 2 model and shows additional contributing variables. It should be noted that for VEM Long Term Forgetting, in addition to the Chapter 3 variable 'sleep quality', gender from Chapter 2, is now re-introduced.

The next chapter (Chapter 4) will examine how certain Circadian behaviours change across the lifespan, and can be demonstrated by the actigraphy data, as well as the relationship between Circadian behaviours, memory domain performance and good sleep quality.

CHAPTER 4: CIRCADIAN BEHAVIOUR AND MEMORY DOMAIN PERFORMANCE IN NORMAL AGEING

INTRODUCTION

4.1. Purpose of this Aspect of the Research

In the last chapter, it was shown how differences in sleep quality, and specifically between PSQ good and poor sleepers, differentially affected memory domain performance beyond the straightforward age-related differences in memory shown in Chapter 2. The results in the last chapter were based mainly on PSQ self-report, albeit corroborated by actigraphy. In this chapter, the results are based primarily on actigraphy data, not self-report, and extend the findings from Chapter 3 to include Circadian sleep behaviour. In contrast to the good and poor sleeper distinction of Chapter 3, subjects are here divided into two Circadian categories of 'owls' and 'larks', based on actigraphy data, and broadly representing later and earlier chronotypes. This chapter examines how Circadian behavioural characteristics are affected by ageing, and how they may in turn affect performance in different memory domains.

This chapter will begin with a short explanation of why Circadian behaviour is relevant to this study and will be followed by an overview of Circadian research, including its relevance to hippocampal-based memory. The distribution of chronotypes in the general population will be explained, along with the effects of ageing on Circadian behaviour and how this has been shown elsewhere to affect cognition and certain psychological factors. Finally, two 'modern world' Circadian attributes, Sleep Debt and Social Jet Lag, which both feature with increasing prominence in research on sleep and cognition, will be examined in their relationship to chronotype, ageing, and memory domain performance.

4.2. Why is Circadian Behaviour Important to this Study

4.2.1. Circadian Behaviour Changes occur at age 50, with Earlier Going to bed and Getting up Times

Circadian behaviour regulates sleep and any study involving sleep analysis should also therefore consider Circadian behaviour. Chapter 3 described certain changes occurring in bed and sleep behaviour across detailed age groups; for example, results showed that the oldest age group (aged 66 plus) had longer self-reported bed duration and longer assumed sleep duration (ASD) than the next youngest group (aged 51-65). However, sleep *timing* is independent from sleep *duration* (Roenneberg, 2007a; 2007b). There are well-reported age-related changes in

Circadian behaviour; older adults tend to go to bed earlier, wake up earlier and have more disturbed Circadian rhythm (Buysse, 2005). Age differences in Circadian rhythm function are said to emerge around age 50 (Ishihara, 1992; Tankova, 1994) and the importance of Circadian behaviour to general health, and healthy cognitive ageing, is a rapidly-growing area of new research (Fabbian, 2016; Abbott, 2020; Leng, 2019; Uddin, 2020; Mohandas, 2022; Foster, 2022). This makes it important to consider whether Circadian behaviour differences contribute to the age group and sleep group differences described in Chapters 2 and 3.

4.2.2. Circadian Rhythm is important for Effective Sleep Regulation, Good Sleep Quality and Memory Performance

The co-occurrence of Circadian rhythm changes and memory performance decline in older age has led some to hypothesise that a weakening Circadian rhythm may contribute to normal age-related brain and cognitive decline (Hofman & Swaab, 2006; Kondratov, 2007; Kondratova & Kondratov, 2012; Deibel, 2015). Research has suggested that the Circadian clock contributes to memory performance, including consolidation of declarative memory, through its key role in sleep regulation, specifically in relation to sleep quantity (i.e. duration) and quality (Gerstner & Yin, 2010; Kondratova & Kondratov, 2012). Desynchronisation studies, where subjects are forced into unnaturally short (20 hours) or long (28 hours) days, have shown cognitive performance is strongly linked to the 24 hour Circadian rhythm (Wyatt, 1999).

Disruption in Circadian rhythm has been associated with cognitive dysfunction and memory impairment, with higher Circadian disruption being reflected in more severe impairment (Deibel, 2015). One question is whether Circadian behaviours may affect memory domains differently or independently from measures of sleep quality described in Chapter 3. This Chapter will examine in particular whether more extreme Circadian behaviour (i.e., higher disruption) may be associated with lower performance in the studied memory domains. Finally, this Chapter will examine whether there is any evidence for Circadian-based psychological differences between subjects (sometimes referred to as "chronopsychological" differences; Tankova, 1994) and, if there are any, what relevance these may have for memory in ageing.

4.3. Overview of Circadian Differences and Behaviour

4.3.1. The Circadian Clock plays a Major Role in Effective Sleep Regulation

Circadian rhythm (or the Circadian clock) is attuned to the 24 hour period of the earth's rotation, which has allowed organisms to adapt to an advantageous diurnal or nocturnal rhythm,

as appropriate (Bell-Pedersen, 2005). Leaving the special consideration of 'shift work' to one side, humans are essentially a diurnal species. Human Circadian rhythm describes certain endogenous and externally-driven processes and behaviours which undergo 'cyclical oscillation' over a 24 hour period (Kyriacou & Hastings, 2010; Deibel, 2015). These include oscillations in body temperature, metabolism, cardiac function, levels of certain hormone secretion, such as melatonin and cortisol and, importantly, the sleep-wake behaviour cycle (Dijk & Duffy, 1999; Deibel, 2015). The operation of the Circadian clock is one of two main interacting systems responsible for sleep regulation (Kondratova & Kondratov, 2012), the other one being the homeostatic-based sleep-drive system, which involves the build up of the 'sleep-pressure' hormone, adenosine, during wakefulness and its release during sleep (Walker, 2017). The division of the 24 hour day between periods of waking and sleep is thus determined by the homeostatic sleep drive process and its interaction with the Circadian clock's oscillating signal (Borbely, 1982). As described below, Circadian phases are different for larks and owls, and also change over the lifespan. Extreme dysregulation in Circadian rhythm is also an early stage marker for neurodegenerative diseases, including Alzheimer's dementia (Oosterman, 2009; Wulff, 2010; Naismith, 2011).

4.3.2. Circadian Rhythm is set by the Suprachiasmatic Nucleus (SCN)

In the mammalian brain, the suprachiasmatic nucleus (SCN), a pair of bilateral nuclei in the anterior hypothalamus, is the master Circadian rhythm pacemaker (Dijk & Duffy, 1999; Reppert & Weaver, 2002; Green, 2008; Deibel, 2015) and has major projections to the locus coeruleus, the noradrenergic brain nucleus regulating physiological arousal (Aston-Jones, 2001; Lee, 2018). Circadian rhythm is synchronised in the SCN primarily by external light-dark signals (Dijk & Duffy, 1999) arriving from the retina (Kondratova & Kondratov, 2012). Neurons in the SCN have a fixed daily oscillation of electrical activity which set the phases of biological processes and physiological outcomes, such as body temperature and metabolism (Kondratova & Kondratov, 2012; Kwapis, 2018). For example, the SCN drives the nocturnal onset of melatonin, the sleep-promoting hormone (Dijk & Duffy, 1999) and is thus responsible for regulating the time and consolidation of sleep (Dijk & Duffy, 1999). The Circadian system thus promotes arousal and alertness (Buysse, 2005).

4.3.3. Body Temperature is the Main Physiological Marker of Circadian Rhythm

Body temperature, one of several endogenous indicators of Circadian rhythmic physiological arousal (Hahn, 2012), is often taken to be the 'gold standard' physiological marker of Circadian

rhythm (Kelly, 1996). Normally, the acrophase (high point) in body temperature occurs mid-to-late afternoon (Walker, 2017) with the nadir occurring in the very early morning (between 4 and 6 am) (Kelly, 1996). There are differences in the timing of these physiological processes between larks and owls (broadly meaning persons who prefer morningness or eveningness, as further explained below); the onset and offset, as well as the acrophase, of melatonin secretion occurs approximately 3 hours earlier in larks than owls (Gibertini, 1999; Terman, 2001). Generally, larks show higher and earlier levels of cortisol, which has been suggested as a reason why larks 'feel better' about waking early than owls (Adan, 2012). Increased cortisol in the Circadian period has been associated with improved cognition and memory encoding (Whitehead, 2013; Yuen, 2011).

4.3.4. 'Clock gene' Variants have been associated with Circadian Differences

The human Circadian clock appears to be similar to that for other mammals at a genetic as well as behavioural level (King & Takahashi, 2000). Whilst in humans the precise mechanisms which underly associations between gene variations and different Circadian phenotypes remain unclear, some gene variations in different Circadian systems have been associated with individuals' Circadian differences (Adan, 2012). Over the last twenty years, in both animal and human studies, a collection of 'clock genes' has been identified in the SCN which exhibit patterns of oscillation in expression as well as modification of protein and secretion (King & Takahashi, 2000). These genes and their outputs are connected in what is described as a "transcriptional-translational feedback loop" (Shearman, 2000) which drives the repeating pattern of oscillations (Kondratova & Kondratov, 2012) and which, more generally, drives the biological processes underpinning the 24 hour Circadian period (Ko & Takahashi, 2006; Deibel, 2015; Kwapis, 2018). Clock gene expression is also altered by acute and chronic stress (Bolsius, 2021).

4.3.5. The Hippocampal Region is subject to Circadian Rhythm and Hippocampal Clock Genes may sub-serve Hippocampal-dependent Memory Processes

As well as the SCN, clock genes also oscillate in other regions of the brain, such as the hippocampus, and in other organs of the body (Deibel, 2015). The hippocampal region has a subordinate pattern of Circadian oscillation with more than ten per cent of genes and proteins fluctuating in line with Circadian rhythms (McCauley, 2020). The hippocampal formation is critical for learning and memory formation and these cognitive functions have been shown to be modulated by Circadian rhythms (Gerstner, 2009; Rawashdeh, 2018; Ruby, 2008; Shimizu,

2016; Smarr, 2014; Snider, 2016). The oscillation rates of clock genes in the hippocampus may affect different memory processes, such as acquisition, consolidation and recall, although research in this area is still at a comparatively early stage (Deibel, 2015).

Further to the main finding in Chapter 3 concerning long-term forgetting, it should be noted that clock genes also contribute to formation of long-term hippocampal-dependent memory (Bolsius, 2021). A recent study (Kwapis, 2018) has shown that the function of the clock gene PER1 in the hippocampus has an autonomous influence on long-term memory formation. The clock gene PER2 has also been shown to oscillate autonomously in the dentate gyrus hippocampal region (Deibel, 2015). Unusual associations have been found with polymorphisms in the PER3 gene (Jones, 2007), including one polymorphism ($PER3^{5/5}$) that is associated with increased time in bed on work-free days (Lazar, 2012), reinforcing the necessity of examining both weekday *and* weekend Circadian behaviours (which the present study does).

4.3.6. The Circadian Clock may provide a 'Time-stamp' for Episodic Memory

Long-term memory acquisition has been shown to be easier at certain times of day, i.e., there is a Circadian modulating effect on the formation of long-term memory (Kwapis, 2018). One theory for why Circadian rhythm plays such a role is that oscillation in the SCN and hippocampus may effectively 'time-stamp' memory encoding to a specific point in the Circadian phase (Deibel, 2015). This time-stamp may underpin hippocampal sequence replay and may play an important role in the consolidation of episodic memory (Diebel, 2015).

Animal studies have shown the link between Circadian rhythm and hippocampal-based memory function; older animals with disrupted Circadian rhythm performed worse in a hippocampal-based memory task than older animals with normal Circadian rhythms (Antoniadis, 2000). It has also been shown that reducing expression of PER1 in the dorsal hippocampus of younger mice impairs memory formation, but increasing expression of PER1 in older mice improves memory function (Kwapis, 2018). As these manipulations did not take place in the 'master clock' (the SCN), this supports the view that the role of the clock gene PER1 in the hippocampus functions independently of the SCN (Kwapis, 2018).

4.4. Owls and Larks

4.4.1. Persons with Owl tendencies tend to Outnumber Persons with Lark tendencies in the General Population by about 60/40

The terms ‘larks’ and ‘owls’ are colloquially used to describe individual preferences on the Morningness/Eveningness spectrum of Circadian activity and behaviour (Tankova, 1994). Chronotype has a genetic basis and there are three main types: morning types (or larks), evening types (or owls) and intermediate types who are not at one of the chronotype extremes (Lara, 2014; Walker, 2017). It has been estimated that approximately 40% of the population are larks and 30% are owls, with the remaining 30% somewhere in between, but with owl-like tendencies (Walker, 2017). Alternatively, it has been suggested (Adan, 2012) that only about 40% of the population may be at one of the behavioural extremes with clear owl or lark tendencies (compared with 70% in Walker, 2017), and the remainder are inconsistent. There are therefore different views on where to draw the line for chronotype extremes, reflecting the fact that these categories are not grounded in any precise or consistent methodology.

4.4.2. An Owl prefers later Eveningness and (consequently) later Morningness; A Lark prefers earlier Morningness and (consequently) earlier Eveningness

Categorisation of subjects as larks or owls should primarily be determined by chronotype which, being based on the mid-point of sleep on a work-free night takes account of behavioural preference at both ends of the day; i.e. ‘getting up’ time and ‘going to bed’ time (Roenneberg, 2007b; 2019). Assuming that owls and larks sleep for broadly the same duration as each other, owls preferring later Eveningness must inevitably also prefer later Morningness; larks preferring earlier Morningness must inevitably also prefer earlier Eveningness (Adan, 2012). In practice, categorisation has often been based on a single question (e.g. Piffer, 2014; see further below). Such a short-cut approach may give a broad indication of a subject’s preference, but may also miss some of the complexity in Circadian behaviour. It is the combination of Morningness and Eveningness which characterises behaviour at the Circadian extremes, but it is the inconsistency between Morningness and Eveningness behaviours, particularly between work days and work-free days, that make many subjects harder to categorise, e.g., subjects who stay up late and get up early during the week but who may change behaviour at weekends. A single, simple question such as ‘do you prefer evenings or mornings?’ may not therefore capture the complexities of intermediate classification.

In summary then, categorising a person as an 'owl' or 'lark' is not always straightforward, and this is why, as described above, in the general population there is a sizeable number of persons who are at neither extreme (depending on different views, between 30-60%). In the present study, as further described in Methods, actigraphy (with data collected for two full weeks including two weekends) has been used to calculate chronotype, and a basis for categorising subjects as owls or larks has been used which takes into account some of these complexities.

4.4.3. Chronotype (MSFsc) is Determined by the Mid-sleep point on Work-free days (MSF), sleep-corrected (sc) for Accumulated Loss of Sleep (Sleep Debt) on Work days

Calculation of a subject's chronotype is the mid-point of sleep on 'work-free' days (or MSF), adjusted for 'Sleep Debt' (Roenneberg, 2007b; 2019); this is often abbreviated to MSFsc (Roenneberg, 2019), 'sc' standing for 'sleep-corrected'. Sleep Debt is broadly the difference between the amount of sleep on work-free days and the average amount of sleep overall. The adjustment for Sleep Debt is made because, broadly, some part of sleep duration on work-free days may consist of catching up with sleep lost on working days (i.e., Sleep Debt adjusts the mid-point of sleep at the weekend for the catch-up element of additional sleep). Often chronotype (MSF_{sc}) is calculated by questionnaires such as the Morningness-Eveningness Questionnaire (Horne & Ostberg, 1976; Adan & Almirall, 1991) or the Munich Chronotype Questionnaire or MCTQ (Roenneberg, 2007b; Santisteban, 2018).

4.4.4. Lark Tendencies increase with Older Age, in line with Physiological Markers

Earlier research has shown that, from adolescence onwards, there is a trend towards more lark-like behaviour with older age (Kim, 2010; Merikanto, 2012; Monk & Kupfer, 2000; 2007; Paine, 2006; Man Park, 2002; Taillard, 2004; Tonetti, 2008; Fischer, 2017), sometimes referred to as a 'weakening' of the Circadian clock or 'Circadian phase advance' (Kondratova & Kondratov, 2012; Panagiotou, 2021). Accordingly, lark chronotypes tend to predominate in older populations, but not in younger or middle-aged populations (Deibel, 2015). As age increases, there is a shift to an earlier time for physiological and biological markers such as body temperature and release of melatonin and cortisol (Duffy, 1999; Dijk & Duffy, 1999). Older subjects have more difficulty maintaining sleep after the body temperature nadir (Duffy, 1999; Dijk & Duffy, 1999), so that the nadir in body temperature (c. 04:00 AM) moves closer to the waking time (Monk, 1991; Duffy, 1999; Dijk & Duffy, 1999). In older age, there is a fall in the peak amplitude of both body temperature and secretion of melatonin (Deibel, 2015). Maintaining strong melatonin secretion may be a biological indicator of successful ageing

(Adan, 2012) whereas a decrement has been associated with the onset of neurological pathologies (Magri, 2004; Wu & Swaab, 2005).

4.4.5. Lark Tendencies in Older Age are More Apparent in Earlier Morningness

Age-related changes in the propensity for sleep relate mainly to the morning (Dijk & Duffy, 1999). In an early study (Monk, 1991), it was found that a group of older subjects (M=83 years old) went to bed 17 minutes earlier than a younger group (M=25 years) but also got up 34 minutes earlier (the net effect in that study must, obviously, result in a 17 minutes shorter bed duration for older subjects—which is not consistent with the findings for self-reported bed duration in the present study; see Chapter 3). However, although the age-related Circadian changes drive a tendency to awaken earlier in older age, they are not accompanied by any shortening of the overall Circadian rhythm period (Dijk & Duffy, 1999; Czeisler, 1999). There is also no evidence of SCN neuronal decrease in older age (Madeira, 1995), although hormone secretion (melatonin) and gene expression in the SCN both decline with older age (Kondratova & Kondratov, 2012). Negative feelings about earlier waking times also decrease with older age (Dijk & Duffy, 1999).

4.4.6. External Factors such as Working Commitments may influence Circadian Behaviour

Socio-environmental factors may also act to modify behaviour, most obviously work patterns and retirement (Tankova, 1994). It is possible that underlying biological changes in the Circadian clock and lark-based socio-environmental pressures become mutually reinforcing over the lifespan, resulting in stronger lark tendencies in older age (Tankova, 1994; Walker, 2017). However, the studies that reported a clear Circadian phase advance at age 50 are now 25-30 years old (Ishihara, 1992; Tankova, 1994) and pre-dated much recent research into characteristics of Circadian behaviour, such as Sleep Debt and Social Jet Lag. Although the present study is only cross-sectional, results here suggest that there may be a substantially earlier behavioural shift towards more lark-like behaviour around age 35 (rather than 50), and which is attributable more to Morningness changes than Eveningness changes, consistent with the earlier findings (Monk, 1991).

4.4.7. The Synchrony Model proposes that Larks Perform Better in the Morning and Owls Perform Better towards the Evening (performance is synchronous with Circadian preference)

There are different theories for how Circadian behaviour might affect cognitive performance. The arousal model (Colquhoun, 1971) proposed that, because body temperature increases

during the day for both larks and owls, therefore both chronotypes should show higher arousal, and better cognitive performance, later in the day. In the synchrony theory, performance will broadly peak in line with an individual's Circadian preference and will be lower at other 'non-optimal' times of the day, so that time of day interacts with Circadian preference to determine performance level (May & Hasher, 1998; Goldstein, 2007; Hasher, 1999).

The synchrony theory thus assumes, broadly, that larks will test better in the morning and owls will test better in the afternoon (Taillard, 2021). However, the benefits of synchrony on cognitive performance may depend upon the type of cognitive or memory task (Folkard & Monk, 1981; Kelly, 1996). It has been suggested that the synchrony effect may be more apparent in more rigorous cognitive tasks where sustaining attention or exercising inhibition is required, such as, e.g., the Stoop interference task (Taillard, 2021). A related question is whether *non-synchrony* is equally disadvantageous to owls and larks. Some recent evidence suggests that larks may perform better than owls at non-synchronous times (Nowack & Van Der Meer, 2018) although a possible explanation given for this (namely that owls accrue higher Social Jet Lag) is not supported by the results in the present study.

4.5. Effects of Chronotype

4.5.1. Previous Findings that Owls have Cognitive Advantages may reflect Population Samples with Larger numbers of Younger, More Highly-educated Subjects

Many studies have examined whether one chronotype has innately higher levels of cognition and/or intelligence, somewhat regardless of synchrony theory (e.g. Roberts & Kyllonen, 1999; Kanazawa & Perina, 2009; Piffer, 2014). For example, the view that persons with owl-like chronotypes are more likely to have higher intelligence was suggested in a case where young (M=20 yrs) US air force recruits were tested (Roberts & Kyllonen, 1999). Unlike earlier samples (often university students showing a strong tendency to owl-like behaviour) these air-force recruits, uncharacteristically for younger people, were high in lark-like behaviour, but those who were more owl-like still performed better. The authors noted that their findings were consistent with findings elsewhere that students (high in Eveningness) are more likely to be highly educated and older persons (higher in Morningness) are more likely to have lower cognitive performance, although it is not clear how either finding adds much support to the argument that owls have higher innate cognitive ability. Older persons may have once been highly educated students, and younger persons will certainly grow older.

4.5.2. Circadian Preference may interact with Time of Day of Testing for More Cognitively-demanding Tasks

Variation in cognitive performance attributed to Circadian type has also been shown to be dependent upon both the nature of the task and the cognitive strategy used to undertake the task (Monk & Leng, 1986; Kelly, 1996). Cognitive tasks requiring higher levels of cognitive resource over an extended period may be affected to a greater extent by Circadian rhythm and time of performance than more straightforward cognitive tasks (Monk & Leng, 1986). In one study, (Schmidt, 2012), higher performance in the evening on the Stroop test (a test requiring sustained attention) was positively associated with higher brain activity in owls (compared to larks) in the locus coeruleus and anterior hypothalamic regions. Larks are less able to recruit these brain regions to complete certain complex cognitive tasks as the day progresses, it has been suggested, because they have a decreasing hypothalamic 'waking' signal later in the day, and may be less able to resist the homeostatic-drive for sleep (Schmidt, 2012).

Performance of complex tasks at times that are *not synchronous* with Circadian rhythm may be associated with reduced vigilance and impaired executive and inhibitory control (Lara, 2014). Vigilance decreases over the period of any given task, possibly due to a reduction in arousal or available cognitive resources (Lara, 2014). However, there are counter-balancing factors to Circadian rhythm, such as practice, training and motivation (Kelly, 1996). Also, when undertaking testing in free-living conditions, the contribution of Circadian rhythm may be affected by uncontrolled factors such as use of stimulants (e.g. caffeine), or food and nutrient intake, e.t.c. (Lara, 2014). Accordingly, isolating any contribution to performance made by Circadian rhythm preference and time of day of testing (Kelly, 1996) is complex. Performance in any particular cognitive test at any particular point in the day is likely to depend upon a wide range of different factors, including Circadian predisposition and synchrony effects, other forms of arousal (e.g. stimulants), vigilance, motivation, practice, training, task complexity and changing strategy (over the course of the day) for task performance. The present study was not set up with the necessary controls to allow for detailed consideration of any synchrony effects on memory domain performance.

4.5.3. Owls may have Higher Extraversion than Larks, and this may represent Greater Sociability

Studies have shown that Circadian rhythm is also involved in regulating mood (McClung, 2007). Owls tend to have higher extraversion (Tankova, 1994) whereas larks are more introverted and conscientious (Langford and Glendon, 2002). Although the results from some

studies are equivocal (e.g. Mecacci & Roccchetti, 1998) no studies have shown that owls are *less* extraverted than larks (Adan, 2012). More detailed analysis has identified that it is the 'sociability' component of extraversion that is more closely associated with owl-type behaviour, rather than 'impulsivity' (Larsen, 1985). Larks have also been shown to have better self-control and higher propensity towards delayed gratification (Nowack & Van Der Meer, 2018).

4.6. Modern World Effects on Sleep and Circadian Behaviour: Social Jet Lag and Sleep Debt

4.6.1. Sleep Debt and Social Jet Lag are Modern World Effects on Circadian and Sleep Behaviours

Two 'modern world effects' on sleep and Circadian behaviours are Sleep Debt and Social Jet Lag. Whereas Social Jet Lag may be an indicator of Circadian behaviour misalignment, Sleep Debt primarily indicates a behavioural discrepancy or mismatch between 'sleep need' and 'sleep achieved' (i.e., to some extent, a measure of working day sleep deprivation). Even if these phenomena may have existed for some time, it is only comparatively recently that they have begun to be considered more extensively in sleep studies (see, e.g. Roenneberg, 2019; Fox, 2018; Taillard, 2021; Nowack & Van Der Meer, 2018).

4.6.2. Social Jet Lag is the Difference between Mid-sleep times on Work days (MSW) and Work-free days (MSF)

Social Jet Lag measures the difference in the mid-sleep times between work-free days (or MSF) and working days (or MSW) (Wittmann, 2006; Roenneberg, 2007b); very broadly then, it is a measure of how far the demands of a subject's working (or school) week knocks them out of their normal Circadian rhythm, which is set by the sun and the presence of daylight (Roenneberg, 2007a). The best example of Social Jet Lag is the twice-yearly clock change and the advance of clock time by one hour in the spring, meaning that a person whose 'getting up' time advances to 6:30 am after the spring change will have an unaltered body clock time of getting up that is (still) 5:30 am. Unsurprisingly, the switch to daylight saving time has been associated with a number of physical and psychological health disorders (Manfredini, 2018; Zhang, 2020) including, in particular, for AD patients (Todd, 2020). However, some level of Social Jet Lag may be self-inflicted and this is particularly the case in younger persons whose social behaviour at the weekend may drive later 'going to bed' and 'getting up' times.

It has been estimated that 44% of the population incur at least an hour of Social Jet Lag and 15% incur two or more hours (Roenneberg, 2019); although the findings in the present study

are much lower than this (see further below). Social Jet Lag is often calculated using the MCTQ questionnaire about sleep behaviour but "can also be assessed with actigraphy data"; Roenneberg 2019 at page 13. That is the method used here. Actigraphy offers the advantage of objective data based on what subjects actually do on workdays and work-free days, rather than on what they say they do (Wong, 2015; Santisteban, 2018). Some researchers have suggested that the calculation of Social Jet Lag should be adjusted for Sleep Debt (Jankowski, 2017), although as explained below, that has not been done here in order mainly to keep the measures separate and distinct.

4.6.3. Some Research suggests that Social Jet Lag may Explain some Instances of Cognitive Under-performance and May Affect Mood

Social Jet Lag has been used to explain differences in cognitive performance by different chronotypes. For example, in a recent study (Nowack & Van Der Meer, 2018), where no calculation of Social Jet Lag was actually reported, it was suggested as the possible reason why larks showed better performance than owls in a task carried out at sub-optimal (or non-synchronous) performance times. The suggestion was that higher Social Jet Lag is exclusively associated with a later owl-like chronotype which depletes owls' cognitive resources. The present study shows that this may be a misconception.

Social Jet Lag has been shown to have adverse effects on metabolism and mood, including depressive disorders (Levandovski, 2011; Roenneberg, 2012; Wittmann, 2006). Higher Social Jet Lag has also been shown to be associated with higher impulsivity and attention deficit disorder in adults (McGowan, 2016) and in a recent study (McGowan, 2020), it has been shown that the association with impulsivity may influence performance on attention and inhibition-based tasks (such as the Stroop test); the same study showed that chronotype did not affect attention and inhibition.

4.6.4. Sleep Debt is the Shortfall between Sleep Needed and Sleep Actually Obtained

Sleep Debt is broadly the difference between sleep acquired and sleep required (Kitamura, 2016). Sleep required is taken to be the average amount of sleep a person will have if there are no constraints on their sleep duration (i.e., the amount of sleep normally taken on a 'work-free' night). Sleep acquired is the average amount of nightly sleep a person manages to obtain overall (i.e., across the whole week). Sleep Debt therefore is a measure of sleep deprivation across the week (sleep amount), whereas Social Jet Lag is a measure of disruption or inconsistency in *timing* of sleep across the week.

In a recent study (Fox, 2018), Sleep Debt was calculated in a large sample (N=8,752) by deducting self-reported achieved sleep from self-reported required sleep. The authors reported a novel finding that Sleep Debt decreased with older age (replicated here), and they concluded from this that older adults might sleep less but may also require less sleep to feel rested. Such a conclusion, if correct, would appear to have important implications for arousal and cognitive performance, as well as matters such as sleep memory consolidation discussed in Chapter 3. Sleep Debt is however arguably a measure of consistency in sleep duration across the whole week, and as such may not provide any indication of whether older persons *need* less sleep than younger persons, i.e., their nightly sleep duration may just be more consistent across the whole week than for younger persons. The results in the present study tend to confirm this different view.

4.7. Measurement and Methodological Issues in Examining Circadian Behaviour

4.7.1. Questionnaires have been Predominantly Used to measure Circadian Behaviour in Earlier Research

In Circadian behavioural studies, questionnaires have been predominantly used to make chronotype assessments but three issues commonly arise. First, self-report questionnaires are often abbreviated to a few questions (Adan, 2012; Saksvik, 2011). Both chronotype (Kanazawa & Perina, 2009) and Sleep Debt (Fox, 2018) have been reduced to two questions. When 201 college students were asked a single question "Are you a night owl or an early morning person?" (Piffer, 2014), 170 (85%) chose one of the categories and only 15% were 'don't know' (as described above, estimates are that between 30-60% of people are intermediate). However, it has also been reported as "remarkable" that chronotype results from a single question may be as effective as a 19-item questionnaire (Roenneberg, 2007 at page 435). In the present study, a system has been used to categorise subjects as owls or larks, including subjects of intermediate status, based on objective actigraphy data. Although this is different from other methodologies, it is suggested as a more robust approach than basing chronotype analysis on one or two questions.

Second, while questionnaires may lend themselves easily to large scale studies, some measures can be difficult to self-report accurately. For example, subjects might be able to record their bedtimes with reasonable accuracy but estimating sleep duration and therefore the mid-point of sleep, is more challenging and, perhaps, better suited to objective actigraphy recording (Di Milia, 2008; Di Milia & Muller, 2012). Social Jet Lag, for example, should be calculated by

reference to the mid-point of sleep, rather than the mid-point of time in bed (Roenneberg, 2019), although in practice, there may be very little difference between the two.

Third, many self-report studies tend to involve wholly student populations who, on the whole, may over-represent later chronotypes, as well as having higher levels of education and cognition. It has been suggested (Tankova, 1994) that those studies which did not find an association between older age and lark-type behaviour were either because only students were tested or the age-range in the sample was too narrow. Student populations are generally not required to follow strict lark-type behaviour (no study appears to have yet examined the relationship between Social Jet Lag and attendance levels at morning versus afternoon classes). On the other hand, with increasing age, societal work pressures may force the adoption of lark-type behaviour (Walker, 2017). Early morning starts may in turn require earlier bedtimes to avoid excessive sleep deprivation and these lark-type behaviours may become entrenched habits that are not easily abandoned in the relative work freedoms of older age. As seen with younger persons who were not students (Roberts & Kyllonen, 1999), owl-type behaviour may just be an aberrant indulgence of student life that is not representative of Circadian phase trends in the wider population.

4.7.2. Hypotheses: Questions Addressed

Based on the above, the following hypotheses will be addressed in Results.

- It is expected that older age will be associated with earlier chronotype.
- It is expected that age groups aged 50 and above may show markedly different Circadian behaviours from younger age groups, consistent with Circadian changes at age 50.
- It is expected that older subjects will have lower Social Jet Lag and lower Sleep Debt than younger subjects. It is also expected that later chronotype will be associated with greater Social Jet Lag and that owls may have greater Social Jet Lag than larks. Older subjects with lower Sleep Debt should have lower device-recorded sleep duration than younger subjects, if they simply ‘need less sleep’.
- It is not expected that there would be any marked difference in memory domain performance between owls and larks (i.e. no inherent advantage in cognitive performance by reason of Circadian preference alone).

- As both Social Jet Lag and Sleep Debt are effectively measures of Circadian dysregulation, it is possible that they may be characteristic of 'poorer' sleep and, as such, may have a bearing on sleep benefits to memory consolidation and, consequentially, performance in VEM Long Term Forgetting
- Although the present study has not been designed to measure time-of-day effects on testing, it is possible that more cognitively demanding tests may reveal differential time-of-day performance that is dependent on Circadian preference.
- In line with findings elsewhere, it is expected that Owls may have higher Social Connectedness and/or higher sociability than larks.

Finally, in view of the unfamiliarity of some of the terms and acronyms commonly used in the literature on Circadian measures, a short key is provided below and will be repeated at the end of both the Methods and Results sections.

MSF: the average mid-sleep time on a work-free day (night)—taken to be Friday and Saturday nights in the present study, except (e.g.) where Sunday night is followed by a Bank Holiday when Sunday is also included

MSW: the average mid-sleep time on a work day (night)—taken as Sunday to Thursday night inclusive in this study, except (e.g.) where Sunday night is followed by a Bank Holiday when Sunday is not included

Chronotype (MSFsc): MSF (as defined above) but 'sleep corrected' (SC), meaning that Sleep Debt (normally accrued during the working week) is deducted to provide a corrected and preferred MSF

Assumed Sleep Duration (ASD): the total duration between the first and last device recorded minutes of sleep, i.e., disregarding any period of awakening during the night. ASD is used to determine the mid-sleep times for both MSF and MSW

Sleep Debt: the average difference in minutes between 'sleep acquired' and 'sleep required' (taken in this study to be the difference between average ASD on Work-free nights less average ASD overall calculated in minutes)

Social Jet Lag: The average difference in minutes between MSF and MSW

Owl: A subject with a preference for Eveningness, demonstrated in the present study by a consistent preference for both later 'going to bed' and 'getting up' times across work and work-free days

Lark: Subject with a preference for Morningness, demonstrated in the present study by a consistent preference for both earlier 'getting up' and 'going to bed' times across work and work-free days

Circadian preference: meaning, in the present study, the preferred bed-time behaviour of a subject based on their categorisation as an owl or a lark

4.8. METHODS

4.8.1. Calculation of Chronotype, Sleep Debt and Social Jet Lag

ASD was used to determine 'sleep commencement' and 'sleep end' times and, from this, to calculate the 'mid-point of sleep' for each of the measurement days over a subject's two week period of assessment. ASD is the total amount of time in minutes from the first to the last minute of actigraphy-recorded sleep. ASD may therefore include some periods of waking up from sleep and represents the maximum assumed nightly period of sleep. Averages for the mid-point of sleep on 'work' days (MSW) have usually been taken as the averages for ten 'weekdays' and averages for the mid-point of sleep on 'work-free' days (MSF) have usually been taken as the averages for 4-6 days of weekend days, with upper-end variation depending on whether the devices were also worn on Bank Holidays (which have also been treated as work-free days). The terms 'weekday' and 'weekend' are used interchangeably with the terms 'working day' and 'work-free day' respectively, including in Tables and Figures. No subject wore the device (or wanted to wear the device) while on extended holiday.

A clock-time for Eveningness has been converted into a score where 0=9:00 PM, 60=10 PM and continuing throughout the night so that 420=4:00 AM and 480=5:00 AM. Average scores have been calculated for sleep onset times and offset times (as recorded by the devices) for work-days and work-free days. These scores have been used to calculate average mid-sleep scores (translated back into clock times) for both work-days (MSW) and work-free days (MSF). A worked example is shown in Supplementary Tables 4.1 and 4.2.

Sleep Debt is the average period in minutes by which ASD on work-free days exceeds weekly average ASD (see, e.g. Fox, 2018). Sleep Debt has been subtracted from MSF to calculate chronotype or MSFsc (Roenneberg, 2007b; 2019) and a worked example is shown in Supplementary Table 4.1. In the present study, all Sleep Debt differences have been taken into account in calculating MSFsc, including differences for subjects with lower ASD on work-free days. Social Jet Lag has been calculated in minutes as average MSF less average MSW (Roenneberg, 2019). An example of a calculation of Social Jet Lag is also shown in Supplementary Table 4.1.

4.8.2. Circadian Categorisation

The sleep onset and sleep offset times shown in Supplementary Table 4.1 will not exactly match 'going to bed' or 'getting up' times (which will normally be earlier and later clock times respectively than those for sleep onset and sleep offset). 'Going to bed' and 'getting up' times have been separately converted into scores (using the system shown in Supplementary Table 4.2) to calculate average Eveningness and Morningness for work days and work-free days. Each subject has an average Morningness score for work days, work-free days and overall (i.e., for work days and work-free days combined), and similarly also has an average Eveningness score for weekdays, weekends and overall. The purpose of this system was to use *combined* Eveningness and Morningness behaviour as the basis for owl/lark distinction, as calculated by objectively-recorded actigraphy data, rather than to rely upon (e.g.) self-report of a Morningness or Eveningness preference. This methodology is also different from calculation of chronotype based on work-free behaviour (often used to determine owl or lark status) because *both* work day and work-free day behaviour is taken into account in categorising subjects as either owls or larks. The rationale for this bespoke methodology is that 64% of the sample population are older subjects who have more freedom to plan their bed behaviours (as is borne out in the results; see below). For consistency, younger subjects have been treated in the same way. In addition, many of the younger subjects in this study are professionals; modern working practices arguably allow more freedom for these subjects to plan their own working hours which, to some extent, may then reflect their Circadian behavioural preferences. It is accepted that this bespoke methodology is a different approach and may produce a different categorisation of subjects as owls or larks than may be obtained by using different methodologies applied in other studies.

A 'consistent' lark would both go to bed early and get up early, and a 'consistent' owl would both go to bed late and get up late. However, behaviour may not always be consistent and an advantage of the combined scoring system used in the present study (for both Eveningness and Morningness) is to provide for objective categorisation of subjects who may not be at one of the extremes, but who may show inconsistent behaviour, such as (say) late Eveningness and early Morningness. For the purposes of identifying a preference for Eveningness, it has been assumed that a subject would have an average 'going to bed' time of 23:30 PM or later (and therefore a score of 150 or higher). For the purposes of identifying a preference for Morningness, it has been assumed that a subject would have an average 'getting up' time of 06:30 AM or earlier (and therefore a score of 210 or below).

Binary categorisation in this study as an owl or lark is based on a *combinatorial* calculation which depends on the overall combined score (allocated to clock times) for *both* 'going to bed' (Eveningness) and 'getting up' (Morningness) times on *both* work-free days and work days across the two week measurement period. A consistent owl is a subject who, on average, combines going to bed after 11:30 PM with getting up after 6:30 AM (a clear preference for Eveningness) and scoring >360. A consistent lark is a subject who, on average, combines getting up before 6:30 AM with going to bed before 11:30 PM (a clear preference for Morningness) and scoring <360. As scores fall below 360, the more extreme is lark-type behaviour, and similarly, as scores rise above 360, they indicate more extreme owl-type behaviour. This combined score provides for flexibility in the assessment. For example, a subject will be assumed to have (very marginal) owl tendencies overall if she goes to bed at 23:29 PM (score 149, one minute before the Eveningness cut-off) but gets up at 06:32 AM (score 212, two minutes after the Morningness cut-off), total score=361. Supplementary Tables 4.3A to 4.3C show example calculations for four separate subjects; two of the subjects are consistent and two of the subjects are inconsistent in their bed behaviour patterns.

Combined scores of all subjects have an average of M=385 (i.e. showing a slight owl-tendency among all subjects, taken as a whole). As might be expected, a higher combined score (stronger owl tendency) is very strongly correlated with a later chronotype; Pearson's r=.771, $p<0.0001$. This strong association arises despite the fact that, broadly, chronotype is based on Circadian behavioural data for work-free days only (sleep-corrected MSF), whereas owl/lark categorisation here is based on data for the entire week. This strong correlation suggests that using chronotype to categorise subjects might not produce any material difference in the categorisation of owls and larks in the present study.

MSF: the average mid-sleep time on a work-free day (night)—taken to be Friday and Saturday nights in the present study, except (e.g.) where Sunday night is followed by a Bank Holiday when Sunday is also included

MSW: the average mid-sleep time on a work day (night)—taken as Sunday to Thursday night inclusive in this study, except (e.g.) where Sunday night is followed by a Bank Holiday when Sunday is not included

Chronotype (MSFsc): MSF (as defined above) but 'sleep corrected' (SC), meaning that Sleep Debt (normally accrued during the working week) is deducted to provide a corrected and preferred MSF

Assumed Sleep Duration (ASD): the total duration between the first and last device recorded minutes of sleep, i.e., disregarding any period of awakening during the night. ASD is used to determine the mid-sleep times for both MSF and MSW

Sleep Debt: the average difference in minutes between 'sleep acquired' and 'sleep required' (taken in this study to be the difference between average ASD on Work-free nights less average ASD overall calculated in minutes)

Social Jet Lag: The average difference in minutes between MSF and MSW

Owl: A subject with a preference for Eveningness, demonstrated in the present study by a consistent preference for both later 'going to bed' and 'getting up' times across work and work-free days

Lark: Subject with a preference for Morningness, demonstrated in the present study by a consistent preference for both earlier 'getting up' and 'going to bed' times across work and work-free days

Circadian preference: meaning, in the present study, the preferred bed-time behaviour of a subject based

4.9. RESULTS

4.9.1. Replicated Finding: Approximately 61% of Subjects have Owl tendencies and 39% have Lark tendencies, but there is no difference in age between them

In the present study, consistent owls account for 31.7% of the sample population, and 13.1% are consistent larks; i.e. 44.8% exhibit consistent lark or owl behaviour overall. When a binary distribution is applied (i.e., when inconsistent subjects are categorised as owls or larks based on their behavioural tendencies), owls account for 61.4% (N=89) and larks account for 38.6% (N=56). This is reasonably consistent with the overall 60/40 division in the general population, suggested elsewhere (Walker, 2017).

If the two main age groups are examined separately, the proportions are slightly different from 60/40. In the younger group (N=52), 52% are owls and 48% are larks. In the older group (N=93), 67% are owls and 33% are larks. There are more larks than might be expected in the younger group and, conversely, more owls than might be expected in the older group. These differences may reflect different work and social commitments in the two groups (i.e., a predominantly non-student, working younger group aged below 50 and a socially active older group aged over 50 with fewer full-time work commitments) and the fact that work day behaviour has been taken into account in making the categorisation.

In the whole sample (N=145), as seen in Table 4.1, owls (M=56.4 years) are not younger or older than larks (M=53.4 years); t_{143}=1.012, p=.31. However, when the two age groups are analysed separately, in the younger group, owls (M=32.5 years) are younger than larks (M=39.9 years); t_{50}=-3.229, p=.002, Cohen's d=0.91. In the older group however, there is no difference in age between owls (M=66.8 years) and larks (64.4 years); t_{91}=1.159, p=.25.

Table 4.1: Sleep and Circadian Measures by Age Group, Owl/Lark status and PSQ categorisation as a Good or Poor Sleeper

	All	Younger	Older	Difference Younger/Older	Owl	Lark	Difference Owl/Lark	Good Sleepers	Poor Sleepers	Difference Good/Poor Sleepers
Age	55.26 (17.14)	36.06 (8.94)	66 (9.51)	t_{143}=-18.575 p<.0001	56.4 (18.3)	53.4 (15.1)	t_{143}=1.012 p=.31	52.91 (16.74)	59.03 (17.07)	t138=-2.127 p=.035
PSQI Score	5.53 (2.83)	5.37 (2.51)	5.62 (3)	t_{138}=-.493 p=.62	5.53 (2.71)	5.52 (3.04)	t_{138}=.033 p=.97	3.56 (1.23)	8.08 (2.21)	$t_{88.176}$=-14.381 p<.0001
Sleep Diary Sleep Quality Assessment	3.48 (.56)	3.35 (.54)	3.53 (.57)	t_{105}=-1.469 p=.15	3.46 (.58)	3.51 (.54)	t_{105}=-.399 p=.69	3.67 (.51)	3.25 (.52)	t_{103}=4.216 p=.0001
Mid-point of Sleep Workday (MSW)	03:09 AM	03:00 AM	03:14 AM	t_{143}=-1.958 p=.052	03:33 AM	02:31 AM	t_{143}=11.473 p<.0001	03:08 AM	03:11 AM	t_{138}=-.319 p=.75
Mid-point of Sleep Free day (MSF)	03:41 AM	03:58 AM	03:32 AM	$t_{80.508}$=2.557 p=.012	04:08 AM	02:58 AM	$t_{140.5}$=10.180 p<.0001	03:40 AM	03:40 AM	t_{138}=.034 p=.97
Chronotype (MSF_{sc})	03:24 AM	03:30 AM	03:21 AM	t_{143}=.820 p=.41	03:53 AM	02:38 AM	t_{143}=8.263 p<.0001	03:19 AM	03:27 AM	t_{138}=-.660 p=.51
Sleep Debt (mins)	17 (34)	29 (32)	11 (34)	t_{143}=3.091 p=.002	15 (32)	20 (38)	t_{143}=-.857 p=.39	21 (39)	13 (28)	$t_{137.078}$=1.338 p=.18
Social Jet Lag (mins)	32 (40)	59 (41)	17 (30)	t_{143}=6.966 p<.0001	35 (44)	27 (30)	$t_{141.196}$=1.372 p=.17	32 (38)	29 (38)	t_{138}=.428 p=.67

Table 4.1 shows differences between younger and older age groups, owls and larks and good and poor sleepers under the PSQ categorisation on various sleep and Circadian measures. Orange shading highlights significant differences. The pattern that emerges is for differences in the age groups in MSF, Sleep Debt and Social Jet Lag. By contrast, owls and larks differ (not unexpectedly) in Circadian measures of MSW, MSF and chronotype but *not* in Sleep Debt or Social Jet Lag; see text for further detail. Good and poor sleepers, as categorised by the PSQ, only differ in age and on measures of sleep quality (whether assessed by the PSQ or sleep diaries) and are not different from each other on any of the principal Circadian measures, including notably, Sleep Debt and Social Jet Lag.

4.9.2. There are No Differences in Chronotype between Younger and Older Subjects

There is no difference in chronotype between older persons (03:21 AM) and younger persons (03:30 AM); t_{143}=.820, p=.41; see Figure 4.1. Males are no different from females in chronotype (t_{143}=.524, p=.6) and there is no difference in chronotype between those with a PSQ classification of 'good' as opposed to 'poor' sleeper (t_{138}=-.660, p=.51).

In the present study, there is only very marginal evidence that later chronotype is associated with younger age (Pearson's r=-.159, p=.056; Spearman's r_s=-.081, p=.33); see Figure 4.1. Distribution of chronotype is not normal and is concentrated in the 2:00 AM to 3:30 AM timescale. In the younger group, older age is strongly associated with an earlier chronotype (Pearson's r=-.447, p=.001; Spearman's r_s=-.408, p=.003), whereas in the older group, there is no association between older age and earlier chronotype (Pearson's r=-.035, p=.74; Spearman's r_s=-.017, p=.87). Broadly, chronotype appears to advance towards Morningness with increasing age in the younger group, but appears to be relatively stable after age 50. This seems to be in line with the findings elsewhere (Tankova, 1994) that age 50 is a cut-off point in Circadian behavioural change (but see further below).

Figure 4.1: Chronotype or Mid-Sleep on Work-Free Days, Sleep Corrected (MSFsc) Analysed by Age and in Age Groups

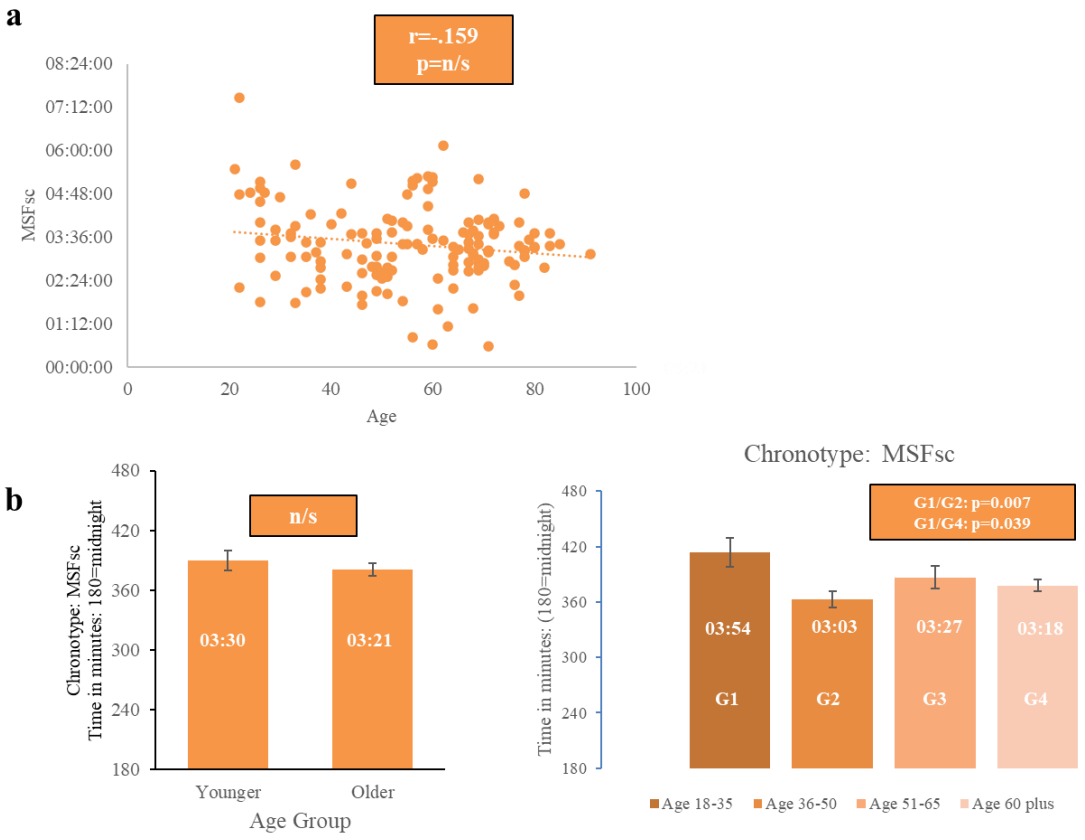


Figure 4.1. KEY to b and c: 0=9PM, 180=Midnight, 360=3AM. See Supplementary Table 4.2 for full details of the Circadian Scoring System. Chronotype (MSFsc) is not associated with age: **a**. There is only a marginal association between younger age and later chronotype; Pearson's r=-.159, p=.056. Chronotype is calculated as the mid-point of sleep on work-free nights (MSF) adjusted for sleep debt or 'sleep corrected' (sc), (MSFsc). As can be seen from the x axis, the majority of subjects have MSFsc falling between approximately 02:30 a.m. and 04:00 a.m. Assuming an average 7 hours of sleep duration, this would mean most subjects go to bed between 11:00 p.m. and 12:30 a.m. and get up between 6:00 a.m. and 7:30 a.m. **b**. There is no significant difference between younger and older subjects in chronotype. Younger subjects have MSFsc of 03:30 a.m. and older subjects have MSFsc of 03:21 a.m. **c**. The 18-35 age group (Group 1) has a later chronotype than both the 36-50 age group (Group 2) ($t_{39.854}$=2.824, p=.007) and the 66 plus age group (Group 4) ($t_{33.065}$=2.148, p=.039). There are no differences between other age groups and specifically, there are no differences between the 36-50 and the 51-65 age groups (Groups 2 and 3); i.e. between the two age groups spanning age 50. This suggests that age 50 may not be a critical tipping point for a change in chronotype (see, e.g., Tankova, 1994). Error bars show +/- one s.e.m.

*4.9.3. **New finding:** A Tendency towards More Lark-like Behaviour May Arise around age 35+*

In order to examine more closely the development of chronotype preferences, subjects were also divided into four age groups; see Figure 4.1c. The four age groups are 18-35 (Group 1),

36-50 (Group 2), 51-65 (Group 3) and 66 plus (Group 4). There is a moderate difference in chronotype between the youngest and oldest groups ($t_{33.065}$=2.148, p=.039, Cohen's d=0.75), with Group 4 (M=73.2 years) having earlier chronotypes than Group 1 (M=28.3 years).

However, statistically, the most significant difference is between Group 1 (aged 18-35) and the next youngest group, Group 2 (aged 36-50, M=44.2 years); ($t_{39.854}$=2.824, p=.007, Cohen's d=0.89). There are no differences in chronotype between the other groups. The behaviour change in Group 2 appears to suggest that the development of a lark-like behavioural chronotype may begin *substantially earlier* than age 50, and possibly from about age 35 onwards.

Older age is correlated with earlier MSF (Pearson's r=-.333, p<.0001; Spearman's r_s=-.240, p=.004) (see Figure 4.2) and this is also reflected in differences between the two main age groups in MSF (younger, N=52 and older, N=93; $t_{80.508}$=2.557, p=.01, Cohen's d=0.57). This contrasts with the position for MSW, where there is no association between earlier MSW and older age (Pearson's r=.082, p=.33), and no difference in MSW between the younger and older age groups. Within more detailed age-groups, MSF is different between Group 1 (18-35 years, M=04:22 AM) and Group 2 (36-50 years, M=03:32 AM); $t_{40.352}$=2.884, p=.006, Cohen's d=0.91 and represents a very large shift by Group 2 to an earlier MSF by approximately 50 minutes. However, there is no difference in MSF between Group 2 and Group 3 (51-65 years, M=03:41 AM; t_{66}=-.694, p=.49) or between Group 3 and Group 4 (66 plus years, 03:25 AM; $t_{65.190}$=1.484, p=.143).

4.9.4. Expected Finding: Younger Subjects have Later Getting up times (later Morningness) than Older Subjects, but only on Work-free days (i.e. at weekends)

There is no difference in overall Eveningness or Morningness in the two main age groups (Figure 4.2). Figure 4.3 breaks this down into comparisons for Eveningness and Morningness on work-days and work-free days. When analysed separately, the only difference between these two age groups is for Morningness on work-free days (i.e., at weekends) where the younger group gets up on average 42 minutes later than the older group; $t_{73.012}$=3.714, p=.0004, Cohen's d=0.87.

Figure 4.2: Younger Age is associated with later Mid-Sleep on Work-Free Days (MSF) but not with later Mid-Sleep on Work Days (MSW); Younger and Older Subjects do not differ overall in Eveningness or Morningness

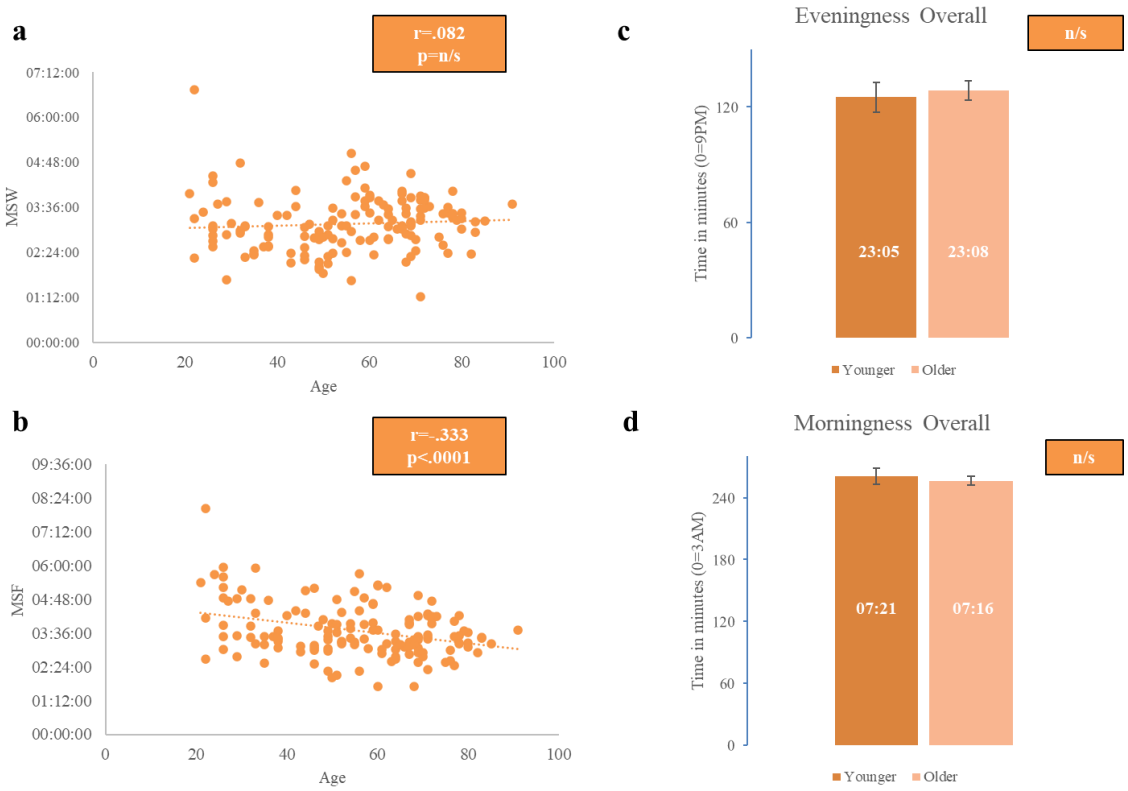


Figure 4.2: KEY to c and d: in c, 0=9PM and 120= 11PM; in d, 0=3AM and 240=7AM. Younger and older groups differ significantly on mid-sleep points on free days/nights (MSF) but not on work days/nights (MSW). **a**. On work days, there is no association between age and MSW (Pearson's r=.082, p=.33). The mid-sleep point on work nights clusters, for most subjects, between 02:30 a.m. and 04:00 a.m. **b**. On work-free nights, there is a significant association between younger age and later MSF (Pearson's r=-.333, p<.0001). The mid-sleep point on work-free nights is more attenuated than MSW although much later MSF becomes increasingly rare with older age. **c** and **d**: Younger and older subjects do not differ in overall Eveningness or Morningness (i.e. including both work days and work-free days). Error bars show +/- one s.e.m.

Figure 4.3: Eveningness and Morningness Compared for Work Days and Work-free Days in the Younger and Older Age Groups

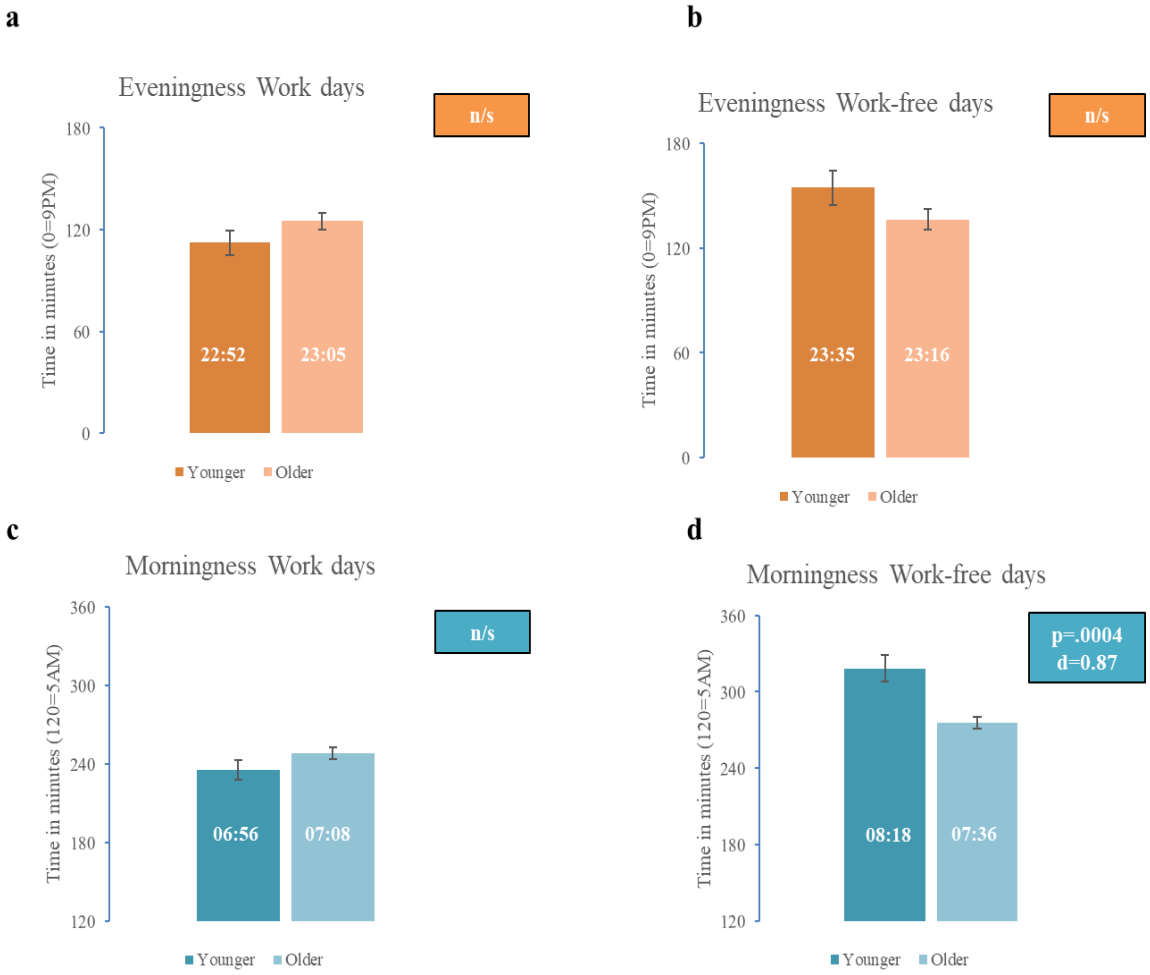


Figure 4.3:**KEY to a and b:** 0=9PM and 180=Midnight. **KEY to c and d:** 120=5AM, 240=7AM and 360=9AM. Comparing Eveningness and Morningness on both Work Days and on Work-free Days between the Younger and Older Age Groups. The younger and older age groups do not differ in (**a**) Eveningness on Work Days (13 mins difference, p=.14) (**b**) Eveningness on Work-free Days ((19 mins difference, p=.12) or (**c**) Morningness on Work Days (12 mins difference, p=.14). The only significant difference between the two age groups is for morningness at weekends (**d**) where the younger group get up later than the older group ($t_{73.012}$=3.714, p=.0004, Cohen's d=0.87). See text for further detail. Error bars show +/- one s.e.m.

*4.9.5. **New Finding:** Examining Detailed Age Groups reveals a Nuanced Development of Eveningness and Morningness Behaviour*

Examining overall (i.e. work and work-free day combined) Eveningness and Morningness behaviour in the four detailed age groups reveals a more nuanced picture of developing behaviour than that provided in Figure 4.2 (where there were no differences between the main older and younger groups); see Figure 4.4.

Figure 4.4: Detailed Breakdown of Overall Eveningness and Morningness by Four Age Groups

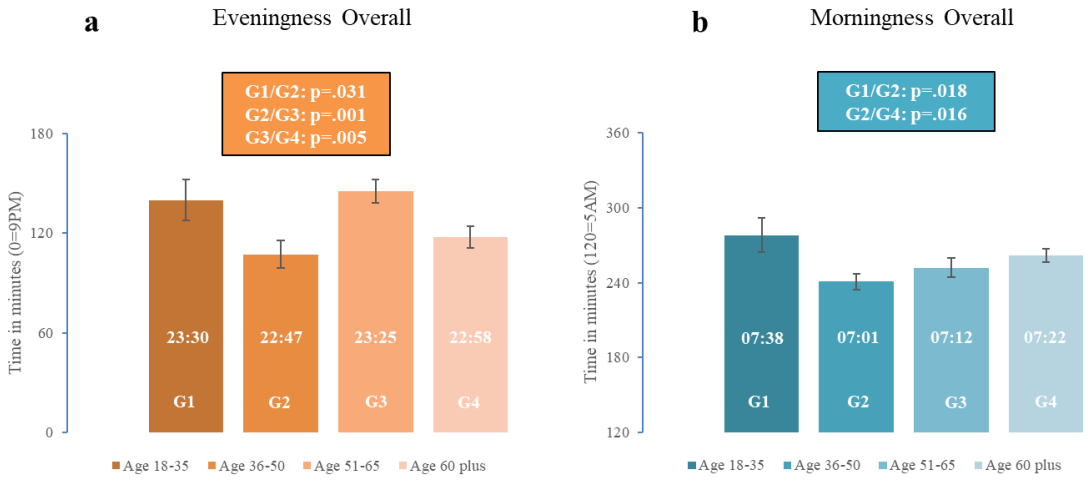


Figure 4.4: Detailed Breakdown of Overall Eveningness and Morningness by Four Age Groups. **a**. Eveningness: There is an uneven pattern of changing overall Eveningness between the four detailed age groups. The change is statistically significant at each successive age group (i.e., from Group 1 to Group 2, Group 2 to Group 3 and Group 3 to Group 4) but not otherwise between the groups; the significance level of the differences are shown in the text box; see main text for further details. **b**. Morningness: There is a single significant change to earlier overall Morningness between Group 1 and Group 2 by 37 minutes on average ($t_{34.625}$=2.483, p=.018, Cohen's d=0.84), as explained in full in Chapter 4, but thereafter Morningness times become gradually later until Group 4 (like Group 1) also has a significantly later morningness time than Group 2 (t_{77}=-2.459, p=.016, Cohen's d=0.56). Error bars show +/- one s.e.m.

Figure 4.4 shows an inconsistent (uneven) pattern of development in overall Eveningness behaviour across the four age groups. There is a significant change from more owl-like behaviour to more lark-like Eveningness behaviour between Group 1 (18-35) and Group 2 (36-50); t_{52}=2.220, p=.031, Cohen's d=0.62. There is a significant change back by Group 3 (51-65) to more owl-like Eveningness behaviour; t_{66}=-3.476, p=.001, Cohen's d=0.86. Finally, there is a significant change back to more lark-like Eveningness behaviour in the oldest sub-group (66

plus); t_{89}=2.870, p=.005, Cohen's d=0.61. In short, across the 4 age groups, the switch in 'going to bed' times is from later to earlier to later and finally back to earlier.

In contrast, the pattern for overall Morningness behaviour shown in Figure 4.4 is more consistent. There is a significant 37 minute fall from more owl-like to earlier, more lark-like Morningness behaviour between Group 1 (18-35) and Group 2 (36-50); $t_{34.625}$=2.483, p=.018, Cohen's d=0.84. Thereafter, there is a gradual return to later, more owl-like Morningness behaviour (in 11 and 10 minute increments) which culminates in Group 4 (66 plus) also having significantly more owl-like Morningness behaviour than Group 2 (36-50); t_{77}=-2.459, p=.016, Cohen's d=0.56.

*4.9.6. **New Finding:** The Key Consistent Behavioural Development is a Switch to Later Morningness at Weekends around age 35+*

Figure 4.3 compared Morningness and Eveningness on working days and work-free days (i.e., weekends) in the two main age groups and showed that the single area of difference in the two main age groups was weekend Morningness ($t_{73.012}$=3.714, p=.0004, Cohen's d=0.87). To complete the exploratory analysis, Figure 4.5 shows work day and work-free day Morningness and Eveningness across the four detailed age groups.

On both work days and work-free days, there is an apparent shift to more lark-like Morningness between Group 1 (18-35) and Group 2 (36-50), but this change is only statistically significant on work-free days (i.e. at weekends); $t_{39.992}$=2.682, p=.011, Cohen's d=0.85. On work days, there is a gradual accretion back up to later, more owl-like Morningness behaviour, culminating in the oldest group (66 plus) having a significantly later work day getting up time than Group 2 (36-50) (t_{77}=-4.032, p=.0001, Cohen's d=0.92), as might be consistent perhaps with diminishing early-morning work commitments in the oldest group.

The significant change to earlier, more lark-like Morningness behaviour at weekends between Group 1 and Group 2 is maintained and reinforced by earlier weekend getting up times in the older age groups. As well as differing from Group 2, Group 1 (18-35) therefore also has significantly later, or more owl-like work-free day Morningness than Group 3 (51-65, $t_{37.062}$=3.401, p=.002, Cohen's d=1.12) and Group 4 (66 plus, $t_{29.968}$=3.761, p=.001, Cohen's d=1.37). The shift to earlier work-free day Morningness that appears to occur in the 35-50 age group is therefore embedded by consistent earlier work-free day Morningness behaviour in each successive age group.

Figure 4.5: Detailed Breakdown of Eveningness and Morningness on Weekdays and at Weekends by Four Age Groups

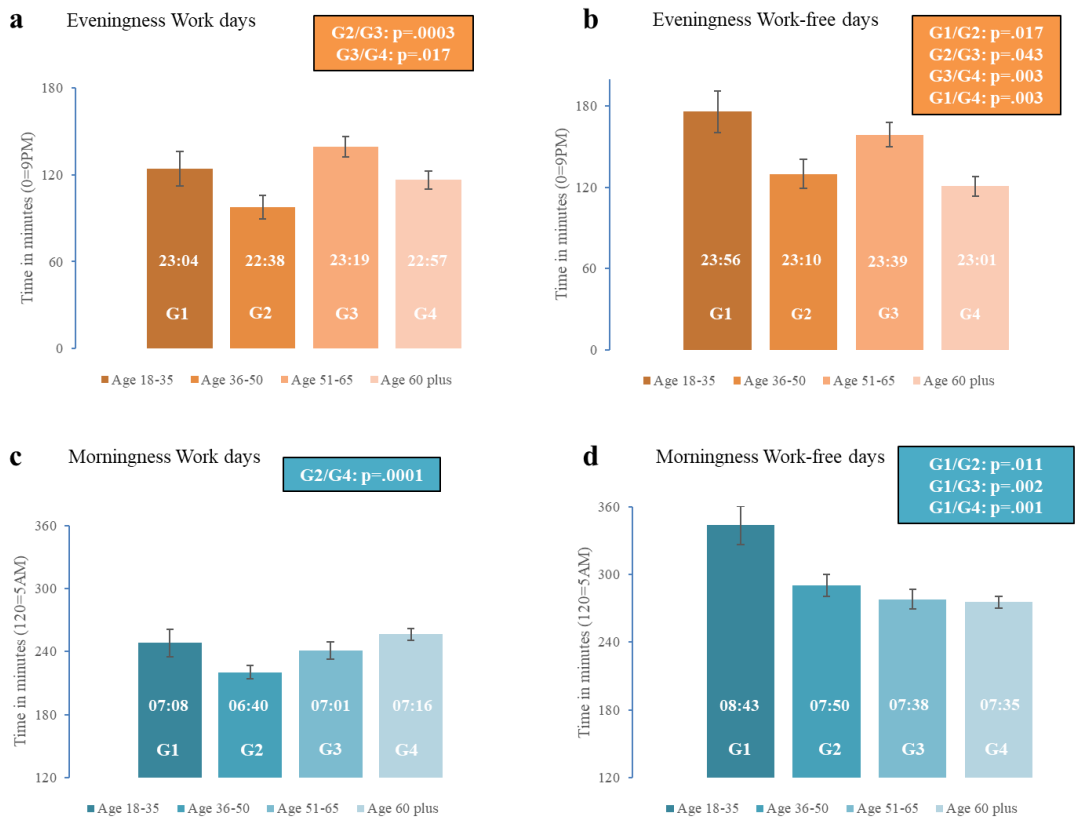


Figure 4.5: **a**. Eveningness Weekdays: Group 1 is not different in going to bed time (Eveningness) from any other group but Group 3 goes to bed later than both Group 2 and Group 4. **b**. Eveningness Weekends: Group 1 and Group 3 are not different from each other but both Groups go to bed later than Groups 2 and 4. **c**. Morningness Weekdays: The only difference is that Group 2 has an earlier getting up time (Morningness) than Group 4. There are no other differences between the Groups. **d**. Morningness Weekends: Group 1 gets up later than each of the 3 other Groups, but otherwise there are no differences between the Groups. See text for full details of results. Error bars show +/- one s.e.m.

This is to be contrasted with the profile of work-day and work-free day Eveningness (Figures 4.5 a and b) which both reflect the more inconsistent profile of overall Eveningness (Figure 4.4 a). In particular, work-free day Eveningness (Figure 4.5 b) shows the identical pattern of switching from Owl-to-Lark, Lark-to-Owl and back to Owl-to Lark that is seen with overall Eveningness (described above).

*4.9.7. **New Finding:** There is a Gradual Conformity between Weekday and Weekend Behaviour in both Eveningness and Morningness across Detailed Age Groups*

Examining the four detailed age groups, all four age groups go to bed later on work-free days than on work days (i.e., there is more owl-like Eveningness behaviour at weekends). The smallest increase is 4 minutes later (Group 4) and the largest increase is Group 1 (52 minutes). Group 2 goes to bed 32 minutes later and Group 3, 20 minutes later at weekends. Across the 4

age groups, with older age there is therefore a gradual shift towards conformity between work day and work-free day Eveningness. Across the 4 age groups, there is also a gradual shift towards conformity between work day and work-free day Morningness with older age. All four age groups get up later on work-free days; the smallest increase is 15 minutes later (Group 4) and the largest increase is Group 1 (95 minutes). Group 2 gets up 70 minutes later and Group 3 gets up 37 minutes later at work-free days. The developing age-related conformity in 'going to bed' and 'getting up' times on working and work-free days is unsurprisingly mirrored in a gradual approximation of bed duration on work days and work-free days across older age groups and this is illustrated in Figure 4.6. The difference between bed duration on workdays and work-free days narrows with age (Pearson's r=-.250, p=.002; Spearman's r_s=-.263, p=.001); see Figure 4.6c.

Figure 4.6: There is Greater Conformity in Weekday/Weekend Bed Duration with Increasing

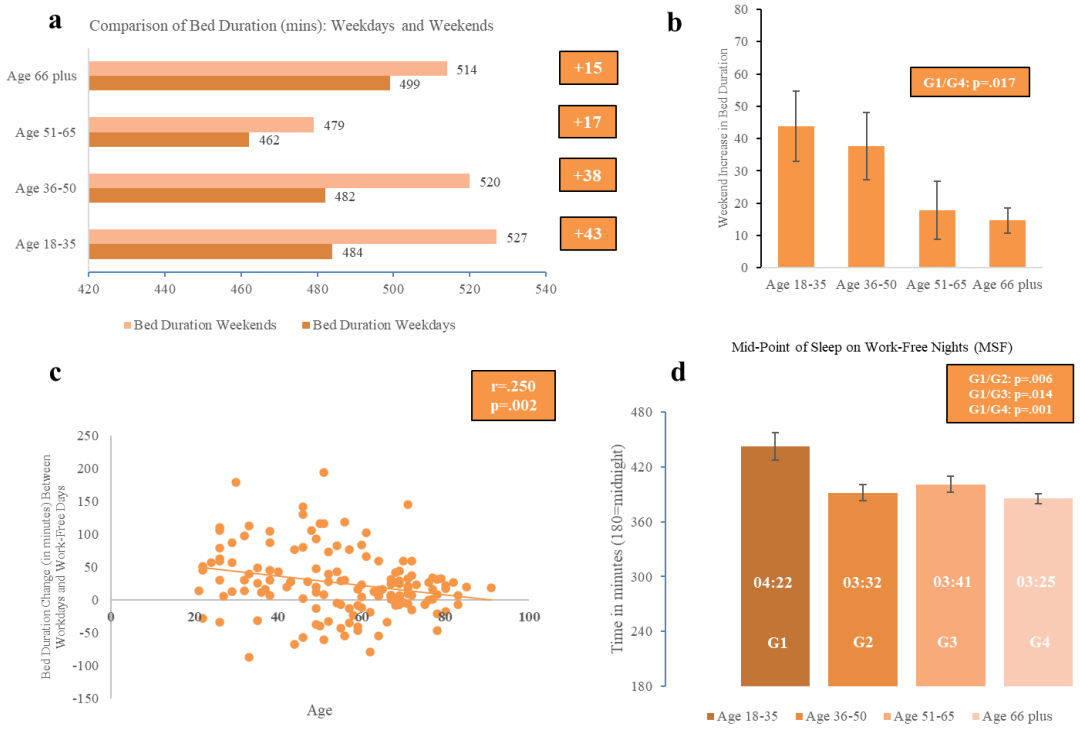


Figure 4.6: There is greater conformity in Weekday/Weekend Bed Duration with Increasing Age. **a**. All age groups show longer bed duration at the weekend than on weekdays and the two youngest groups have large changes. **b**. The only significant difference in weekend increase in bed duration is between the youngest group and the oldest group; $t_{31.683}$=2.517, p=.017, Cohen's d=0.89. In successively older age groups, there is increasing conformity between weekday and weekend bed durations. Error bars show +/- one s.e.m. **c**. The difference in bed duration time between working days and work-free days shortens progressively in older age; Pearson's r=-.250, p=.002. **d**. The linear progression towards a smaller bed duration increase at weekends is not reflected in MSF changes. The youngest group (18-35) has a later MSF than *each* of the three older age groups (p=.006, p=.014 and p=.001 respectively) but the older age groups are no different from each other; see main text for further details. Error bars show +/- one s.e.m.

Even though the data suggests a gradual conformity between weekday and weekend behaviour in older age groups, MSF does not mirror this gradual decline but shows instead a substantial fall at an earlier point (36-50) which is fairly stable thereafter; see Figure 4.6d. This also supports the contention that a key change in Circadian behaviour may occur well in advance of age 50. If large changes in Circadian behaviour in fact occur at a relatively early age, this is relevant to any contention (based on the view that these changes occur in later life) that there may be a relationship between such changes and age-related cognitive performance (see, e.g. Hofman & Swaab, 2006; Kondratov, 2007; Kondratova & Kondratov, 2012; Deibel, 2015). In simple terms, changes in memory domain performance in older age may not be attributable to Circadian behavioural changes, if these changes occur during younger age.

*4.9.8. **New finding:** Younger Subjects have higher Sleep Debt and higher Social Jet Lag than Older Subjects. Higher Sleep Debt is Maintained into Middle Age but Social Jet Lag Declines More Progressively from Younger Age*

In this sample of subjects, only 33 (23%) have Social Jet Lag of more than one hour and only 5 (3%) have more than 2 hours, compared with suggestions of 44% and 15% (see 4.6.2. above). This may reflect the relatively older average age of subjects in the current study (M=55 years).

Figure 4.7 shows that both Sleep Debt and Social Jet Lag reduce with older age; Sleep Debt: Pearson's r=-.255, p=.002, Spearman's rs=-.254, p=.002; Social Jet Lag: Pearson's r=-.567, p<.0001, Spearman's rs=-.583, p<.0001. Older subjects have substantially lower Social Jet Lag than younger subjects; t_{143}=6.966, p<.0001, Cohen's d=1.17; see Table 4.1. Older subjects also have lower Sleep Debt than younger subjects (t_{143}=3.091, p=.002, Cohen's d=0.52). However, exploratory analysis of more detailed age groups reveals differences in how Sleep Debt and Social Jet Lag may decline with age.

Sleep Debt is not different between Group 1 (18-35) and Group 2 (36-50); t_{52}=-.033 p=.97. Sleep Debt is significantly longer in both Group 1 (18-35) and Group 2 (36-50) compared with Group 4 (66 plus): Group 1/Group 4: t_{75}=3.289, p=.002, Cohen's d=0.76; Group 2/Group 4: $t_{41.097}$=2.827, p=.007, Cohen's d=0.88. However, Sleep Debt is not shorter in Group 3 (51-65) than it is in either Group 1 or Group 2 (p=.15 and p=.14 respectively). Accordingly, if Sleep Debt is, to some extent, a measure of sleep deprivation, then some loss of 'sleep required' appears to continue until about normal retirement age (i.e., the 66 plus age group).

Figure 4.7: Age Differences in Sleep Debt and Social Jet Lag

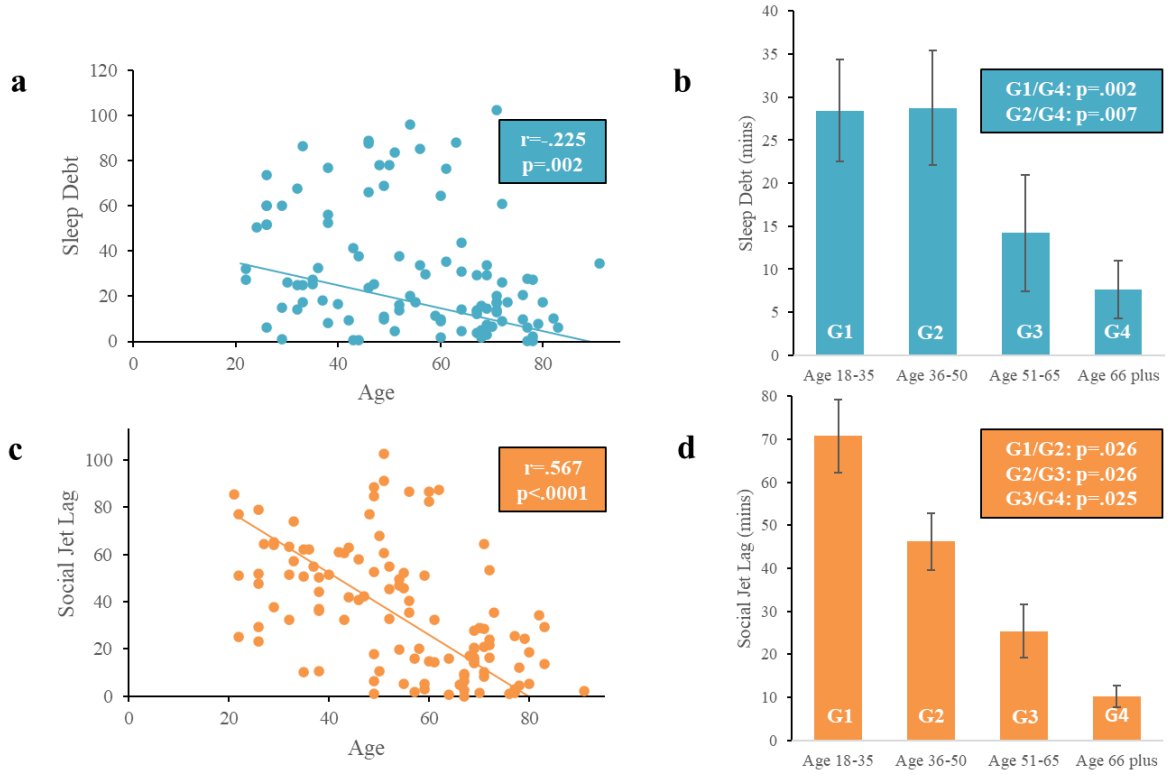


Figure 4.7: Older age is associated with improved Circadian regulation. Social Jet Lag and Sleep Debt are shown in average daily minutes**. a.** Sleep debt declines with older age; Pearson's r=-.225, p=.002. **b.** Examining detailed age groups, both of the two youngest age groups (18-35 and 36-50) have higher Sleep Debt than the oldest group (66 plus) but there are no differences elsewhere between the age groups (see text for further details). **c.** Social Jet Lag decreases significantly with age; Pearson's r=-.567, p<.0001. **d.** Social Jet Lag declines steadily across the four age groups; see text for further analysis. Error bars show +/- one s.e.m.

Social Jet Lag shows a different pattern. There is a more straightforward progression between shorter Social Jet Lag and older age. Group 1 (18-35) has longer Social Jet Lag (M=71 minutes) than Group 2 (M=46 minutes); t_{52}=2.290, p=.026, Cohen's d=0.64. Group 2 (36-50) has longer Social Jet Lag than Group 3 (M=25 minutes); t_{66}=2.273, p=.026, Cohen's d=0.56; and Group 3 (51-65) has longer Social Jet Lag than Group 4 (M=10 minutes); $t_{52.146}$=2.307, p=.025, Cohen's d=0.64.

Finally, there is no difference in average Assumed Sleep Duration (ASD) between younger and older subjects (t_{143}=1.456, p=.15). Age-group differences seen in Sleep Debt may not necessarily therefore be an indicator of older persons requiring less sleep to feel rested, as has been suggested elsewhere (Fox, 2018). Rather, older persons may accrue lower Sleep Debt because their ability to sleep in a regular pattern is less constrained than younger persons who may have greater need to catch up on 'lost sleep' (or 'sleep required') at weekends. This is also

supported by the gradual narrowing of differences in going to bed and getting up times in older age groups, described above.

*4.9.9. A **Main New Finding:** Both Owls and Larks Change their Morningness and Eveningness Behaviour on Work-free days Compared with Work days*

As Figure 4.8 shows, owls and larks are no different in age (p=.31). This is consistent with Circadian preference not being primarily a matter of ageing, but rather of behavioural disposition. However, as might be expected, owls have much later average chronotypes than larks. The difference in MSF_{sc} between owls and larks is, on average, 75 minutes; t_{143}=8.263, p<.0001, Cohen's d=1.38. However, Figure 4.8 also shows that *both* owls and larks adjust their behaviour between working and work-free days. Larks have MSF that is 27 minutes later than their MSW (t_{55}=6.651, p<.0001, Cohen's d=1.79) while owls have MSF that is 35 minutes later than their MSW (t_{88}=7.536, p<.0001, Cohen's d=1.61). The difference is significant with a large effect in both cases.

This finding of significant differences within both owls and larks between their MSW and MSF (see Figure 4.8) suggests that *both* Circadian behavioural types change their work-free day behaviour from their work-day behaviour. As this is a novel finding, further exploratory analysis was carried out and the detailed results are shown in Figure 4.9.

Figure 4.8: Comparisons between Owls and Larks in Age, Chronotype, Mid-Sleep on Work Days (MSW) and Mid-Sleep on Work-free Days (MSF)

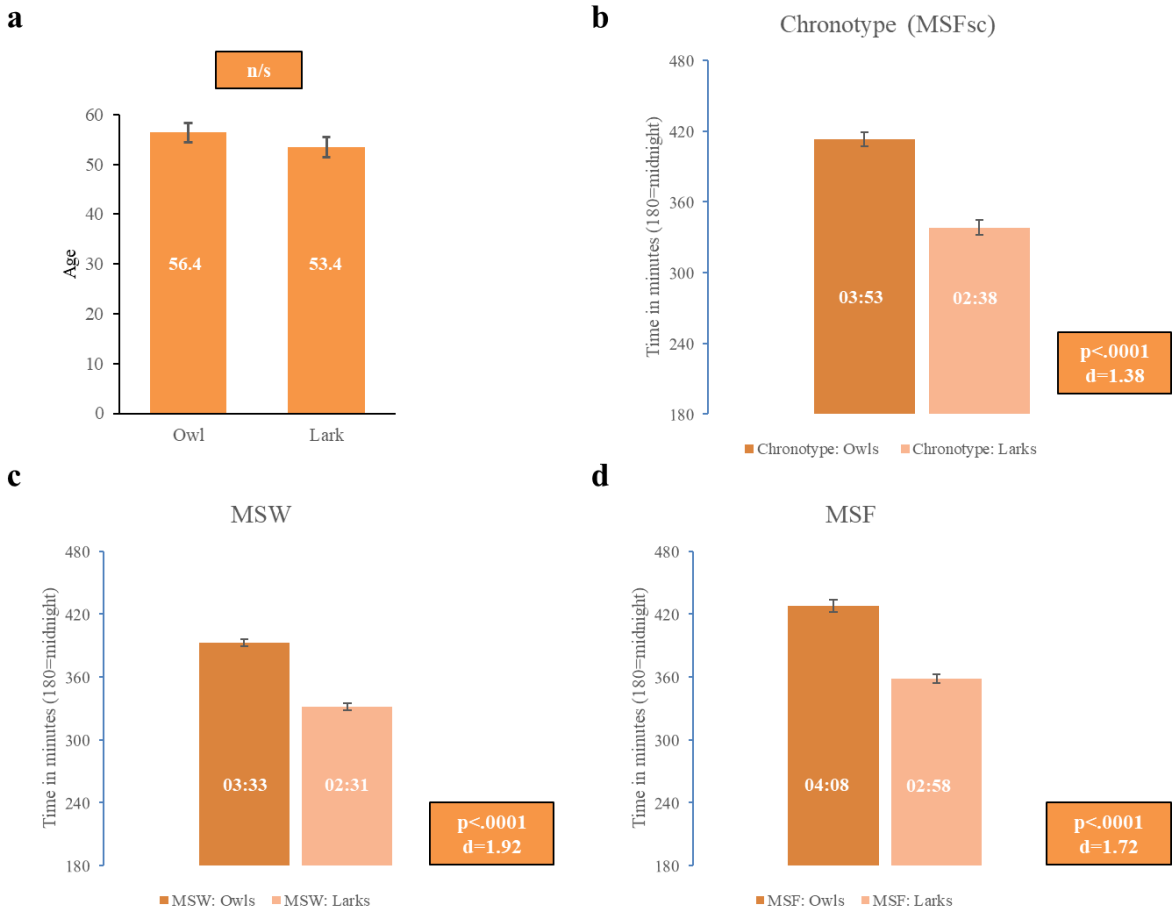


Figure 4.8: a and b. Owls and larks do not differ in age but have very different chronotypes. a. Owls (N=89) have an average age of 56.4 and larks (N=56) have an average age of 53.45; there is no statistical difference between owls and larks in age (p=.31). b. Owls have a chronotype score of 412.83, equivalent to MSFsc of 03:53 a.m. compared with larks who have a score of 338.09, equivalent to MSFsc of 02:38 a.m. There is a significant difference in chronotype (MSFsc); t_{143}=8.263, p<.0001, Cohen's d=1.38. : **c and d.** Although chronotype (MSFsc) is only determined by MSF adjusted for Sleep Debt (or 'sleep corrected'), in the present study, categorisation of owls and larks by reference to both Work Day and Work-free Day Morningness and Eveningness means that owls and larks differ on both MSW and MSF, as well as MSFsc. a. Owls have a later mid-point of sleep on a Work Day than larks; t_{143}=11.473, p<.0001, Cohen's d=1.92. b. Owls also have a later mid-point of sleep on Work-free Days than larks; $t_{140.500}$=10.180, p<.0001, Cohen's d=1.72 Error bars show +/- one s.e.m.

Figure 4.9: Both Owls and Larks Adjust their Behaviour on Work-free Days (Weekends) compared to Work Days (Weekdays)

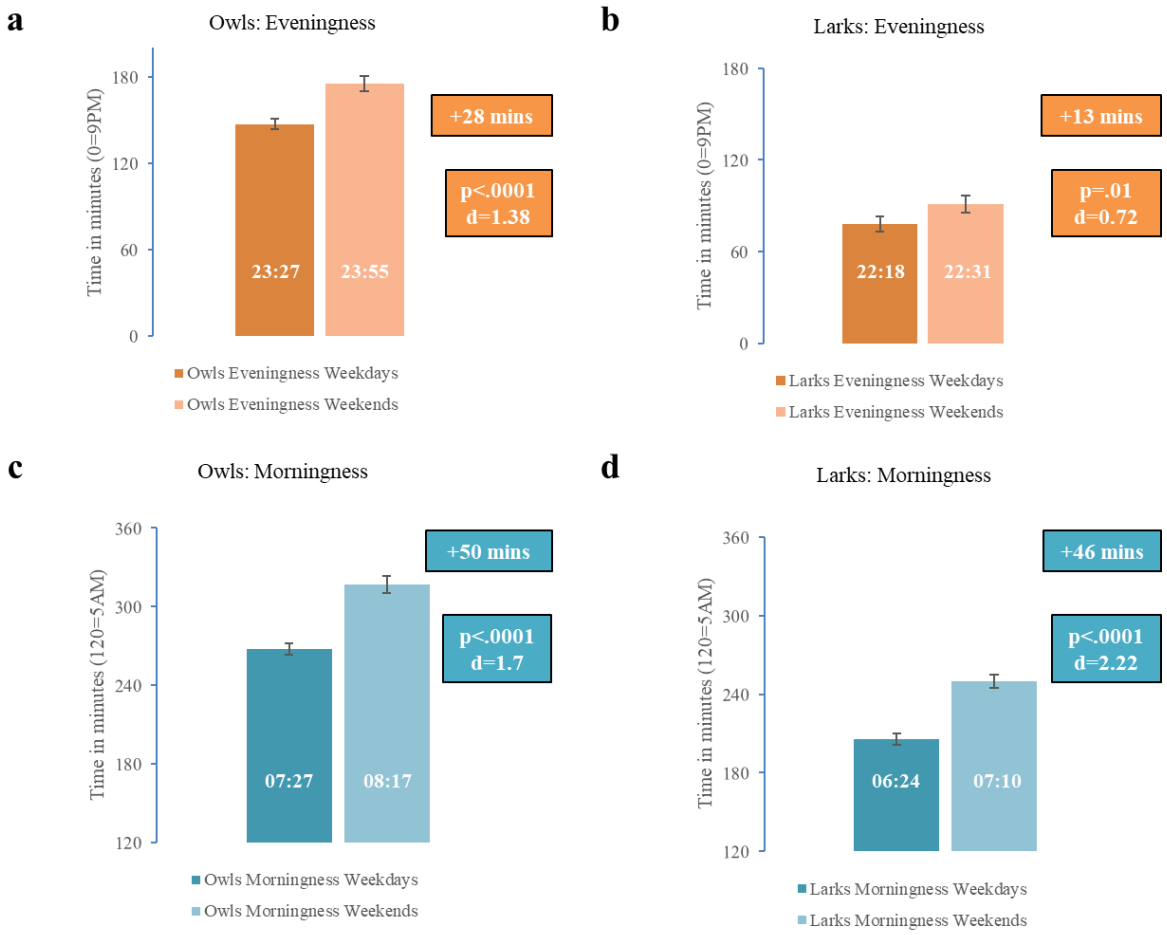


Figure 4.9: Both Owls and Larks adjust their Eveningness and Morningness behaviour between Weekdays and Weekends: **a and b**. Owls and larks both go to bed later at weekends than on weekdays; owls: t_{88}=-6.473, p<.0001, Cohen's d=1.38 and larks: t_{55}=-2.654, p=.01, Cohen's d=0.72; and by 28 minutes and 13 minutes later, respectively. **c and d.** Similarly, owls and larks both get up later at weekends than they do on weekdays; owls: t_{88}=-7.991, p<.0001, Cohen's d=1.7 and t_{55}=-8.227, p<.0001, Cohen's d=2.22; and by 50 minutes and 46 minutes later, respectively. This explains why there is no difference in Social Jet Lag between Owls and Larks (as MSF-MSW will give rise to proportionate adjustments for both Owls and Larks). See text for further discussion. Error bars show +/- one s.e.m.

Figure 4.9 shows that (unsurprisingly) owls have a tendency to become more owl-like in their work-free day Eveningness and Morningness behaviours, compared with their work-day behaviours, i.e., they go to bed later and get up later than they do on weekdays. However,

Figure 4.9 shows that this is *also* the case for larks. Larks become more owl-like on work-free days in both Eveningness and Morningness; in fact, the change with the largest effect size (Cohen's d=2.22) is the 46 minutes later time in larks' Morningness at weekends (M=7:10 AM) compared with their Morningness on weekdays (M=6:24 AM).

This is an important new finding because other methods of categorising Circadian preference based only on work-free behaviour would not reveal this adjustment made by both Circadian types. Specifically, if larks' behaviour is determined by their work-free day behaviour, it may seem to be more owl-like than it really is when considered across the whole week. In addition, this finding also translates into an *absence of differences* between owls and larks in Sleep Debt and Social Jet Lag, where differences have been sometimes assumed to exist (see, e.g. Nowack & Van Der Meer, 2018).

*4.9.10. A **Main New Finding**: Owls and Larks Do Not Differ in Sleep Debt or Social Jet Lag*

As shown in Figure 4.10, owls and larks do not appear to differ in either Sleep Debt or either Social Jet Lag. Figure 4.10 also shows, for contrast, the significant differences in both Sleep Debt and Social Jet Lag between the two main age groups. The explanation for the absence of differences is that Sleep Debt is not associated with chronotype, and for Social Jet Lag, that both owls and larks make comparatively similar adjustments to their weekday and weekend behaviours, as described. The fact that MSF and MSW are at different points on the 24 hour clock for owls and larks is irrelevant; both make similar adjustments to their weekend behaviour and both will therefore incur *some* Social Jet Lag. Consequently, in this study, there is no difference in Social Jet Lag between them ($t_{141.916}$=-1.372 p=.17).

It has been suggested elsewhere that Social Jet Lag should be adjusted for Sleep Debt (Jankowski, 2017) but this has not been done here. Such an adjustment would ordinarily reduce Social Jet Lag but, if such an adjustment were made in the present study, there would still be no difference in Social Jet Lag between owls and larks (owls=20.17 minutes adjusted and larks=6.65 minutes adjusted; t_{143}=1.763, p=.08). It might be argued that a different 'standard questionnaire' categorisation basis for owls and larks (using MSF_{sc}) might have produced the result that only owls incurred Social Jet Lag, but this seems unlikely given the strong association in this study between higher combined score and later chronotype.

Figure 4.10: Older Subjects have lower Social Jet Lag and lower Sleep Debt than Younger Subjects but because both Owls and Larks Adjust their Behaviour at Weekends (Work-free Days) from Weekdays (Work Days), they do not differ in Social Jet Lag or Sleep Debt

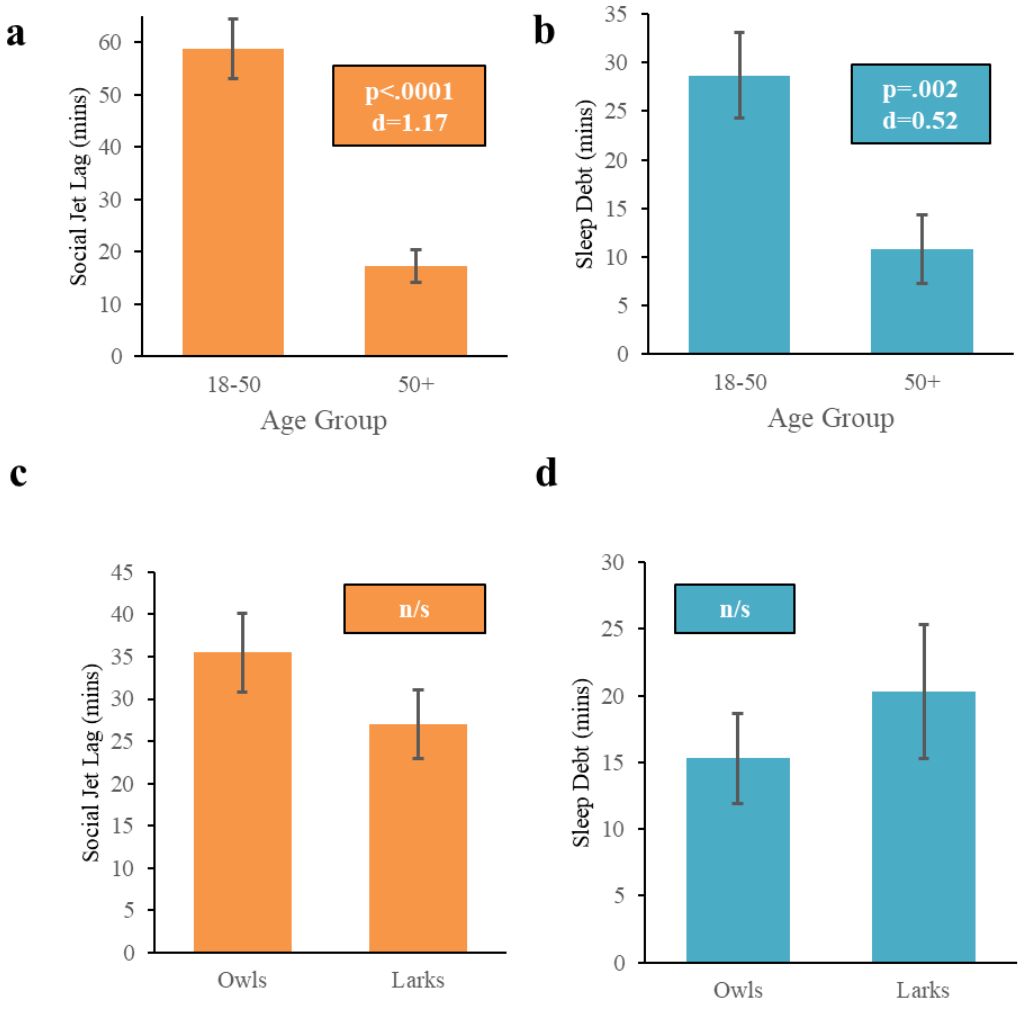


Figure 4.10 a and **b** shows that the younger age group has higher Social Jet Lag and higher Sleep Debt than the older age group (see also Figure 4.7) but, because both owls and larks make adjustments to their behaviour on work-free days (see Figure 4.9), they do not differ in Social Jet Lag or Sleep Debt (**c** and **d**). Error bars show +/- one s.e.m.

*4.9.11. A **Main New Finding:** Circadian Preference has No Bearing on VEM Long Term Forgetting Performance and Suggests that there is No Relationship between Circadian Preference and Sleep-based Long-term Memory Consolidation*

A comparison of memory domain performance by owls and larks reveals no differences in performance in any of the four PCA factor memory domains. This is perhaps unsurprising because there is no difference in age between owls and larks and no difference in PSQI score (the basis for being a good or poor sleeper); see Table 4.1. Specifically, Circadian preference

does not affect VEM Long Term Forgetting (in the way that good/poor sleep does; see Chapter 3) and there is no difference between owls and larks in VEM Long Term Forgetting (t_{143}=-.335, p=.74). Accordingly, while being cautious that an absence of evidence does not equate to evidence of an absence, there is no evidence in the present study that Circadian preference has any bearing on the process of sleep-based long-term memory consolidation (Gerstner & Yin, 2010; Kondratova & Kondratov, 2012).

Finally, within the two main age groups, older owls do not perform better than older larks (or vice versa) in any of the four memory-domain factors.

*4.9.12. A **Main New Finding:** Good and Poor Sleepers Do Not Differ in Sleep Debt or Social Jet Lag. Neither Attribute appears to be Akin to a component of PSQ Sleep Quality that Contributes to Better VEM Long Term Forgetting*

Neither Sleep Debt nor Social Jet Lag is associated with VEM Long Term Forgetting (p=.19 and p=.43 respectively) and neither measure makes any contribution to predicting better performance in this memory domain. Moreover, as seen in Table 4.1, PSQ good and poor sleepers do not differ on any of the Circadian measures of MSW, MSF and chronotype, *and including* Sleep Debt and Social Jet Lag. This is not known to have been previously reported.

This is important because it suggests two important new conclusions. First, although Sleep Debt and Social Jet Lag may often be referred to in terms of dysfunctional sleep or Circadian behaviours (see, e.g., Roenneberg, 2019; Taillard, 2021), they do not appear to be associated with PSQ sleep quality, and there is no difference in either of them as between good and poor sleepers. Second, even if they do represent dysfunctional sleep behaviours, they do not appear to contribute to worse VEM Long Term Forgetting in the way that poor sleep quality does (see Chapter 3).

*4.9.13. **Replicated Finding:** Owls have Better Social Connectedness than Larks*

Owls have higher levels of PCA factor Social Connectedness than larks; t_{136}=2.651, p=.009, Cohen's d=0.45 (see Figure 4.11). The PCA factor score for Social Connectedness is based on underlying scores for both the Family and Friendship subscales of the Lubben Social Networks questionnaire (see Chapter 6 for details). Examining each of these components separately shows that owls have both stronger family and stronger friendship networks than larks; see Figure 4.11b and 4.11c. Later chronotype (MSF_{sc}) is also moderately associated with stronger Friendship networks; Pearson's r=.186, p=.028. However, owls do not appear to be more sociable than larks (as measured by the Social Situation questionnaire) and larks are not lonelier

than owls (as measured by the UCLA Loneliness Scale). For full details of all questionnaires, see Chapter 6.

Figure 4.11: Owls have better Social Connectedness than Larks

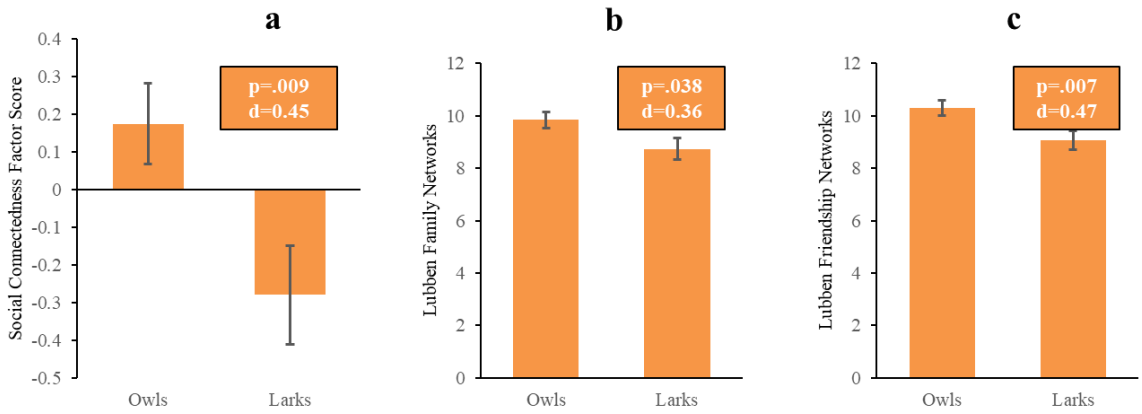


Figure 4.11: Differences in Social Connectedness between Owls and Larks: **a.** Owls score higher than larks on PCA factor scores for Social Connectedness (t_{136}=2.651, p=.009, Cohen's d=0.45). Positive factor scores denote higher Social Connectedness than negative factor scores. **b.** Owls have larger Family Networks than larks (t_{138}=2.097, p=.038, Cohen's d=0.36). **c.** Owls also have larger Friendship Networks than larks (t_{138}=2.738, p=.007, Cohen's d=0.47). However, owls do not have higher sociability than Larks (as determined by the Social Situation Questionnaire, p=.26) and Owls do not have lower loneliness than Larks (as determined by the UCLA Loneliness scale, p=0.9). See text for further details. Error bars show +/- one s.e.m.

4.9.14. There is only Very Modest Evidence to Support the Synchrony Effect in the RAVLT but this is Not Sufficient to suggest either a Replication or a New Important Finding in the Present Study

The present study was not designed to examine memory performance differences based on Circadian type and time of day of testing, although data for time of day of testing was collected in order to ascertain whether any large effects may arise. There is no strong evidence of any synchrony effect. Some very limited statistical support for a synchrony effect is seen with the RAVLT and for completeness, and to facilitate any future research using the RAVLT, these results are provided in Supplementary Figure 4.4.

MSF: the average mid-sleep time on a work-free day (night)—taken to be Friday and Saturday nights in the present study, except (e.g.) where Sunday night is followed by a Bank Holiday when Sunday is also included

MSW: the average mid-sleep time on a work day (night)—taken as Sunday to Thursday night inclusive in this study, except (e.g.) where Sunday night is followed by a Bank Holiday when Sunday is not included

Chronotype (MSFsc): MSF (as defined above) but 'sleep corrected' (SC), meaning that Sleep Debt (normally accrued during the working week) is deducted to provide a corrected and preferred MSF

Assumed Sleep Duration (ASD): the total duration between the first and last device recorded minutes of sleep, i.e., disregarding any period of awakening during the night. ASD is used to determine the mid-sleep times for both MSF and MSW

Sleep Debt: the average difference in minutes between 'sleep acquired' and 'sleep required' (taken in this study to be the difference between average ASD on Work-free nights less average ASD overall calculated in minutes)

Social Jet Lag: The average difference in minutes between MSF and MSW

Owl: A subject with a preference for Eveningness, demonstrated in the present study by a consistent preference for both later 'going to bed' and 'getting up' times across work and work-free days

Lark: Subject with a preference for Morningness, demonstrated in the present study by a consistent preference for both earlier 'getting up' and 'going to bed' times across work and work-free days

Circadian preference: meaning, in the present study, the preferred bed-time behaviour of a subject based on their categorisation as an owl or a lark

4.10. DISCUSSION

4.10.1. Summarising the Main Findings in this Chapter: Circadian Behaviour, including Dysregulation in Sleep and Bed Behaviours, May Not Materially Affect Memory Domain Performance in the same way as Poor Sleep Quality

In the previous chapter, it was shown that PSQ sleep quality strongly predicted performance in VEM Long Term Forgetting. Circadian behaviour has been described as "the new science of the body clock" (Foster, 2022) and research on how Circadian behaviour changes in ageing and how Circadian preferences may affect cognition is still relatively undeveloped. In this chapter, Circadian behaviour has been examined in ageing, with particular focus on how that behaviour may affect memory domain performance. In contrast with much previous research in this area which has been questionnaire-led, the present study has used actigraphy to study Circadian behaviour over a two week period. Actigraphy has revealed results that are consistent with earlier questionnaire based research, such as the findings that both Sleep Debt and Social Jet Lag decline with age (Fox, 2018; Roenneberg, 2019). However, it has also revealed a number of important new findings about Circadian behaviour.

One such finding is that behaviour may become more lark-like at an earlier age than previously considered to be the case (e.g., Tankova, 1994) and this earlier behavioural change may be driven by changes in weekend Morningness (i.e., developing lark-like tendencies) around age 35-50. This is important because Circadian behaviour changes may not co-occur with, and may substantially pre-date, later-life sleep quality or cognitive performance changes. In addition, the present study demonstrates that both owls and larks alter their behaviour at weekends, by going to bed later and getting up later. This is important because it means that dysfunctional behaviours, such as Social Jet Lag, may not be the sole preserve of owls (e.g., Nowack & Van Der Meer, 2018). This finding makes good sense when trying to reconcile the 30% of the population that are consistent owls (Walker, 2017) with the 44% that accrue at least an hour of Social Jet Lag (Roenneberg, 2019).

Finally, the main finding in this chapter which is directly relevant to memory domain performance is that PSQ sleep quality is unaffected by Circadian preference and specifically neither Sleep Debt nor Social Jet Lag differs between good and poor sleepers. As a result, neither measure is associated with VEM Long Term Forgetting, which in turn suggests that neither measure materially influences the process of sleep-based long-term memory consolidation.

4.10.2. Consistent Finding: The Proportion of Owls and Larks in the Present Study Appears to be Consistent with that Seen Elsewhere and the Basis for Categorisation Appears Reasonable

The proportions of owls and larks in the present study appears to be consistent with those reported elsewhere, whether looking only at owl/lark extremes (e.g., Adan, 2012) (in the present study 44.8%) or a binary distribution based on owl/lark tendencies (e.g. Walker, 2017), (in the present study, 61% owls and 39% larks). This suggests that the basis for categorisation of owls and larks used in the present study was reasonable.

Examining categorisation in the younger group (N=52), 52% are owls and 48% are larks. In the older group (N=93), 67% are owls and 33% are larks. This contrasts with findings elsewhere (e.g. Tankova, 1994) where later chronotypes are uncommon in older populations and early chronotypes are uncommon in younger groups. One question the results in the present study raise is whether such a straightforward age-related division properly represents Circadian behaviour in the wider population, i.e., and in particular, beyond the stereotypes of student and older, retired populations. In this sample, chronotype does not differ between the older (still working) and the younger (working, non-student) group (t_{143}=.820, p=.41) and there is no age difference between owls and larks (t_{143}=1.012, p=.31). In addition, the socio-demographic profile of the older group in the present study is generally active, and with higher levels of social engagement and, possibly, post-retirement age work. After age 50, there may be less pressure to adhere strictly to social or work requirements for lark-type behaviour patterns (Walker, 2017) and greater freedom for active, older persons therefore to 'revert to preferred behavioural type', which may involve some greater level of owl-like behaviour. It is consequently hard to conclude whether the results for this sample are typical or atypical of the wider population.

*4.10.3. **New Findings:** (1) Examining Detailed Age Groups reveals a Nuanced Development of Eveningness and Morningness Behaviour with Increasing Age (2) the Key Consistent Behavioural Development is a Switch to Later Morningness at Weekends around age 35+ and (3) there is a Gradual Conformity between Weekday and Weekend Behaviour in both Eveningness and Morningness in Older Age, effectively eliminating Circadian Behavioural Dysfunction, such as Sleep Debt and Social Jet Lag*

The new findings relating to the development of Eveningness and Morningness behaviours are important because previous studies have suggested that age 50 is the critical age at which more lark-like behaviour emerges (Tankova, 1994; Ishihara, 1992). Some results here support this view. Although older age is not associated with earlier chronotype across the whole group (p=.056), within the separate younger and older age groups, the position is contrasting. In the

younger group (21-50), older age is strongly associated with earlier chronotype (p=.001), whereas in the older group (50+), there is no association between age and chronotype (p=.74). Also, in the younger group, owls are younger than larks (p=.002). This tends to suggest that age 50 may indeed be a cut-off point for lark-like tendencies to become embedded. However, a more nuanced position is seen when analysing four different age groups across the wide 70-year age range (ages 21-91) represented in this sample.

Examining the detailed age group differences reveals that earlier chronotype behaviours appear to change in the 36-50 age group and, if so, this may be relevant to studies purporting to link later mid-life (50+) Circadian changes to declining cognitive performance; in short, the Circadian change may occur at a much earlier stage than previously thought, and *before* the onset of age-related cognitive performance changes described in Chapter 2. While there are significant differences between the main older (50+) and younger (<50) age groups in VEM Short Term Recall, Face Memory & Perception and Working Memory, there are *no differences* in performance in any of those memory domains between the 18-35 age group and the 36-50 age group (p=.17, p=.23 and p=.20 respectively).

The finding in the present study that behavioural chronotype changes may occur before age 50 was only enabled by more detailed exploratory analysis of the actigraphy-based results. Actigraphy is an important methodological difference that has only emerged relatively recently since the research establishing age 50 as the critical point for change (Ishihara, 1992; Tankova, 1994). A straightforward comparison of Morningness and Eveningness between the two main age groups in the present study shows much later weekend Morningness behaviour in the younger group than in the older group (p<.001, Cohen's d=0.87) and tends to reinforce the view that age 50 may be a key cut-off point. However, in the four detailed age groups, for overall Morningness, actigraphy revealed that there is a single, significant fall from owl-like behaviour (18-35) to more lark-like behaviour (36-50) before a gradual, non-significant reversion to slightly more owl-like Morningness behaviour in successive age groups. Detailed exploratory analysis of the actigraphy data across the four age groups between Morningness on work-days and work-free days helped to pinpoint how the key change occurs between the 18-35 group and the 36-50 age group in work-free day Morningness, a change that becomes embedded and reinforced in subsequent age groups. Accordingly, actigraphy has been instrumental in illustrating the earlier age-point of Circadian change to more lark-like behaviour and in showing the key type of behavioural change (i.e., Morningness on work-free days).

The results overall also show a gradual narrowing of differences between weekend and weekday Circadian and bed behaviours across the four age groups. This developing conformity between weekday and weekend Eveningness and Morningness Circadian behaviour and bed duration across the detailed age groups also helps to substantially reduce any adverse impact of Circadian dysfunctional attributes, such as Sleep Debt and Social Jet Lag, in later life.

4.10.4. ***Replicated finding:*** *Younger Subjects have higher Sleep Debt and higher Social Jet Lag than Older Subjects.* ***New Finding:*** *Higher Sleep Debt is Maintained into Middle age but Social Jet Lag Declines more Progressively from Younger Age*

In this sample, younger age is strongly associated with both higher Sleep Debt (p=.002) and higher Social Jet Lag (p<.0001), as reported previously (see, e.g. Fox, 2018 and Roenneberg, 2019). Age is not associated with shorter or longer Assumed Sleep Duration ('ASD') (p=.81) and there is no difference between younger and older groups in average daily minutes of ASD overall (p=.15). It therefore seems unlikely that Sleep Debt is lower in older subjects because they need less sleep (see e.g. Fox, 2018). It is perhaps more likely that Sleep Debt is lower in older subjects because behavioural differences in their weekday and weekend Eveningness and Morningness have been minimised, although unlike Social Jet Lag, Sleep Debt appears to persist into early older age. This may be because Sleep Debt is effectively tied to the demands of working, whereas Social Jet Lag is tied to work-free day socialising. Put simply, the older age groups are less constrained by work demands and more able to go to bed and get up at broadly the same times during the week as they do at the weekend, with the result that bed and sleep duration times are more stable than they are for younger subjects and this naturally results in lower accretion of Sleep Debt. Work-free day socialising, by comparison, declines much sooner in life.

4.10.5. ***New Finding:*** *(1) Both Owls and Larks change their Morningness and Eveningness Behaviour on Work-free days* ***New Finding****: (2) Owls and Larks do not differ in Sleep Debt or Social Jet Lag*

It has been suggested (e.g. Nowack & Van Der Meer, 2018; Taillard, 2021) that Social Jet Lag may be a key factor in owls' poorer cognitive performance at "sub-optimal" (i.e. non-synchronous Circadian) times. Decline in Social Jet Lag with increasing age is steady and consistent across all age groups, from approximately seventy minutes in the youngest group (18-35) to just ten minutes in the oldest group (66+); i.e., with increasing age, MSW and MSF become more consistent (or the gap between them reduces).

However, the present study shows that both owls and larks appear to adjust their weekend behaviour from their weekday behaviour so that *some* gap between MSF and MSW is maintained by both Circadian types; owls and larks both have later Eveningness and Morningness at weekends than on weekdays, and the differences are particularly large for Morningness; Owls=50 mins difference, p<.0001, Cohen's d=1.7 and Larks=46 mins difference, p<.0001, Cohen's d=2.22. As Social Jet Lag is a measure of mid-sleep point adjustment between working and work-free days, and as both owls and larks appear to make significant adjustments between weekday and weekend sleep behaviours, it is perhaps not unusual to find that owls and larks do not differ in Social Jet Lag (p=.17). It may not be correct to assume therefore that only owls accrue Social Jet Lag (and, in part, such conclusions about 'owl' behaviour may be highly dependent on how 'owls' and 'larks' are categorised to start with). This means that Social Jet Lag may not be the basis for any under-performance by owls on cognitive tests carried out at sub-optimal times of the day; (Nowack & Van Der Meer, 2018).

*4.10.6. **New Finding:** Circadian Preference has no bearing on VEM Long Term Forgetting performance and there is No Evidence of any Relationship between Circadian Preference and Sleep-based Long-term Memory Consolidation*

Although other studies have variously suggested that owls (e.g., Kanazawa & Perina, 2009) or larks (e.g., Roberts & Kyllonen, 1996) may have an inherent cognitive advantage, no evidence was found in the present study for any performance difference in any of the four studied memory domains by owls or larks. In particular, neither chronotype nor Circadian categorisation (as an owl or lark) has any effect on lower VEM Long Term Forgetting, where good sleep has been shown (in Chapter 3) to be critical. There is no evidence in the present study therefore that Circadian preference has any large bearing on sleep-based long-term memory consolidation, or memory performance more generally.

*4.10.7. **New Finding:** Neither Sleep Debt or Social Jet Lag appear to be Characteristics of PSQ Sleep Quality and neither attribute is associated with VEM Long Term Forgetting*

Neither Sleep Debt (p=.68) nor Social Jet Lag (p=.79) is associated with the PSQI score, and in the same way that there are no differences between owls and larks in Sleep Debt or Social Jet Lag, there are also no differences between PSQ good and poor sleepers in Sleep Debt or Social Jet Lag. This is important because although (higher) Sleep Debt and Social Jet Lag may commonly be reported elsewhere as, essentially, Circadian or sleep behaviour dysfunctions (see, e.g. Roenneberg, 2019; Taillard, 2021), importantly these behaviours are not (in this sample) associated with poorer sleep quality.

Even if they do represent dysfunctional sleep behaviours, they do not appear to contribute to worse VEM Long Term Forgetting in the way that poor sleep quality does (see Chapter 3). Neither Sleep Debt nor Social Jet Lag is associated with VEM Long Term Forgetting and neither Circadian measure makes any contribution to predicting better performance in this memory domain. *This is a point of great importance* to the main finding in Chapter 3 that good sleep predicts lower VEM Long Term Forgetting, i.e., there is no evidence, in the present study, for any impact of either Sleep Debt or Social Jet Lag on sleep-based, long-term memory consolidation.

4.10.8. ***Replicated Finding:*** *Owls have Better Social Connectedness than Larks*

Owls have been reported to have greater extraversion than larks (Adan, 2012) and the sociability component of extraversion has been more closely associated with owl-like behaviour than impulsivity (Larsen, 1985). In the present study, and using the bespoke methodology described in Methods for categorising owls and larks, owls have both stronger Family and Friendship networks than larks. In the sample as a whole, owls do not appear to be more sociable than larks (as measured by results on the Social Situation questionnaire).

4.10.9. Limitations

No chronotype questionnaire has been used in this study either to assess or corroborate actigraphy-calculated chronotype. In addition, the chronotype score has not been used to distinguish owls from larks. Instead, a combinatorial system has been devised which seeks to categorise subjects based on *both* weekday and weekend Morningness and Eveningness. It could be argued that the cut-off points of 23:30 PM and 06:30 AM are somewhat arbitrary; however, because it works on combined Eveningness and Morningness, there is sufficient flexibility in the scoring system to reduce the impact of small variations in Eveningness and Morningness, as described in Methods. Just as with age groups (see Chapter 1), definitive category boundaries for owls and larks need to be approached with caution. The fact that ratios of owls and larks in this sample match the reported general trends in the wider population affords some comfort that the categorisation used here is reasonable, as does the strong correlation between combined score (basis for categorisation) and chronotype.

Data provided by actigraphy for weekend behaviour (which largely drives the calculation of chronotype) may not be ‘typical’ or represent subjects’ usual weekend behaviour. The fact that

there are at least two full weekends of measured behaviour should however help to dilute the impact of any exceptional or 'one-off' weekend events or behaviours.

Finally, student populations tend to be heavily represented in Circadian behaviour studies and usually exhibit stronger owl-like patterns of behaviour. By contrast, older studied populations have tended to be non-working and to show earlier lark-like behaviour (Kerkhof, 1985; Tankova, 1994). Behavioural patterns shift with increasing age, and working-time obligations may be a large contributing factor to Circadian behavioural change (Roberts & Kyllonen, 1999; Walker, 2017). In this sample of 145 subjects, 52 are aged below 50, but there is only a very small number of full-time students (c.3). Also, 93 subjects are included in the older group, but are fit and active, and many had ongoing work commitments, especially in the 51-65 sub-group (N=40). It is reasonable to assume however that working activity was lower in the 66 plus group here (N=51). The fact that the sample population in the present study tends to be older, non-student and still active may affect the question whether the Circadian results reported here are generalisable to a different demographic sample.

4.11. Summary of Chapter 4

PSQ good and poor sleepers did not differ on the Circadian measures of Social Jet Lag and Sleep Debt and these sleep dysregulation measures have no bearing on performance in VEM Long Term Forgetting. Two important new conclusions can be drawn from this. First, neither Social Jet Lag nor Sleep Debt appears to correspond to a good/poor sleep quality characteristic. Second, and consequently, neither measure appears to affect 'good sleep' benefits to sleep-based long-term memory consolidation (seen in Chapter 3).

Although Social Jet Lag is strongly associated with later chronotype, an unexpected new finding is that owls and larks do not differ in Social Jet Lag. This is because both owls and larks go to bed later and get up later at weekends than on weekdays, albeit at different clock times. This has important implications for future research into differences between owls and larks, and any assumed effect that such categorisation may have on cognitive performance (Nowack & Van Der Meer, 2018). Also, owls had larger friendship networks than larks (in line with previous findings, e.g.,Tankova, 1994).

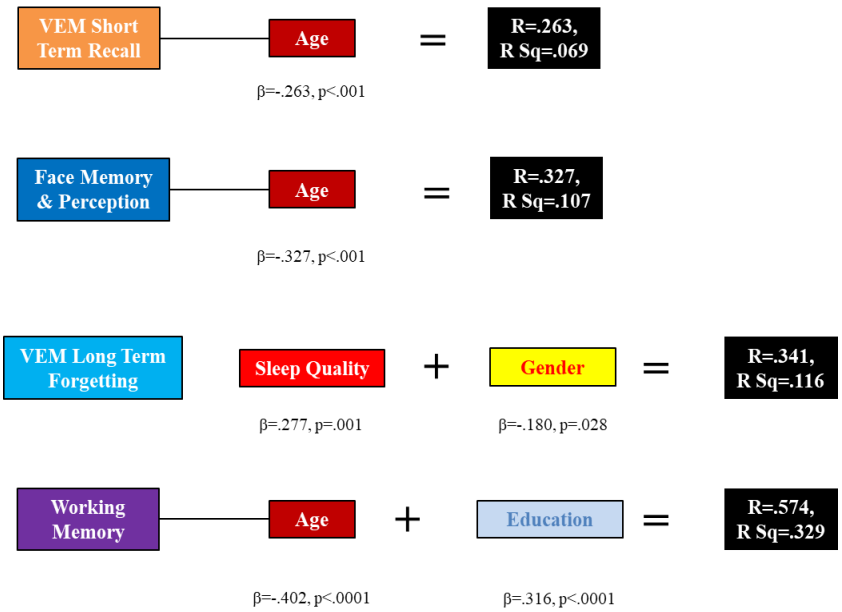
Both Sleep Debt and Social Jet Lag decreased with older age. However, a further new finding is that Sleep Debt differences between younger and older subjects were not attributable to any differences in sleep required (Fox, 2018). Lower Sleep Debt in older subjects appears to be

attributable to more consistent bed times (and consequentially more stable sleep duration) across weekdays and weekends than is the case in younger subjects.

Finally, the trend for earlier chronotype in older age may begin with a substantial shift from later to *earlier weekend Morningness* in earlier middle-age (36-50). This change is concealed in a more gradual age-related narrowing of differences between weekday and weekend behaviours and which might be hard to discern without actigraphy (e.g.) in 'single question' studies of Circadian preference or behaviour.

The updated regression models are shown in Figure 4.12.

Figure 4.12: Updated Regression Models for Chapter 2, 3 & 4



Note: the model is unchanged from Chapter 3

In the next chapter (Chapter 5), once again a mixture of actigraphy data and self-report will be used to examine physical activity in ageing and what contribution different levels of activity may make to the preservation of good memory domain performance.

CHAPTER 5: PHYSICAL ACTIVITY AND MEMORY PERFORMANCE

5.1. INTRODUCTION

The previous two chapters, Chapters 3 and 4, have examined age-related changes in sleep and Circadian behaviour and how these factors may affect the preservation of healthy memory performance. Whilst the distinction between being a good and poor sleeper appears to have an important bearing on memory performance, there is no evidence in this study that being an owl or a lark has an equivalent impact. Circadian dysregulation measures are not characteristic of good or poor sleep. This chapter considers how physical activity (and in some instances, being 'active' rather than 'inactive') may affect memory domain performance. Measurement methods are once again actigraphy combined with questionnaire self-report.

5.1.1. Recent Research into Physical Activity (PA) and Exercise suggests Benefits can be Obtained from Modest Increases in Light PA

It has been generally well known for some years that physical activity and exercise have a beneficial effect on physical and cognitive health (Pereira, 2007; Deslandes, 2009; Erickson, 2011). However, a number of unresolved questions still remain, including what type of activity or exercise, intensity level and duration is best for different physical and cognitive domains (Di Liegro, 2019; Jakicic, 2019). Current research, which has demonstrated that benefits are secured by even very modest increases in PA, is less concerned with recommending very exacting PA or specific exercise regimes. For example, in a recent, well-publicised case (Lee, 2021), it was found that older adults who undertook more housework had improved attention and memory; specifically, heavy housework was associated with improved attention, whereas light housework (such as washing up, dusting, ironing and making the bed) was associated with better immediate and delayed memory. No such benefits were found in younger adults. The Lee, 2021 study highlights two important points which feature strongly in the results presented in this chapter; first, that different cognitive benefits may accrue from lighter as opposed to heavier (or more strenuous) activity, and second, that the same PA and exercise levels may have quite different effects (or indeed, none at all) on subjects in different age groups.

In this study, subjects' PA has been measured for two continuous weeks using actigraphy and, in addition, subjects have also self-reported how active they are, using the UK Department of Health General Practice Physical Activity (GPPA) questionnaire (Physical Activity Policy, 2009), devised for use by health professionals in the NHS, see e.g., Ahmad, 2015. As further described below, the GPPA assigns persons to one of four activity levels, 'active', 'moderately

active', 'moderately inactive' and 'inactive'. The GPPA has two main component scores, for structured exercise and for occupational-based PA. This means, for example, that a person can secure an 'active' rating either by having a 'vigorous' occupation (e.g., scaffolder or construction worker) or by undertaking extended periods of structured exercise each week.

5.1.2. PA Comprises All Skeletal Movement whereas Exercise is Specific, Structured PA

PA and exercise are often used as interchangeable terms in media reports, and sometimes even in the research literature, although it is reasonably clear that they are not the same (Di Liegro, 2019). Exercise is a sub-division of PA that involves "planned, structured, repetitive and purposive" activity (Caspersen, 1985 at page 128) that is "voluntarily aimed at improving and/or maintaining our physical fitness" (Di Liegro, 2019 at page 2) whereas PA is all skeletal movement, whether planned or not, involving some energy expenditure (Di Liegro, 2019). Making the distinction between PA and exercise might seem a little pedantic but it can be important for distinguishing different and sometimes contradictory research findings. For example, most experimental research in laboratory or other controlled conditions involves exercise, specifically examining the effects of temporarily manipulated levels of activity (e.g. Baker, 2010; Lautenschlager, 2008). By contrast, daily PA (which may or may not include exercise) is often the measure of interest in 'free living' studies of daily activity. Occasionally, subjects in PA studies may still be instructed to undertake a specific exercise program in free living conditions (e.g., Teri, 2003) or to 'swap' one type of normal, daily activity for another (e.g., Fanning, 2017). However, findings for the beneficial effects of exercise on cognition may not generalise to daily PA, and vice versa. Also, the distinction between exercise and PA may contribute to confusion as to the best intervention for prolonging healthy cognitive ageing, i.e., 'is having a non-sedentary occupation or lifestyle better than going to the gym three times a week?'. Similarly, what type of exercise is best embedded as a daily routine, e.g., 'is lifting weights for an hour a day of equivalent cognitive benefit as, say, an hour of Tai Chi?'.

This study has not been designed to answer those difficult questions of comparative benefits. Instead it concerns measurement of all daily PA, rather than exercise, and is cross-sectional. By including a measure of *sustained* PA (see under Methods below), it may be possible to infer some indication of subjects' deliberate and purposeful activity (i.e., akin to exercise), but this is not expressly intended to represent exercise, and it has not been encouraged as part of the study. For example, such sustained PA may simply represent periods of longer, more intense PA, such as heavy-duty housework, gardening or DIY. As this is not a longitudinal study, it is

not possible to draw conclusions from these results about changes in PA over the lifespan and how any such changes may relate to changes in cognitive functioning over time. However, it is possible to examine differences in PA levels between different age groups and any associations between different activity levels and cognitive performance in those groups, in much the same way as occurred in the recent cross-sectional 'heavy versus light housework' study by Lee, 2021. Importantly, whereas Lee, 2021 relied exclusively on self-report, PA in different age groups has been assessed objectively here using accelerometer data (c.f., Hayes, 2015). Some older subjects here, for example, belong to Tai Chi and Keep Fit classes and broadly encompass a wide range of different PA and exercise behaviours and lifestyles. For this reason, this study has taken account of *all* levels of daily PA, howsoever categorised (using actigraphy) as 'light', 'moderate' or 'vigorous'. The main purpose has been to consider the relationship between PA and memory function in older and younger subjects, and specifically by reference to all levels of PA and not just those, such as moderate to vigorous PA (or MVPA) which have been traditionally measured in PA studies (see, e.g., Menai, 2017; Saint-Maurice, 2018; Kraus, 2019).

5.1.3. PA Guidelines no longer Recommend only Uninterrupted Bouts of Daily Activity

There have been some important changes in the last decade to public guidance aimed at providing advice on healthy levels of PA. The Physical Activity Guidelines for Americans (Nelson, 2007; Health & Services, 2008) made recommendations for weekly levels of moderate-intensity and or vigorous-intensity aerobic physical activity (150-300 minutes per week and 75-150 minutes per week respectively; together, 'MVPA'). However, research since 2008 has suggested that free-living PA is not necessarily performed in an uninterrupted or continuous fashion, particularly where it is undertaken occupationally, e.g., in agricultural or manufacturing jobs; (Jakicic, 2019). In addition, emerging evidence also determined that short bouts of activity of less than 10 minutes duration also secured health benefits (Menai, 2017; Saint Maurice, 2018; Jakicic, 2019). As a result, the revised American Guidelines (2018 version, Piercy, 2018) no longer specify minimum bouts of MVPA and the requirement for PA to be met effectively through planned exercise has disappeared. The current World Health Organisation Guidelines (Organisation, 2010) are similar to the American Guidelines. One recent study specifically recommended that further research should be undertaken to study the effects of light intensity PA because "studies do not contribute to an understanding of how light intensity physical activity may influence health outcomes" (Jakicic, 2019 at page 9). Recent

studies like the Lee, 2021 study into heavy and light housework are beginning to remedy this lack of research.

5.1.4. Practical Issues in Measuring PA: Subjects can easily Self-report Exercise regimes but Accurate Assessment of levels of Light PA is More Challenging, limiting the Usefulness of Self-report alone

Subjective self-assessment of PA can give quite different results from objective measures of PA (Burzynska, 2015) and this can be a limitation of PA studies using only self-report (e.g., Papenberg, 2016). Moreover, the fact that persons may meet PA guidelines in quite short bouts of activity during a day makes self-report of PA levels quite challenging. Unlike structured episodes of exercise, subjects may find it more difficult to recall or report all of the daily instances of intermittent, relatively light activity. This is borne out to some extent by the findings in the present study that, whereas subjects appear to be reasonably good judges of whether they are at one of the two extremes of the GPPA ('active' or 'inactive'), possibly because they are more easily able to recall periods of strenuous activity or exercise, more difficulty seems to arise in the intermediate categories, where a subject is assessed as only 'moderately active' or 'moderately inactive'. As described below, this appears to be a limitation of the GPPA.

'Free living' objective measures of PA are therefore increasingly using accelerometry, rather than, or in addition to self-report. Accelerometers may be used to measure all daily PA and typically allow 'activity' to be consigned into different levels: 'sedentary', 'light', 'moderate' and 'vigorous'. Determining the benefit (if any) from light PA is best undertaken in free-living conditions over the course of an entire day, because levels of light PA may vary substantially between more and less active subjects. Some research has investigated 'very modest' levels of supervised exercise or light activity (see, e.g., Suwabe, 2018) but it is not clear whether or how the results from experimental short bouts of light exercise would generalise to daily levels of more sporadic light activity. The general health benefits of light activity have been reasonably clear for some time (see, e.g., Wannamethee, 1998). However, until quite recently, health Guidelines have generally been concerned only with moderate and vigorous activity levels and, as a result, most research has also tended to focus on these levels of activity, which are generally speaking, confined to more purposeful activity or exercise and which are potentially easier to recall and measure. The present study was concerned with *all* PA levels, and in particular the less-well studied 'light' and 'light to moderate' PA levels are also objectively measured and analysed.

5.1.5. There is a Wide Range of Health Benefits to be Derived from Increasing PA levels

In an 'umbrella' review of meta-analyses, benefits to general health were found to be secured with very modest amounts of activity, with the general rule being that 'more is better than none at all' (Kraus, 2019). Regular exercise benefits a range of general health issues, including cardiovascular health, cancer, diabetes and stroke (Cotman & Engesser-Cesar, 2002). For example, moderate PA may reduce the risk of Parkinson's disease (Thacker, 2008) and may even alleviate the symptoms (Kurtais, 2008). PA Guidelines have tended to make recommendations concerning *aerobic* physical activity only but much research has also examined the potential benefits of non-aerobic exercise; for example, resistance training has also been shown to have cognitive benefits for older persons (Ozkaya, 2005; Cassilhas, 2007), although as actigraphy is based on acceleration (movement), it may not always be possible for it to detect easily such non-aerobic exercise.

The findings of positive benefits to general health from PA apply equally to cognitive health (Colcombe, 2006; Pereira, 2007; Erickson, 2009; 2010; 2011; 2012a; 2014; 2015). In an RCT, adults with probable AD who undertook supervised aerobic exercise improved cardiorespiratory fitness compared with similar adults who undertook non-aerobic exercise such as stretching and toning; higher levels of cardiorespiratory fitness were also positively associated with better performance on neuropsychological tests (including the Stroop test and Selective Reminding Test) and with larger bilateral hippocampal volume (Morris, 2017). The results in the present study tend to confirm that performance on the Stroop test is enhanced by higher levels of moderate PA.

5.1.6. Different Types of Exercise and Activity may Target Different Brain Regions and may Benefit Different Types of Cognition

In RCTs, benefits to verbal memory (as measured by the RAVLT) and spatial memory have also been found with both higher aerobic exercise and non-aerobic resistance training (Nagamatsu, 2013). These results took 6 months to manifest in a group of older women (aged 70-80), the most marked improvement being in spatial memory for the aerobic group (consistent with findings of others; e.g., Erickson, 2011). The benefits of aerobic exercise have also been shown for a younger group (M=33 years) over a shorter period of 3 months (Pereira, 2007). In that study, it was shown that aerobic exercise selectively targets the dentate gyrus in the hippocampal formation, greater cerebral blood volume of this area being correlated with higher aerobic fitness and better performance on a modified version of the RAVLT (Pereira,

2007). Elsewhere it has been shown that different types of exercise or activity may target different underlying brain regions and different cognitive functions. For example, resistance training may improve gait speed and executive functioning, as measured by the Stroop test (Liu-Ambrose, 2010). However, reviews have suggested that the evidence for a clear link between more acute exercise and better memory function is variable, particularly when measured over quite short timeframes (Roig, 2013; Loprinzi, 2018; 2019).

5.1.7. Reducing Sedentary Time in favour of More PA can also be Beneficial

Making small changes from inactive sedentary time to occasional or light activity may be beneficial, and reducing sedentary time has been shown to protect against cognitive decline (Buchman, 2012a; 2012b; Middleton, 2011). Exchanging just 30 minutes of sedentary time for sleep, light, moderate or vigorous activity can have a range of cognitive benefits in older persons, depending on what is substituted (Fanning, 2017). For example, compared with sitting still, a short 10 minute period of very light exercise on a reclining cycle machine rapidly improves hippocampal memory function (Suwabe, 2018). Non-intense running is also beneficial (Swain, 2006; Swain & Franklin, 2006).

Sedentary behaviour might be thought of simply as the opposite of PA, i.e., 'physical *inactivity*' or, all daily waking time that is not spent in light, moderate or vigorous activity. However, it is also clear that sedentary behaviour is more than just an opposite to activity and is an independent measure (Healy, 2008; Owen, 2010; Koster, 2012; Craft, 2012; Voss, 2014; Fanning, 2017). There is a complex relationship between sedentary time and PA. For example, a break of just 5 minutes per hour in sedentary time can lead to benefits in weight management (Swartz, 2011). Some research has suggested that excessive sedentary behaviour may even eliminate the benefits of higher PA levels (Hayes, 2015). In addition, recent research suggests that there may be gradients of sedentary behaviour, in which 'passive' sedentary is more harmful than 'active' sedentary behaviour (see, e.g., Hallgren, 2020; Jackson, 2019). Again, sedentary behaviour is not really measurable in laboratory or experimental settings and is best suited to being examined in free-living conditions (Diaz, 2017). However, although sedentary time has been measured here, no attempt has been made in this study to differentiate between different types of sedentary behaviour or examine whether 'excessive' sedentary behaviour may negate PA benefits in any way.

5.1.8. Regular, Moderate PA may be More Beneficial than Irregular, Intense PA

Although the evidence concerning infrequent, intense exercise is somewhat inconsistent, there is good evidence that more regular, moderate exercise or activity may be most beneficial; regular or frequent exercise taken over a prolonged period has been shown to be beneficial for cognitive function in middle age (Singh-Manoux, 2005) and in older women (Weuve, 2004). It can decrease the risk of dementia and reduce mortality rates (Iso-Markku, 2015; Friedland, 2001) and it can improve learning (Winter, 2007). It may even alleviate symptoms in those who already have MCI or dementia (Heyn, 2004; Nagamatsu, 2013).

Undertaking PA intensely but infrequently has become known as the 'weekend warrior' approach (see, e.g., Lee, 2004; Kruger & Ham, 2007; O'Donovan, 2017; Mantovani, 2020). Although studies have shown, for example, that exercise can benefit the immune system (Di Liegro, 2019), by contrast, there is some contradictory evidence that acute bouts of prolonged exercise may compromise the immune system (Kruger, 2016; Peake, 2017) because acute, rather than regular, exercise may provoke an inflammatory response (Cavalcante, 2017). Being a weekend warrior also raises the risk of physical injury (Roberts, 2014; Psoinos, 2012). Repeated exercise without adequate recovery time increases illness risk (Peake, 2017) and 'over-training' is a harmful condition known to affect athletes (Schwellnus, 2016). In short, it is possible that some types of extreme and/or irregular PA or exercise may do more harm than good, although in a study such as this, it is not possible to differentiate easily between 'extreme' and 'normal' PA or exercise levels. One specific new measure (Sustained MVPA) has been calculated in the present study as a gauge of more intense, continuous PA and this is described further in Methods.

5.1.9. Summarising the Benefits of PA and Exercise: Even Small or Modest Increases May Help

In summary, so far as benefits from PA are concerned, some fairly broad conclusions can be reached from the research literature, namely, 'something is better than nothing', 'more is better than less', and 'benefits may arise at fairly modest levels of PA'. Different types of exercise and PA may target different cognitive domains which may explain occasional contradictory results. Also, there remains the question whether different levels of PA and exercise may affect different age groups in different ways. In addition, whether there might be 'reversing benefits' for overly-intense PA or (say) exercise beyond reasonable levels (e.g. as a consequence of

inflammation, say, or a different physiological or biological response) is still largely unanswered to date.

5.1.10. In Animal Studies, Brain Structure and Function is Enhanced by Increasing Levels of Moderate Activity

The benefits of PA and exercise to brain structure and function have been studied extensively in both animals and humans. It might be thought that other animals might have a very different approach from humans to voluntary PA and exercise, but it seems that some rats will voluntarily run on a wheel as far as 20 km in one night (Cotman & Engesser-Cesar, 2002). Studies with rodents have examined the benefits of PA and exercise on brain structure and function, usually with 'voluntary wheel running' as a proxy for human aerobic exercise and 'ladder climbing' as representative of resistance training (Cassilhas, 2012; van Praag, 2005). These rodent studies have demonstrated the benefits of prolonged periods of both moderate exercise (van Praag, 1999) as well as mild activity (Inoue, 2015) on hippocampal structure and spatial memory function. Exposure to stimulating environments that encourage greater exploratory PA can lead to structural and functional changes in rodent brain regions including the hippocampus (Cotman, 2007; Cotman & Berchtold, 2007). Specifically, PA in wild-type mice living in an enriched environment increases dentate gyrus neurogeneration and improves spatial memory over a period of 11 months (Huttenrauch, 2016).

Aerobic exercise (wheel-running) and resistance exercise (ladder-climbing) benefit spatial memory in rodents by different pathways; aerobic exercise benefits brain-derived neurotrophic factor (or BDNF) and resistance exercise benefits insulin growth factor (or IGF1) respectively (Ang, 2006; Cassilhas, 2012; 2016). In 2002 it was found that, although BDNF supports the health and functioning of glutamatergic neurons, the earliest region to benefit from up-regulation of BDNF (from wheel-running) was the rat hippocampus and not, as the authors expected, motor or sensory brain regions (Cotman & Engesser-Cesar, 2002). In short, aerobic exercise promotes BDNF, and BDNF benefits memory-related areas of the brain in priority to motor areas of the brain. Over 2-7 nights, the authors found a 20% increase in BDNF in voluntary wheel-running rats compared to controls (Cotman & Engesser-Cesar, 2002). Other research has found neurogenesis in mice, but only in those that enjoyed wheel running or enriched environments and not in those who undertook swimming or swimming with learning (van Praag, 1999).

5.1.11. Human Studies have shown the Benefits of Activity and Exercise to Hippocampal Structure and Function

Animal models therefore support the view that exercise may up-regulate BDNF or other neurotrophic factors, and may attenuate cortical atrophy and improve cognitive functioning, even in aged mice (van Praag, 2005). These animal models of PA and exercise benefits to cognitive health help to inform human studies (Voss, 2013). Human studies equivalent to those in rodents (e.g. Huttenrauch, 2016) have shown that moderate exercise over a prolonged period is beneficial for the hippocampus (Erickson, 2011; Colcombe, 2006) and for the dentate gyrus (Pereira, 2007). Aerobic exercise increases BDNF which in turn ameliorates hippocampal atrophy (Eriksson, 1998; Erickson, 2012b) and improves memory function and performance on neuropsychological tests (Kramer, 1999; Laurin, 2001; Erickson, 2012b). Aerobic exercise has been shown to be particularly beneficial for episodic memory (Smith, 2010). The benefit afforded by high PA has also been linked to positive white and grey matter changes, as well as to better brain function and connectivity (Bherer, 2013; Hayes, 2013).

PA reduces hippocampal atrophy in persons with higher genetic risk of AD (Smith, 2014). An association has also been found between more PA and slower loss of brain volume in medial parietal and temporal regions (including entorhinal cortex) as well as the insula and lateral temporal region (Rabin, 2019). In a study using fMRI, it has recently been shown that the benefit of short periods of light activity was very specific to the hippocampal sub-regions, entorhinal and parahippocampal cortices, while perirhinal cortex, temporal pole and amygdala were all unaffected (Suwabe, 2018). PA may not just attenuate atrophy, but may actually induce neurogenesis in the hippocampus (Eriksson, 1998; Erickson, 2011; 2012a).

The mechanisms that have been advanced as responsible for these PA-mediated changes, principally in hippocampal structure and connectivity, are varied and include up-regulation of BDNF, discussed above, (Huttenrauch, 2016), and specifically hippocampal BDNF (Johnson, 2003), heightened cerebral blood flow (Coelho, 2014), and reduced inflammation (Papenberg, 2016). PA is an effective, natural anti-inflammatory strategy (Pedersen, 2017). It has been shown that the pre-frontal cortex (PFC) and hippocampus are especially susceptible to inflammation (A. Lim, 2013) and fit and active adults may be less prone to inflammation than sedentary persons (Shanely, 2013). High levels of inflammation in a physically inactive group may account for smaller PFC and hippocampal volumes (Papenberg, 2016).

5.1.12. Different Explanations have been given for the Hippocampal Benefits of PA and Exercise

BDNF remains a frequently-advanced mechanism for benefits of physical exercise and activity in human brain structure and function (Dinoff, 2017) although, as in rodents (see above), strength or resistance training may not improve human BDNF levels (Goekint, 2010). Aerobic fitness and capacity both correlate with brain size and exercise enhances BDNF (Hill & Polk, 2019). BDNF is important to memory by encouraging hippocampal dendritic, synaptic and neuronal formation (Waterhouse, 2012).

Other explanations for PA benefits to brain structure and function include various feedback mechanisms. For example, it has been suggested that dopamine may be necessary to 'prime the physical activity pump' but, once that occurs, PA can become self-sustaining by promoting dopamine release (Di Liegro, 2019). Intense exercise becomes rewarding, providing for a virtuous feedback circle (Brene, 2007). In rodent studies, mice with high wheel running (the murine equivalent of human aerobic exercise; Eikelboom, 1999) enjoyed a 20% increase in dopamine receptors in the hippocampus compared with controls (Bronikowski, 2004). In addition to the dopaminergic hypothesis, others have suggested the existence of another feedback system between PA and the executive function areas of the brain which may subserve self-regulation, i.e., creating a 'virtuous feedback loop' between choosing PA over, say, watching TV (Daly, 2015; Voss, 2011).

The hippocampal region is not normally a brain region strongly implicated in dopamine-related motivation and reward systems (Bethus, 2010; Knab & Lightfoot, 2010) and activation of the dopaminergic system is usually regarded as the result, rather than the cause, of exercise, i.e., the dependent rather than independent variable (Knab & Lightfoot, 2010). However, if exercise improves hippocampal function (Bronikowski, 2004; Erickson, 2011), an important mediating factor in the benefit of PA to the human hippocampus could be the exercise/PA priming dopaminergic system (Knab & Lightfoot, 2010). This system may reinforce the learning that 'exercise is good' (Wise, 2004) and may effect changes in the dopaminergic system itself (e.g. increase BDNF) that promote the 'wanting' of exercise. It has even been suggested that the decline in PA levels seen in older age may be attributable therefore, at least to some extent, to the natural decline in dopaminergic system functioning in normal ageing (Roth & Joseph, 1994). This dopaminergic-hippocampal hypothesis is potentially relevant to the results in this study which tend to show that more positive psychological mood is associated with higher levels of PA; see further below.

5.1.13. The Effects of Ageing: Physical Activity and Exercise (Engagement and Duration) may Continue into Older Age, although Performance Declines from about age 50

In a large cross-sectional study of 775 adults (ages 30-90+), levels of PA (measured using actigraphy) were compared with measures of physical performance, namely mobility, strength, endurance and balance, across 10 year age groups (Hall, 2017). It was found that strong decline in physical *performance* was evident in the 50s age group but PA *levels* only decreased rapidly in later age groups (60s+). Higher PA levels were associated with better physical performance. There is evidence therefore that PA levels and PA performance are closely connected in healthy ageing. Although physical performance has not been directly measured in this study, subjects have self-assessed their physical functioning, and specifically any physical limitations on performance of their daily activities, using the SF-36 Short Form Health Assessment (the 'SF-36', Ware Jr & Sherbourne, 1992). Responses to the SF-36 in the present study tend to confirm the earlier findings in Hall, 2017 that higher physical functioning (and fewer limitations on physical performance) is associated with higher levels of PA across age groups.

Many of the studies into the beneficial effects of PA and exercise on cognition have been concerned with older subjects (Colcombe & Kramer, 2003). This is perhaps unsurprising insofar as ageing and declining cognitive function are so closely associated; it is therefore relatively straightforward to examine potential candidate activities (e.g., everyday PA or exercise regimes) for arresting that decline. However, the extent to which similar benefits from PA or exercise may also be derived by younger subjects is less clear (Hayes, 2016; Prakash, 2015), although it has been recommended that encouraging younger subjects to maximise PA levels may have later-life benefits for physical performance (Hall, 2017). There is, for example, much less research on the benefits of exercise to memory function in younger adults (Loprinzi, 2018). One reason advanced for why younger subjects may show lower cognitive benefits from PA and/or exercise is that they may be at relatively peak level neural performance and brain structural and functional integrity (Hayes, 2015). An alternative view is that cognitive decline may begin at a comparatively young age (Salthouse, 2009) and, if so, the absence of evidence for benefits of PA in younger subjects is then harder to explain. In the present study, there is evidence to suggest that the association between PA and cognitive performance does not conform to the same pattern that applies for older subjects.

5.1.14. The Cognitive Benefits of Increasing PA may be More Easily Discernible in Older Subjects than Younger Subjects

Hayes, 2015 found that higher PA (accelerometer measured daily step count) benefited a hippocampal task combining visual episodic memory and face name memory in older subjects (N=31, M=64.5 years) but *not* in younger subjects (N=29, M=21 years). In verbal episodic memory, younger subjects out-performed older subjects, but this was unaffected by PA level (step count). This study is important because although earlier studies (e.g. Barnes, 2008; Brown, 2012) had demonstrated PA benefits to executive functioning, this was the first to show PA benefits to episodic memory, possibly (the authors suggested) because previous research was concerned with tests that were insufficiently hippocampal-oriented (Hayes, 2015). (The authors also suggested that their *verbal* episodic memory tests may have been inherently semantic and less hippocampal-oriented.) The Hayes, 2015 study was also the first to show the independent disbenefit of greater sedentary time (posited by Voss, 2014). In other words, it is possible that higher levels of sedentary behaviour may actually outweigh higher levels of PA, or eliminate some benefits of short periods of acute exercise (Craft, 2012).

As well as age group differences in the benefits to be derived from PA and/or exercise, it is also possible that gender (or biological sex) may have an impact. Hall, 2017 found that men had higher PA and higher physical performance levels than women, but the pattern of male and female decline across age groups was very similar. Gender differences in episodic memory performance have been reported for some time (see, e.g. Herlitz, 1997), but it is not until quite recently that the effects of gender in acute exercise benefits for young persons in episodic memory have been investigated (Johnson & Loprinzi, 2019). It was found that young females (N=20, M=21 years) out-performed young males (N=20, M=21 years) in verbal episodic memory (using the RAVLT as the assessment measure) and that females only had higher performance levels after exercise.

5.1.15. Hypotheses

This is not a longitudinal study and it was not therefore possible to measure whether PA levels decline over the lifespan. However, it was expected that the older age group may show lower levels of PA generally than the younger age group.

It was expected that more ‘hippocampal-based’ memory tests would show stronger associations between higher activity levels and better performance than less ‘hippocampal based’ memory tests (Hayes, 2015). Accordingly, benefits of higher PA were expected to be seen in VEM Short

Term Recall, VEM Long Term Forgetting and Working Memory, rather than in Face Memory & Perception.

It was hypothesised that some benefits may arise for older subjects with relatively low levels of activity (Lee, 2021).

As many previous studies on the cognitive benefits of PA have involved older subjects, it was unclear whether similar benefits to memory from PA and exercise would also be seen with younger subjects.

Although it is not intended to represent exercise directly, a measure of 'sustained MVPA' was calculated (see Methods below). It was anticipated that persons with higher levels of sustained MVPA may show better memory domain performance, in line with those studies that have linked higher exercise with better memory.

5.2. METHODS

5.2.1. Actigraphy has been Used to Determine Activity Levels of Subjects

Details of the accelerometer devices worn by subjects are provided in Chapter 2 (section 2.4.1) above. This explains how the devices provide details of daily activity in four baskets: (1) sedentary time (2) light activity (3) moderate activity and (4) vigorous activity. It is relatively common for moderate and vigorous activity to be reported together as 'moderate to vigorous physical activity' or MVPA (see, e.g., Menai, 2017; Saint-Maurice, 2018; Kraus, 2019). MVPA is shown as a composite calculation in these results alongside moderate and vigorous PA levels separately. In addition, as the present study is concerned with analysing 'lower' levels of activity, a composite calculation of 'light to moderate physical activity' or LMPA is also shown, along with a composite calculation of all physical activity other than sedentary time, namely 'light, moderate and vigorous physical activity' or LMVPA.

5.2.2. Sustained Moderate to Vigorous Physical Activity (Sustained MVPA) has been Calculated Separately

As explained above, 'MVPA' is the aggregate of all moderate and vigorous PA and is at the more intense level of the PA spectrum; pre-2008 Guidelines specified minimum levels of MVPA that generally had to be met in sustained 'bouts' of activity, i.e., akin to structured or planned exercise. In the present study, '*Sustained* MVPA' has been calculated by counting only those daily periods of at least ten minutes where moderate or vigorous PA is uninterrupted, i.e., where a spell of moderate and/or vigorous activity lasts at least ten minutes and is not interrupted by any period (counted in complete minutes) of light or sedentary activity. Although it is not intended to be directly representative of exercise, sustained MVPA would be expected to capture bouts of purposeful exercise (whether sporting or purely recreational) better than any of the individual activity levels alone.

5.2.3. Self-assessment of PA Levels and Physical Functioning

As described above, subjects in this study have also self-assessed their own activity levels in the GPPA Questionnaire (Physical Activity Policy, 2009). This is useful as independent corroboration of subjects' device-measured activity levels.

5.3. RESULTS

Associations between the different levels of PA are shown in Supplementary Table 5.1. These show very predictably (e.g.) that higher light, moderate and vigorous PA levels are correlated with lower sedentary time. These correlations are unremarkable and are included therefore only as supplementary information.

*5.3.1. **Expected Finding:** Older Subjects have Higher levels of Light PA and Younger Subjects have Higher levels of Vigorous PA*

Table 5.1: Correlations between Age and BMI and Physical Activity (PA) Levels

Physical Activity (PA) Level (in average daily minutes)	Age		BMI		Age		BMI	
	r	p	r	p	r_s	p	r_s	p
Light (L) PA	.216	.009	-.073	.38	.203	.014	-.069	.41
Moderate (M) PA	-.102	.22	-.148	.077	-.102	.22	-.076	.36
Vigorous (V) PA	-.160	.05	-.025	.76	-.297	<.001	-.080	.34
MVPA	-.114	.17	-.143	.086	-.110	.19	-.079	.34
Sustained MVPA	-.073	.38	-.079	.35	-.097	.25	-.065	.44
LMPA	-.003	.97	-.146	.08	.009	.92	-.078	.35
LMVPA	-.016	.84	-.144	.084	-.005	.95	-.073	.38
Sedentary Time	.015	.86	.177	.033	-.008	.92	.184	.027

Table 5.1: Correlations between Age and BMI and Physical Activity levels. The only association between age and activity level is for higher light activity with older age; Pearson's r=.216, p=.009; Spearman's r_s=.203, p=.014. Older age is marginally associated with lower amounts of vigorous activity; Pearson's r=-.160, p=.054; Spearman's r_s=-.297, p<.001. These associations are reflected in the age group comparisons in Table 5.2. In addition, higher BMI is (perhaps unsurprisingly) moderately associated with higher daily sedentary time; Pearson's r=.177, p=.033; Spearman's r_s=.184, p=.027. Orange shading denotes significant correlations.

Table 5.1 shows simple correlations between activity levels and both age and BMI. There is a positive association between higher levels of light PA and older age (Pearson's r=.216, p=.009; Spearman's r_s =.203, p=.014); see Figure 5.1. There is also a marginal association between younger age higher vigorous activity (Pearson's r=-.160, p=.054; Spearman's r_s=-.297, p<.001). It should not be assumed that older subjects are simply swapping daily vigorous PA for light PA because the average daily amounts of time spent in these activities are very

different (light PA: M=105 mins, SD=30 mins; vigorous PA: M=5 mins, SD=7 mins). Instead, it suggests that, with increasing age it is easier to maintain (or even increase) levels of light PA, and harder to maintain levels of vigorous PA (although there is no difference between the two main age groups in daily levels of vigorous PA; see Table 5.2). Also, as may be reasonably expected, higher sedentary time is associated with higher BMI (Pearson's r=.177, p=.033, Spearman's r_s=.184, p=.027).

Figure 5.1: Maintaining levels of Light PA in Older Age

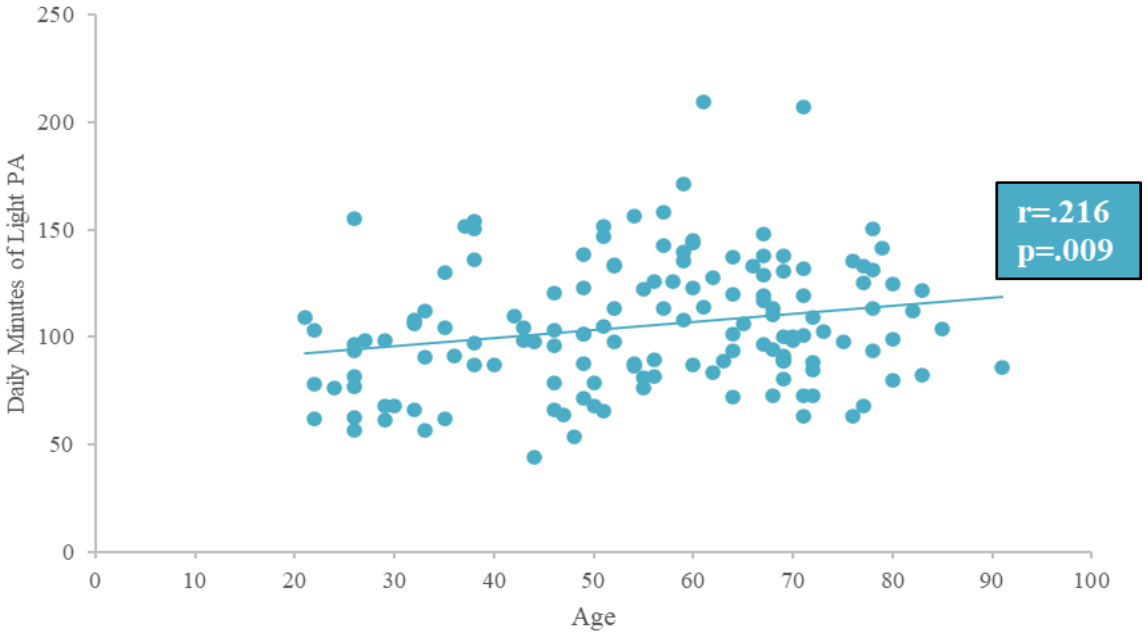


Figure 5.1 illustrates the correlation between older age and higher levels of light PA. This is not replicated or matched by a comparative decline in any other physical activity levels, suggesting perhaps that it is easier to maintain, and even increase, levels of light PA in older age, compared with other levels of PA.

Overall, age does not appear to be associated with any general decline in aggregate levels of all PA (LMVPA) or with any general increase in sedentary time (see Figure 5.2) although it should be noted that the reasons for, and type of, sedentary behaviour may well differ between the younger and older groups.

Table 5.2: Differences between the main Age Groups in Physical Activity Levels

Physical Activity (PA) Level (in average daily minutes)	Younger (N=52)	Older (N=93)	t	p
Light (L) PA	94	111	-3.435	.001
Moderate (M) PA	164	162	.567	.88
Vigorous (V) PA	6	4	1.732	.085
MVPA	170	166	.303	.762
Sustained MVPA	55	52	.435	.66
LMPA	258	273	-1.100	.27
LMVPA	264	277	-.928	.35
Sedentary Time	658	654	.305	.76

Table 5.2: Differences between the main younger (N=52) and older (N=93) age groups in physical activity levels. Apart from light PA, there are no significant differences between the main younger and older age groups in physical activity levels, including sedentary time. Older subjects have significantly higher levels of light activity than younger subjects; t_{143}=-3.435, p=.001, Cohen's d=0.57. Orange shading shows significant results.

Figure 5.2: Sedentary Time and LMVPA are both fairly stable with Older Age

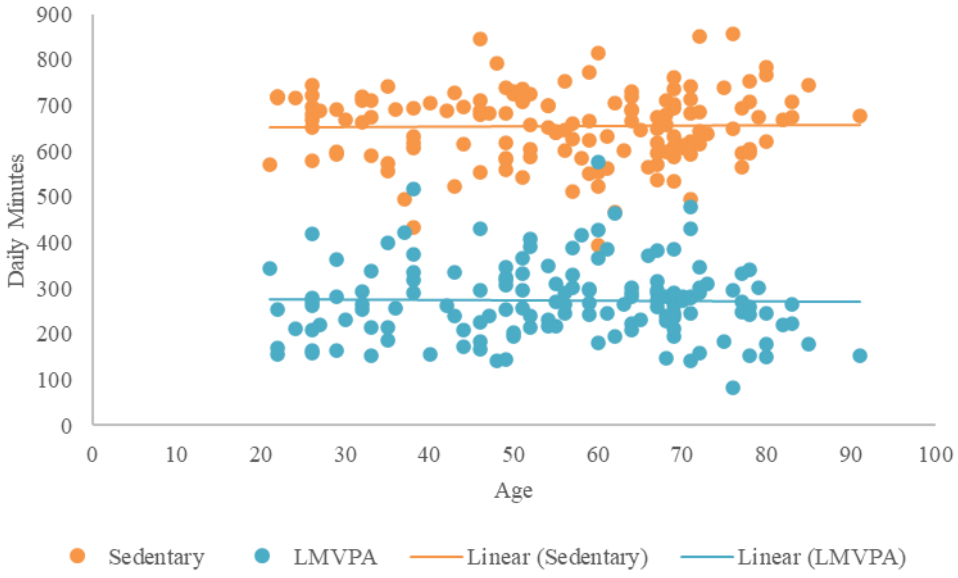


Figure 5.2: Analysis of Sedentary Time and LMVPA by Age: Across the agespan, daily sedentary time generally remains higher than the aggregate of all daily physical activity levels, light, moderate and vigorous (or LMVPA). However, there is no association between older age and either any increase in sedentary time or any reduction in the aggregate of all physical activity (LMVPA).

Comparing the main younger and older age groups, older subjects have higher levels of light activity than younger subjects (t_{143}=-3.435, p=.001, Cohen's d=0.57); see Table 5.2. There are no other differences between the two age groups including, notably, sedentary time and sustained MVPA. There is no difference in total daily 'waking activity' of younger and older subjects (i.e. sedentary time plus all physical activity, or LMVPA); younger=922 mins (SD=51 mins), older=931 mins (SD=56 mins), t_{143}=-.978, p=.33. As was seen in Chapter 3, older and younger subjects do not differ in bed duration (older: M=497 mins, SD=46 mins; younger: M=506 mins, SD=46 mins; t_{143}=1.148, p=.25). Both younger and older subjects have average days of 1428 minutes. There is no single difference in PA, sedentary time, or bed duration that therefore itself explains the 17 minute daily difference in light PA between older and younger subjects.

5.3.2. ***Replicated Finding:*** *Physical Activity Levels appear to be Maintained into Older Age*

Further exploratory analysis was undertaken to determine how the change in light PA develops by examining changes in PA in four detailed age groups. Figure 5.3 shows the change in three activity levels, light, moderate and all PA (LMVPA) across four detailed age groups. There is a general increase in light PA with each successively older age group, except between Group 3 (51-65) and Group 4 (66+) where there is a non-significant reduction in light activity (p=.11). The increases in light PA are otherwise statistically significant between Group 1 (18-35) and Group 3 (51-65) (t_{64}=-4149, p=.0001, Cohen's d=1.04) between Group 1 and Group 4 (t_{75}=-3.153, p=.002, Cohen's d=0.73) and between Group 2 (36-50) and Group 3 (t_{66}=-2.554, p=.013, Cohen's d=0.63).

There is also a reduction in moderate PA between Group 3 (51-65) and Group 4 (66+); t_{89}=2.177, p=.032, Cohen's d=0.46. However, Group 4 does not have lower levels of moderate PA compared with either Group 1 (18-35; p=.73) or Group 2 (36-50; p=.22). The difference in moderate PA between Groups 3 and 4 appears to be driven by a 10-15 minute increase in moderate PA across Groups 1, 2 and 3, followed by a substantial 30 minute fall in moderate PA in the oldest age group (Group 4, 66+).

The decline in moderate PA is not explained by a corresponding increase in light PA across the detailed age groups. Light PA follows the same general trend as moderate PA, increasing across Groups 1 to 3, before falling back (albeit non-significantly) in Group 4 compared with Group 3. This general trend is also emphasised by the differences in the aggregate of all PA levels, light, moderate and vigorous (or LMVPA) across the four age groups. Group 3's LMVPA is

significantly higher when compared to both the youngest group, Group 1 (18-35; t_{64}=-2.607, p=.011, Cohen's d=0.65) and the oldest group, Group 4 (66+; t_{89}=2.411, p=.018, Cohen's d=0.51). These findings appear consistent with findings elsewhere which suggest that, while physical activity *performance* declines from about age 50, physical activity *levels* do not decline until after 65 (Hall, 2017).

Figure 5.3: Comparison of Light, Moderate and Aggregate (LMVPA) Physical Activity Levels in Detailed Age Groups (in average daily minutes)

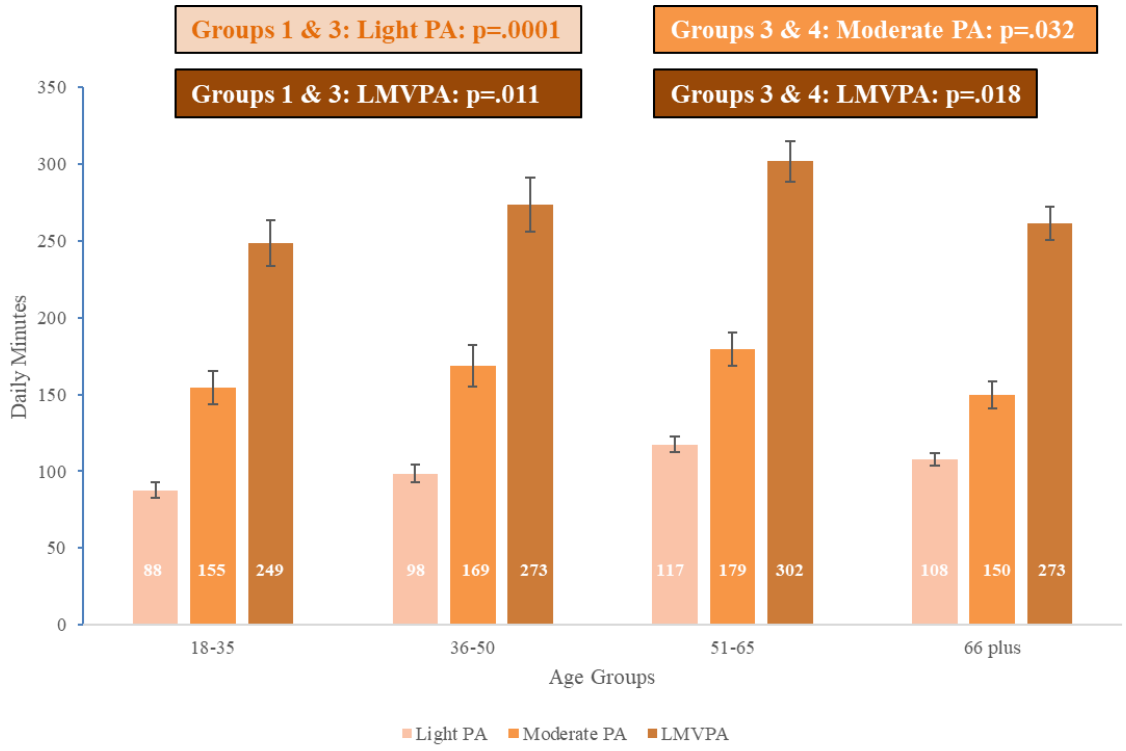


Figure 5.3 compares average daily minutes of light PA, moderate PA and the aggregate of all activity levels (or LMVPA) across four detailed age groups; Group 1=18-35 years, Group 2=36-50 years, Group 3=51-65 and Group 4=66 plus. In line with findings elsewhere, physical activity levels do not appear to decline in the 51-65 age group (although physical *performance* may well decline from age 50); Group 4 has significantly lower moderate PA (p=.032) and lower LMVPA than Group 3. Group 3 also has significantly higher LMVPA than Group 1 (p=.011). There is a slight (non-significant) falling back of light PA in Group 4 compared with Group 3, but otherwise the general trend is for an increase in light PA across the detailed age groups. Group 4 has higher light PA than Group 1 (p=.002) and Group 3 has higher light PA than Group 2 (p=.013). Error bars show +/- one s.e.m. See text for further details.

5.3.3. ***Extended Finding:*** *Females have Higher levels of Light PA than Males but this is not the case in Older Subjects*

There are no differences between males and females in levels of moderate or vigorous PA or in MVPA, LMPA, LMVPA, sustained MVPA or sedentary time. However, females have marginally significant higher levels of light PA (N=99, M=108.28 mins, SD=30.44 mins) than males (N=46, M=97.92 mins, SD=27.15 mins); t_{143}=-1.972, p=.051, Cohen's d=0.33.

Using two-way ANOVA to analyse any interaction between age group (younger/older) and gender in the levels of light PA, for the main effect of age group, $F_{1,141}$=12.352, p=.001, η^2_p=.081, there is a significant difference between the older and younger groups in the levels of light activity; older subjects undertake more light activity. For the main effect of gender, $F_{1,141}$=4.907, p=.028, η^2_p=.034, there is a significant effect of gender on levels of light activity; i.e. females undertake more light PA. For the interaction between age group and gender, $F_{1,141}$=.509, p=.48, η^2_p=.004, this is not significant, and therefore overall, there is no interaction between age group and gender on mean levels of light activity.

Examining the younger and older age groups separately, in the younger group, females (still) have marginally higher levels of light activity than males (males=83.3 mins, SD=23.57 mins, females=98.83 mins, SD=28.2 mins); t_{50}=-1.921, p=.060, Cohen's d=0.54. However, in the older group, there is no difference between males and females in the levels of light activity (males=105.72 mins, SD=25.99 mins, females=113.68 mins, SD=30.56 mins); t_{91}=-1.230, p=.22. There is therefore no support for a hypothesis that generational gender differences in housekeeping responsibilities may underlie higher levels of light activity in females. Whilst older subjects have higher light activity than younger subjects and females tend to have higher light activity than males, older females do not have higher levels of light PA than older males and, in fact, this gender difference is more apparent in the younger group.

5.3.4. Physical Activity Levels: Associations with Memory Domain Performance

Table 5.3 shows Pearson's r correlations between memory-domain performance and some of the underlying PA levels measured by the devices.

Table 5.3: Correlations between PA levels and PCA factor Memory Domain Performance

Physical Activity (PA) Level	VEM Short Term Recall		Face Memory & Perception		VEM Long Term Forgetting		Working Memory	
	r	p	r	p	r	p	r	p
Light (L) PA	-.044	.60	.038	.65	.046	.58	-.054	.52
Moderate (M) PA	-.148	.08	.107	.20	.036	.67	.208	.012
Vigorous (V) PA	.027	.75	-.004	.96	-.076	.36	.109	.19
MVPA	-.139	.10	.101	.23	.027	.74	.209	.012
Sustained MVPA	-.226	.006	.065	.44	-.035	.67	.156	.06
LMPA	-.135	.10	.100	.23	.046	.58	.148	.07
LMVPA	-.130	.12	.097	.24	.038	.65	.153	.07
Sedentary Time	.106	.20	-.077	.35	-.004	.96	-.144	.08
	r_s	p	r_s	p	r_s	p	r_s	p
Light (L) PA	-.059	.48	.030	.72	.034	.68	-.087	.30
Moderate (M) PA	-.163	.05	.094	.26	.095	.25	.132	.11
Vigorous (V) PA	.064	.44	.094	.26	-.012	.88	.172	.039
MVPA	-.153	.07	.084	.31	.091	.28	.136	.10
Sustained MVPA	-.229	.006	.089	.28	.074	.38	.158	.06
LMPA	-.142	.09	.087	.30	.070	.40	.048	.56
LMVPA	-.138	.10	-.084	.31	.065	.44	.056	.50
Sedentary Time	.120	.15	-.031	.71	-.004	.96	-.082	.32

Table 5.3 shows Pearson's r and Spearman's r_s correlations between PA levels and memory domain performance (N=145). Higher moderate PA is associated with better Working Memory performance (Pearson's r=.208, p=.012), as is higher MVPA (Pearson's r=.208, p=.012). There are some marginal associations between higher levels of different PA levels (but not light or vigorous PA) and better Working Memory. For all subjects, higher sustained MVPA is associated with *lower* VEM Short Term Recall (Pearson's r=-.226, p=.006). However, marginal correlations between higher sustained MVPA and better Working Memory suggest that more vigorous sustained PA may work in the opposite direction in that memory domain. This is illustrated in Figure 5.4 below. Orange shading shows significant results.

Figure 5.4: Sustained MVPA appears to have a negative relationship with VEM Short Term Recall but a marginally positive relationship with Working Memory

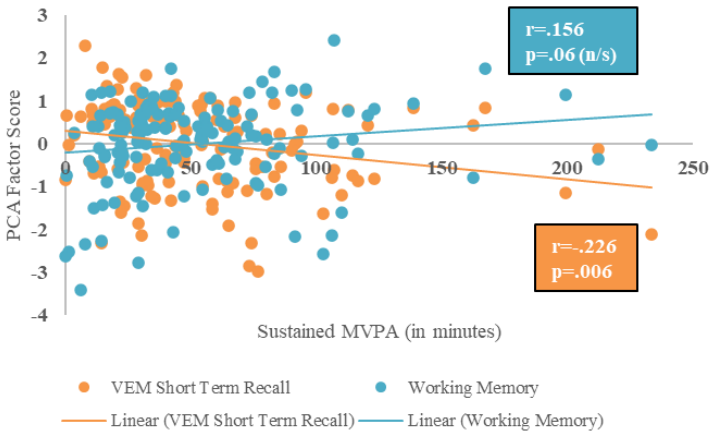


Figure 5.4 contrasts the relationship between higher sustained MVPA and lower VEM Short Term Recall (Pearson's r=-.226, p=.006; Spearman's r_s=-.229, p=.006) with the marginal but very different relationship between higher sustained MVPA and better Working Memory (Pearson's r=.156, p=.06; Spearman's r_s=.158, p=.06). The 'reverse effect' in the relationship of sustained MVPA to Working Memory is supported by the significant correlations between higher moderate PA and higher MVPA with better Working Memory shown in Table 5.3.

There are two main observations to make. First, across all subjects, there is no evidence of any simple correlation between any activity level (higher or lower) and any better performance in either Face Memory & Perception or VEM Long Term Forgetting.

Second, there is evidence of a relationship between PA levels and both VEM Short Term Recall and Working Memory PCA factors, but the relationships appear to be *in opposite directions.* There is some modest evidence that higher amounts of moderate activity (in both the moderate and MVPA categories) are associated with *better* Working Memory (Pearson's r=.208, p=.012 and Pearson's r=.209, p=.012 respectively, although Spearman's non-parametric correlations are non-significant; see Table 5.3). On the other hand, higher amounts of sustained MVPA are strongly associated with *lower* VEM Short Term Recall (Pearson's r=-.226, p=.006, Spearman's r_s=-.229, p=.006). This does not appear to be an anomaly attributable to the methodology for calculating sustained MVPA because there is some evidence that the trend for higher moderate activity and better Working Memory also extends to higher sustained MVPA and better Working Memory; see Figure 5.4.

5.3.5. ***Unexpected Finding:*** *Lower PA and better VEM Short Term Recall Applies Only to Younger Subjects*

Detailed exploratory analysis was undertaken to examine this discrepancy by comparing correlations in VEM Short Term Recall and Working Memory separately in the younger and older age groups; see Table 5.4. This detailed analysis reveals a number of interesting results. First, the negative correlation between lower PA and better VEM Short Term Recall applies only in the younger group and not in the older group. However, a negative trend in the older group for higher sustained MVPA and lower VEM Short Term Recall (Pearson's r=-.176, p=.09) is consistent with the negative correlations in the younger group and contributes to the negative correlation between higher sustained MVPA and lower VEM Short Term Recall in all subjects (see Table 5.3 and Figure 5.4). Second, the negative correlation in the younger group extends beyond sustained MVPA (seen for all subjects in Table 5.3) and applies to all activity levels, including sedentary time (although it is noticeable that Spearman's non-parametric correlations are not significant). Third, the positive correlation between higher levels of PA and better Working Memory is seen in both the younger and older groups. Fourth, and perhaps most interesting, the *levels* of PA that are associated with higher Working Memory performance appear to be different in younger and older subjects.

Table 5.4: Comparing Correlations between PA levels and VEM Short Term Recall and Working Memory in Older and Younger Subjects

Physical Activity (PA) Level	VEM Short Term Recall (Older Subjects N=93)		VEM Short Term Recall (Younger Subjects N=52)		Working Memory Older Subjects N=93)		Working Memory (Younger Subjects N=52)	
	r	p	r	p	r	p	r	p
Light (L) PA	.158	.13	-.303	.029	.100	.34	-.093	.51
Moderate (M) PA	-.038	.72	-.425	.002	.233	.025	.191	.17
Vigorous (V) PA	-.049	.64	.082	.57	-.036	.73	.320	.02
MVPA	-.041	.70	-.399	.003	.218	.036	.217	.12
Sustained MVPA	-.176	.09	-.385	.005	.109	.30	.278	.046
LMPA	.027	.80	-.427	.002	.232	.026	.117	.41
LMVPA	.022	.83	-.412	.002	.221	.033	.141	.32
Sedentary Time	-.030	.78	.419	.002	-.131	.21	-.265	.058
Physical Activity (PA) Level	r_s	p	r_s	p	r_s	p	r_s	p
Light (L) PA	.168	.11	-.203	.15	.062	.55	-.049	.73
Moderate (M) PA	-.087	.41	-.241	.09	.137	.19	.189	.18
Vigorous (V) PA	-.028	.79	.110	.44	.070	.50	.210	.13
MVPA	-.091	.38	-.224	.11	.118	.26	.208	.14
Sustained MVPA	-.190	.07	-.264	.06	.100	.34	.277	.046
LMPA	-.016	.88	-.233	.10	.106	.31	.141	.32
LMVPA	-.017	.87	-.222	.11	.091	.38	.160	.26
Sedentary Time	-.006	.96	.215	.13	-.049	.64	-.294	.034

Table 5.4 shows Pearson's r and Spearman's r_s correlations between PA levels and performance in VEM Short Term Recall and Working Memory analysed separately for older subjects (N=93) and younger subjects (N=52). For VEM Short Term Recall, Pearson's correlations show a pattern of lower activity levels being associated with higher VEM Short Term Recall in younger subjects. This pattern is not repeated in older subjects or in Spearman's r_s correlations for younger subjects. For Working Memory, both older and younger subjects show some pattern of moderate association between higher activity and better Working Memory in Pearson's correlations, but the pattern of moderate associations is slightly different for each age group. For older subjects, more *moderate* levels of activity are associated with better Working Memory, whereas for younger subjects more *vigorous and sustained* MVPA is associated with better Working Memory. In Spearman's r_s non parametric correlations, this pattern of moderate associations is only apparent in younger subjects. Orange shading shows significant results.

*5.3.6. **Main New Finding:** Better Working Memory is associated with Higher Moderate PA in Older Subjects and with Higher levels of More Vigorous PA in Younger Subjects*

Table 5.4 shows that, for older subjects, better Working Memory is associated with higher levels of moderate activity (Pearson's r=.233, p=.025). There are also positive associations between higher Working Memory performance and higher aggregate activity levels which include moderate PA (MVPA, LMPA and LMVPA), but not for vigorous PA or sustained MVPA (or indeed light activity). This suggests that, for older subjects, the beneficial

association between higher levels of PA and better Working Memory is restricted to more moderate levels of PA.

By contrast, Table 5.4 also shows that, for younger persons, better Working Memory is associated with higher levels of vigorous PA (Pearson's r=.320, p=.02) and, because average daily levels of vigorous PA are low, more importantly, with higher levels of sustained MVPA (Pearson's r=.278, p=.046, Spearman's r_s=.277, p=.046). The contrast is not just with how more moderate PA in older subjects is associated with better Working Memory, but can also be made with the negative correlation between higher sustained MVPA and *lower* VEM Short Term Recall in younger subjects (Pearson's r=-.385, p=.005, Spearman's r_s=-.264, p=.06). The result is an apparent dissociation in younger subjects in the relationship between higher sustained MVPA and lower VEM Short Term Recall but higher Working Memory.

5.3.7. ***Unexpected Finding:*** *Higher Sustained MVPA and Younger Age predict worse VEM Short Term Recall;* ***Expected Finding:*** *Higher Moderate PA, Younger Age and Higher Education predict better Working Memory*

If the trend in results in Table 5.4 is taken into account, a broader dissociation may be advanced for all subjects which is consistent with the results shown in Table 5.3, namely that, for all subjects, higher *sustained moderate* and vigorous PA is associated with *worse* VEM Short Term Recall, whereas higher daily *moderate* PA is associated with *better* Working Memory. This more broadly-framed dissociation is borne out by the linear regression models shown in Table 5.5 and Figure 5.5.

Table 5.5 shows that lower age and some *lower* activity levels together predict better VEM Short Term Recall, whereas lower age, higher education and some *higher* activity levels together predict better Working Memory performance. There are no activity levels which, together with lower age, predict better performance in Face Memory & Perception, and there are no activity levels which, together with lower/better PSQI score (see Chapter 3), predict lower/better VEM Long Term Forgetting.

For VEM Short Term Recall, Table 5.5 shows that, as well as lower age, better performance is also predicted by (separately) lower moderate activity (β=-.176, p=.029), lower MVPA (β=-.171, p=.035) and, most strongly, by lower sustained MVPA (β=-.281, p=.002). Better performance is not co-predicted by lower light or vigorous activity, lower LMPA, lower LMVPA or by higher sedentary time. This suggests that better VEM Short Term Recall is

associated with lower age *and lower levels of more intense activity (perhaps comparable to hard exercise).*

Table 5.5: Regression Models for VEM Short Term Recall and Working Memory: Younger Age and Lower Activity Levels predict better VEM Short Term Recall. Younger Age, Higher Education and Higher Activity Levels predict better Working Memory

Memory Domain	R	RSq	Age (β)	Age (p)	PA Level	PA (β)	PA (p)
VEM Short Term Recall	.316	.100	-.281	.001	Moderate	-.176	.029
VEM Short Term Recall	.313	.098	-.282	.001	MVPA	-.171	.035
VEM Short Term Recall	.360	.129	-.281	<.001	Sustained MVPA	-.247	.002

Memory Domain	R	RSq	Age (β)	Age (p)	Edu. (β)	Edu. (p)	PA Level	PA (β)	PA (p)
Working Memory	.600	.360	-.379	<.0001	.336	<.0001	Moderate	.177	.012
Working Memory	.599	.359	-.377	<.0001	.337	<.0001	MVPA	.175	.013
Working Memory	.593	.351	-.401	<.0001	.325	<.0001	LMPA	.148	.034
Working Memory	.593	.352	-.399	<.0001	.327	<.0001	LMVPA	.150	.033
Working Memory	.591	.350	-.397	<.0001	.332	<.0001	Sedentary	-.143	.043
Working Memory	.590	.348	-.388	<.0001	.331	<.0001	Sustained MVPA	.136	.053

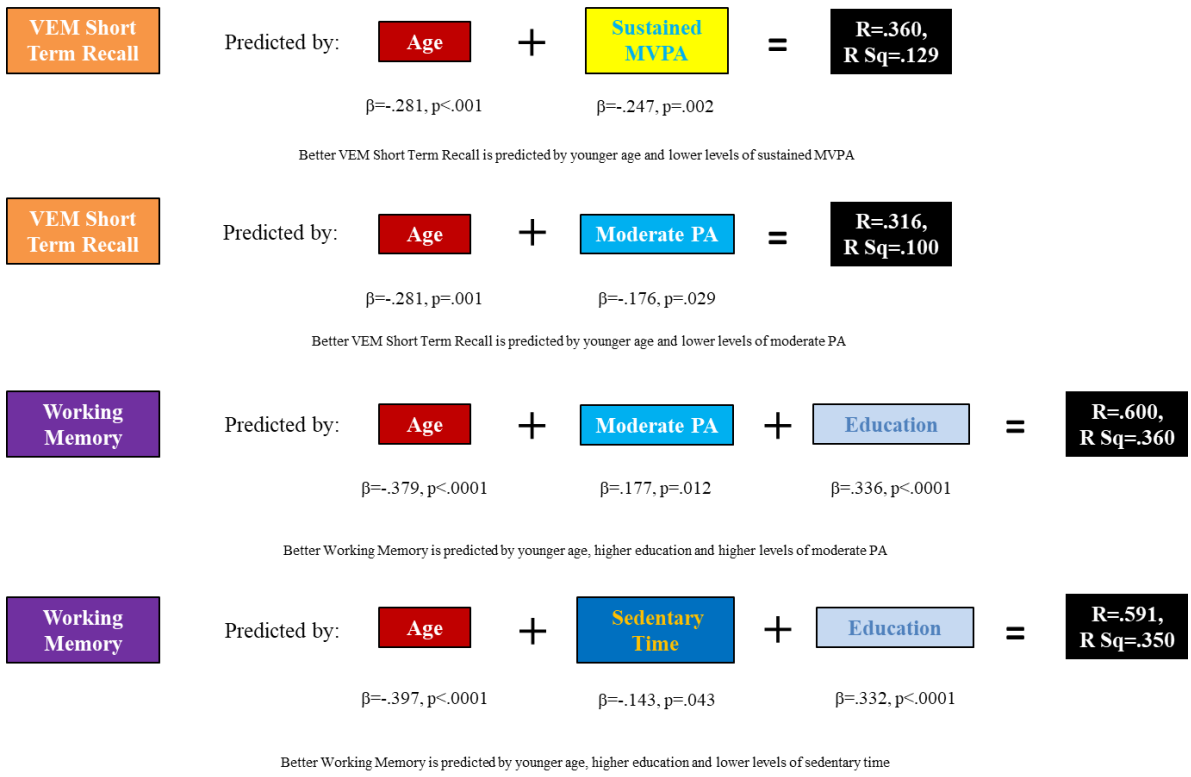
Table 5.5 shows linear regression models using the Enter method for Working Memory and VEM Short Term Recall using age and different PA levels as predictors. In these models, the unusual position suggested by the negative association between higher sustained MVPA and lower VEM Short Term Recall is confirmed and extends to both higher moderate PA and higher MVPA also separately contributing to lower scores on VEM Short Term Recall. By contrast, higher moderate PA, higher MVPA, LMPA and LMVPA all contribute alongside younger age and better education to better Working Memory. Similarly, lower sedentary time also contributes to better Working Memory. There are no linear regression models where, alongside age, any activity level makes any significant contribution towards predicting better Face Memory & Perception, or which, alongside PSQ sleep quality, PA makes any significant contribution towards predicting better VEM Long Term Forgetting. See text for full explanation.

For Working Memory, as well as lower age and higher education, better performance is also predicted by (separately) higher moderate activity (β=.177, p=.012), higher MVPA (β=.175, p=.013), higher LMPA (β=.148, p=.034) and by higher LMVPA (i.e. the aggregate of all daily activity; β=.150, p=.033). Better Working Memory performance is *not* co-predicted by higher light PA, higher vigorous PA or higher sustained MVPA (the latter is also shown for comparison purposes in Table 5.5). Better Working Memory performance is however predicted by lower age, higher education and lower sedentary time (β=-.143, p=.043) although, alongside age, moderate activity and sedentary time do not *together* make any significant contribution towards better Working Memory. The absence of any contribution by sustained MVPA and the separate contribution of lower sedentary time to better Working Memory suggest that higher

performance in this domain is associated with lower age and *any moderate activity level other than sedentary behaviour, but not more intense activity.*

The conclusions about the differential contributions of different PA levels to VEM Short Term Recall and Working Memory respectively are illustrated in Figure 5.5. The two VEM Short Term Recall models show the difference between the best model (with sustained MVPA as the co-predictor) and the next-best model (with moderate PA as the co-predictor). The two Working Memory models show the best model (with moderate PA as the co-predictor) and an alternative model with sedentary time as the co-predictor.

Figure 5.5: Regression Models Predicting Memory Domain Performance: PA Variables



5.3.8. The Unexpected Finding for VEM Short Term Recall may be Explained (in part) by the fact that both VEM Short Term Recall and Sustained MVPA are New 'Composite' Measures in the Present Study

As explained in Chapter 2 (see Table 2.6), the PCA factors labelled VEM Short Term Recall and Working Memory comprise respectively 5 scores and 2 scores in each case from 2 underlying tests.

Examining the scores in the underlying tests for VEM Short Term Recall reveals that the only significant associations between PA levels and scores are for (a) higher sustained MVPA and lower RAVLT Delay score (Pearson's r=-.193, p=.020, Spearman's rs=-.196, p=.018) and (b) in a non-parametric correlation between higher sustained MVPA and lower Buschke's FCSRT delayed recall after 30 mins (Spearman's rs=-.183, p=.028; Pearson's r=-.125, p=.14). There are no other correlations between any activity levels and any scores in the underlying components of VEM Short Term Recall.

This may in part explain why the negative correlation between higher PA and lower VEM Short Term Recall has not been previously reported. In short, VEM Short Term Recall is a composite measure derived from PCA factor analysis and Sustained MVPA is a special calculation made in the present study which does not incorporate *all* daily moderate or vigorous PA, only that which is sustained for uninterrupted bouts of at least ten minutes. As Table 5.3 shows, only this special composite measure of daily PA shows an association with a specially-derived PCA memory domain and only in closer analysis is it possible to discern the relationship between lower activity and higher VEM Short Term Recall in younger subjects.

5.3.9. The Expected Finding for Working Memory Applies Only to the Stroop Test

Examining the underlying test scores for Working Memory reveals that the association between higher PA levels and better Working Memory applies only to the Stroop Test and does not extend to the Four Mountains Test ('the 4MT'); see Figure 5.6 and Table 5.6.

Figure 5.6: Better (lower) Stroop Interference is moderately associated with higher aggregate daily physical activity (LMVPA)

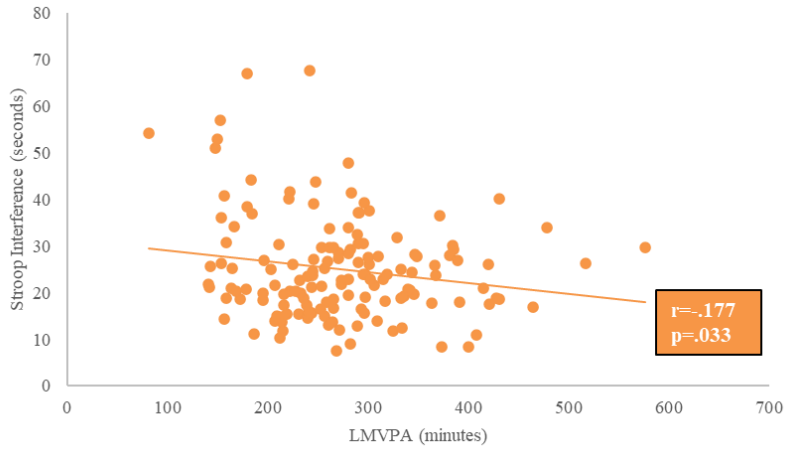


Figure 5.6: Association between Daily LMVPA and Stroop Test performance. Higher levels of daily LMVPA is associated with improved performance on the Stroop Test (lower levels of Stroop interference); Pearson's r=-.177, p=.033.

Table 5.6: Higher PA levels are associated with better Stroop Test performance but not with better 4MT performance

Physical Activity (PA) Level	4MT		Stroop		4MT		Stroop	
	r	p	r	p	r_s	p	r_s	p
Light (L) PA	-.064	.45	.039	.64	-.130	.12	.065	.43
Moderate (M) PA	.129	.12	-.231	.005	.118	.16	-.145	.08
Vigorous (V) PA	.099	.23	-.116	.17	.133	.11	-.256	.002
MVPA	.132	.11	-.232	.005	.125	.13	-.149	.07
Sustained MVPA	.076	.36	-.163	.051	.130	.12	-.149	.07
LMPA	.080	.34	-.172	.039	.036	.66	-.063	.45
LMVPA	.086	.30	-.177	.033	.048	.57	-.070	.40
Sedentary Time	-.103	.22	.157	.059	-.092	.27	.086	.31

Table 5.6 shows Pearson's r and Spearman's r_s correlations between activity levels and performance in the two underlying components of the Working Memory PCA factor, the Four Mountains test (4MT) and the Stroop test. There are no significant associations between activity levels and 4MT performance but there are significant associations between higher moderate PA and higher MVPA and lower Stroop interference (i.e. better Stroop test performance). Orange shading denotes significant correlations.

It is also clear from Table 5.7 and Figure 5.7 that the best predictors of lower Stroop Interference (i.e. better performance) alongside younger age and higher education are higher levels of moderate activity (β=-.178, p=.007) and lower levels of sedentary time (β=.198, p=.003). Table 5.7 also shows models for predicting Stroop Interference using age, education level and either light PA or sustained MVPA. This is to demonstrate that activity levels at the extremes do not help to predict better Stroop Test performance (i.e. light PA: β=-.105, p=.13; Sustained MVPA: β=-.088, p=.20).

Table 5.7: Higher Moderate PA levels help to predict better Stroop Test performance alongside younger age and higher education

Cognitive Task	R	RSq	Age (β)	Age (p)	Edu. (β)	Edu. (p)	PA Level	PA (β)	PA (p)
Stroop Interference	.673	.453	.534	<.0001	-.206	.003	Moderate	-.178	.007
Stroop Interference	.649	.421	.544	<.0001	-.207	.003	MVPA	-.155	.023
Stroop Interference	.652	.425	.564	<.0001	-.197	.004	LMPA	-.165	.013
Stroop Interference	.651	.423	.562	<.0001	-.199	.004	LMVPA	-.162	.016
Stroop Interference	.673	.426	.564	<.0001	-.225	.001	Sedentary	.198	.003
Stroop Interference	.636	.405	.556	<.0001	-.196	.006	Sustained MVPA	-.088	.20
Stroop Interference	.639	.408	.590	<.0001	-.175	.012	Light	-.105	.13

Table 5.7 shows linear regression models using the Enter method for Stroop Interference. Higher education is highly correlated with Stroop Interference (Pearson's r=-.390, p<.0001) but is not correlated with any measure of physical activity or sedentary time. Education makes a significant independent contribution to the regression models for Stroop Interference alongside younger age. In contrast to the position with Working Memory, alongside age and education, higher sustained MVPA does not make any significant contribution to better Stroop performance (b=-.088, p=.20). The model using light activity is also shown in order to show the contrast with the position for moderate activity. Red shading denotes non-significant contributing variables. In these models, 3 outliers have been excluded; 2 subjects had very high interference (67 and 68 seconds) and one subject had very low interference (8 seconds); for all subjects, interference was

Figure 5.7: Lower activity and higher sedentary time is associated with worse Stroop test performance

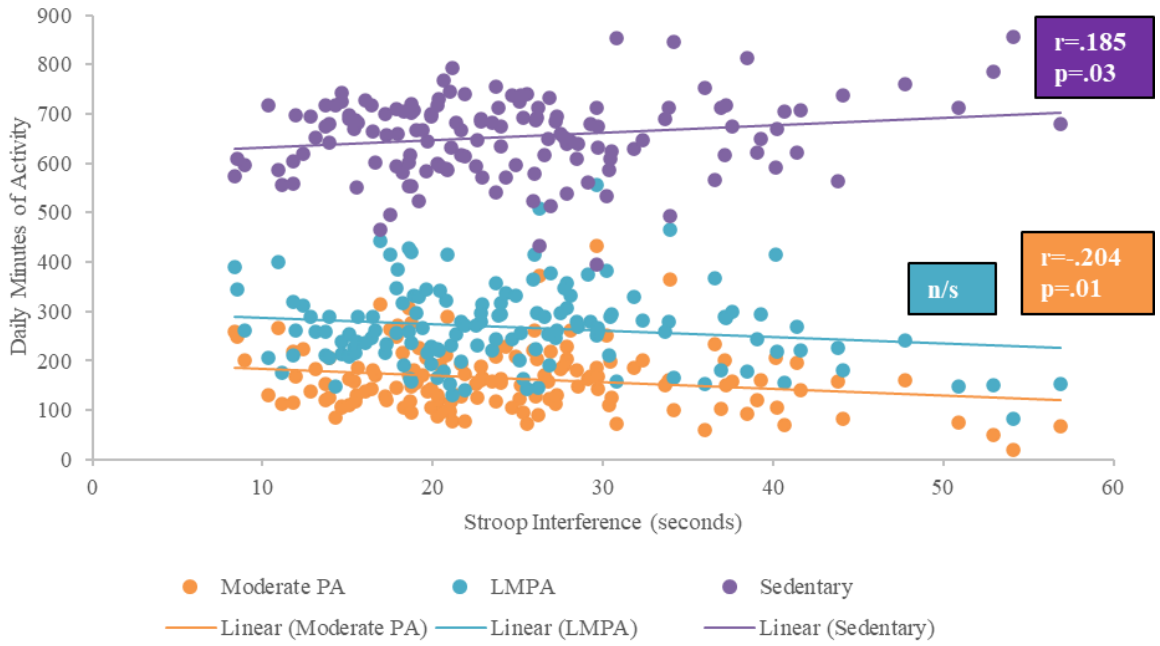


Figure 5.7 shows correlations between Stroop Interference and activity levels, excluding the same outliers as are excluded in linear regression models in Table 5.7 above. Higher sedentary time is associated with worse Stroop interference (Pearson's r=.185, p=.028) whereas higher moderate activity is associated with lower Stroop interference (Pearson's r=-.204, p=.015). Higher LMPA is only marginally associated with lower Stroop interference (Pearson's r=-.153, p=.07), reflecting the fact that light PA (a component of LMPA) makes no contribution to predicting better Stroop performance; see Table 5.7.

Comparable regression models for the Four Mountains test do not show any activity levels (or sedentary time) contributing to performance, either alongside age alone or alongside both age and education. It is clear therefore that the effect of higher activity levels (and lower sedentary time) on better Working Memory is confined to the Stroop test. Moreover, the beneficial effect appears to be limited to moderate level physical activity and does not extend to activity levels at the extremes of light, vigorous or sustained MVPA.

Finally, it should be noted that, alongside higher education, higher moderate PA also contributes to higher/better mentalizing; R=.263, R Sq=.069; education: β=.215, p=.010; moderate PA: β=.168, p=.044. No other activity levels help to predict better mentalizing.

5.3.10. ***New Finding:*** *Subjects are Reasonably Able to Self-assess their PA levels at the extremes of Active or Inactive, but not in between at Moderately Active or Inactive levels*

The Methods section (above) describes how subjects also completed a physical activity self-assessment questionnaire (Physical Activity Policy, 2009) which allocates subjects to one of four activity categories, depending on a combination of how much structured exercise they take and the physical activity levels inherent in any occupation. The four physical activity levels are 'active', 'moderately active', 'moderately inactive' and 'inactive'. Table 5.8 shows different activity levels, as measured by the devices for all subjects, analysed between the four different categories of the GPPA categorisation. Table 5.8 also shows, separately, two combined groups for 'active or moderately active' subjects and 'inactive or moderately inactive' subjects. Combining these GPPA categories allows for straightforward comparisons to be made between two groups of subjects who self-assess as either 'active or moderately active' or 'inactive or moderately inactive'. The combined groups will be referred to respectively as 'Active +' and 'Inactive +'.

Examining the 4 GPPA groups, with the exception of light PA and sedentary time, activity levels generally decrease progressively from the 'active' to 'inactive' categories. However, the 'moderately inactive' category appears to be somewhat anomalous, as this group has some activity levels that are higher than the 'active' and 'moderately active' groups. The 'moderately inactive' group is however substantially smaller (N=14) than the other three GPPA groups (another reason for collapsing these 4 GPPA groups into 2). It is also noticeable that levels of light PA *increase* with higher self-assessed inactivity. In this respect, light activity follows a similar pattern to sedentary time. Subjects with more light PA and more sedentary time tend to be categorised as more inactive.

Table 5.8: There is a generally non-significant trend in declining Physical Activity Levels across Active to Inactive GPPA Categories

Physical Activity (PA) Level (in average daily minutes)	Active	Moderately Active	Moderately Inactive	Inactive	Active & Moderately Active (Active+)	Inactive & Moderately Inactive (Inactive +)
	N=49	N=39	N=14	N=38	N=88	N=52
Light (L) PA	101	103	103	110	102	108
Moderate (M) PA	168	161	174	149	165	156
Vigorous (V) PA	8	6	4	2	7	3
MVPA	176	167	179	151	172	158
Sustained MVPA	66	53	52	37	60	41
LMPA	269	265	277	259	267	264
LMVPA	277	270	281	261	274	267
Sedentary Time	650	658	632	672	654	661

Table 5.8 shows physical activity levels analysed by all 4 levels of the GPPA classification based on self-reported physical activity (active, moderately active, moderately inactive and inactive). In the final two columns, Table 5.8 also shows aggregate minutes for 'active and moderately active' (Active+) and for 'inactive and moderately inactive' (Inactive+). In these two comparison groups, levels of both vigorous activity and sustained MVPA are significantly different; $t_{135.454}$=4.381, p<.0001, Cohen's d=0.75 and $t_{128.192}$=2.873, p=.005, Cohen's d=0.51 respectively, but there are otherwise no differences in other activity levels between Active+ and Inactive+ subjects.

Figure 5.8: Active + and Inactive + Groups do not differ in Age but do differ in Sustained MVPA

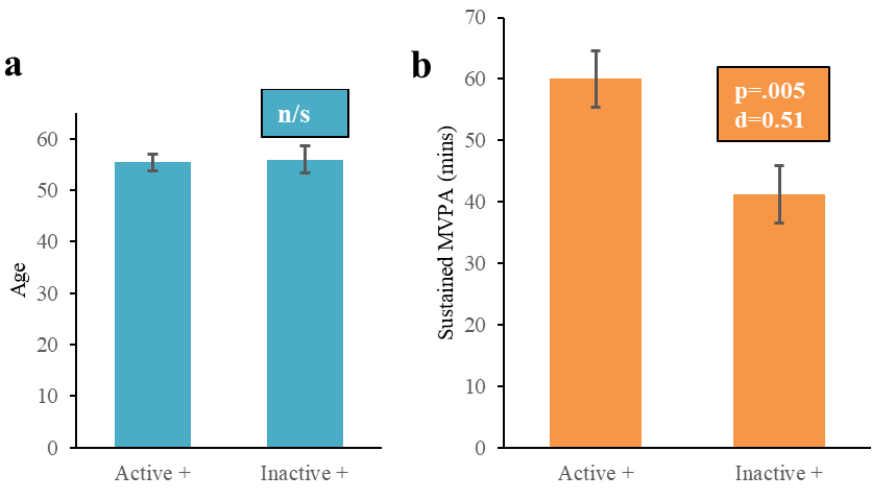


Figure 5.8: **a**. shows that there is no difference in age between the Active+ and Inactive+ combined GPPA categories; t_{138}=-.172, p=.86. **b**. Comparing these two combined groups, the Active+ group has longer daily minutes (M=60 mins) of sustained MVPA than the Inactive+ group (M=41 mins); $t_{128.192}$=2.873, p=.005, Cohen's d=0.51. Error bars show +/- one s.e.m.

Across all four GPPA groups there are no significant differences between any of the groups in levels of sedentary time, light activity, moderate activity, LMPA or LMVPA. There are though significant differences in both vigorous activity and sustained MVPA between the 'active' and 'inactive' groups and between the 'moderately active' and 'inactive' groups. Amounts of daily vigorous activity are very small but more substantial amounts of daily sustained MVPA show significant differences between the GPPA active and inactive groups (active=66 mins, SD=50 mins and inactive=37 mins, SD=23 mins; $t_{71.931}$=3.570, p=.001, Cohen's d=0.84) and between moderately active and inactive groups (moderately active=53 mins, SD=34 mins; $t_{66.814}$=2.369, p=.021, Cohen's d=0.58). It should be noted that there is no difference in BMI between the GPPA active and inactive groups; $t_{62.914}$=-.458, p=.65.

Comparing the two combined GPPA groups, the Active+ group does not differ in age from the Inactive+ group, but the Active+ group has higher sustained MVPA (60 mins, SD=43 mins) than the Inactive+ group (41 mins, SD=34 mins); $t_{128.192}$=2.873, p=.005, Cohen's d=0.51. This is shown in Figure 5.8. In addition, the Active+ group has higher vigorous activity (7 mins, SD=8 mins) than the Inactive+ group (3 mins, SD=4 mins); $t_{135.454}$=4.381, p<0001, Cohen's d=0.75, although the daily amounts of vigorous activity are very small. These differences in PA between the two combined groups (limited to the more sustained and vigorous levels of daily activity) therefore mirror the differences between the sub-groups at the extremes of the GPPA classification (namely the 'active' and 'inactive' groups).

These results appear to suggest that, so far as purposeful, more intense activity is concerned, subjects can self-assess their physical activity levels reasonably well. An alternative view is that the GPPA can discern quite well between subjects who do or who do not undertake quite extreme levels of PA, but it cannot detect differences between subjects at more moderate or modest levels. This appears to be a limiting factor for the GPPA as a robust PA assessment tool.

*5.3.11. **New Finding:** Higher levels of PA are Associated with Higher Social Confidence and Better Self-assessed General Health*

Table 5.9 shows correlations between activity levels and scores in the PCA psychological health factors (see Table 2.9) and also the General Health component score of the SF36 Short Form Health questionnaire ('the SF36', Ware Jr & Sherbourne, 1992).

Table 5.9: Higher PA levels are associated with better Social Confidence and better SF36 General Health

Physical Activity (PA) Level	Positive Social Experience		Social Confidence		Social Connectedness		Negative Social Experience		Social Fearfulness		SF36 General Health Score	
	r	p	r	p	r	p	r	p	r	p	r	p
Light (L) PA	.011	.89	.077	.37	-.050	.56	.039	.65	-.083	.33	.153	.07
Moderate (M) PA	.032	.71	.171	.045	-.026	.76	-.083	.33	-.131	.12	.190	.025
Vigorous (V) PA	.102	.23	.106	.22	-.021	.81	-.141	.098	-.078	.36	.212	.012
MVPA	.042	.63	.173	.042	-.027	.76	-.094	.27	-.133	.12	.203	.016
Sustained MVPA	.041	.63	.213	.012	-.026	.76	-.103	.23	-.171	.045	.174	.04
LMPA	.030	.72	.168	.049	-.040	.64	-.053	.54	-.138	.11	.212	.012
LMVPA	.038	.66	.172	.044	-.041	.63	-.063	.46	-.141	.10	.224	.008
Sedentary Time	-.062	.47	-.058	.498	.008	.92	.087	.31	.009	.92	-.161	.058
	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p
Light (L) PA	.006	.94	.067	.44	-.016	.86	.035	.68	-.059	.49	.100	.24
Moderate (M) PA	-.027	.75	.221	.009	-.002	.98	-.034	.69	-.158	.06	.157	.06
Vigorous (V) PA	.043	.62	.049	.57	.007	.94	-.139	.10	.039	.65	.242	.004
MVPA	-.020	.81	.217	.011	-.006	.95	-.042	.62	-.154	.07	.167	.049
Sustained MVPA	-.070	.41	.220	.009	.028	.75	-.057	.50	-.149	.08	.155	.07
LMPA	-.010	.90	.214	.012	.002	.98	-.015	.86	-.160	.06	.167	.048
LMVPA	-.002	.98	.217	.011	-.009	.91	-.020	.82	-.166	.052	.179	.035
Sedentary Time	.026	.76	-.096	.26	.003	.97	.038	.66	.040	.64	-.105	.21

Table 5.9 shows Pearson's r and Spearman's r_s correlations between different PA levels and PCA psychological health factor scores. Associations between PA levels and the General Health score on the SF36 Short Form Health questionnaire are also shown for comparison purposes. Positive associations exist between higher moderate level activity and higher Social Confidence; Pearson's r=.171, p=.045. This positive association extends to all activity levels which contain moderate activity as a component element (i.e. MVPA, sustained MVPA, LMPA and LMVPA). Higher sustained MVPA is also associated with lower Social Fearfulness; Pearson's r--.171, p=.045. In short, some aspects of higher Sociability (although not better Psychological Mood) are positively associated with higher levels of physical activity. Higher levels of physical activity are generally positively associated with higher positive SF36 scores for General Health. Orange shading denotes significant correlations. For an explanation of the underlying components to the PCA psychological health factors and a detailed breakdown of the SF36 Short Form Health questionnaire, see chapters 2 & 6.

Table 5.9 shows that higher levels of PA are moderately associated with better Social Confidence, although not generally with the other PCA factor scores for psychological health. The strongest correlation is between higher Social Confidence and higher levels of Sustained MVPA (Pearson's r=.213, p=.012). Higher levels of PA are also moderately associated with better SF36 General Health scores; in this case, the highest correlation is between higher LMVPA (i.e. the aggregate of all PA levels) and better SF36 General Health (Pearson's r=.224, p=.008). Further analysis of psychological health is provided in Chapter 6, including how Principal Component Analysis was used to reduce the 8 component scores in the SF36 into two distinct factors labelled 'SF36 Psychological' and 'SF36 Physical'.

5.4. DISCUSSION

5.4.1. Physical Activity Levels do not show Strong Age-related Decline until Quite Late in Life

It was hypothesised that older age may be associated with declining levels of PA. Instead, as Figure 5.2 illustrates, the aggregate of all PA (LMVPA) appears to be relatively stable across the age range of all 145 subjects, as does daily sedentary time. There is no strong association between older age and a decline in any level of PA. Although this is not a longitudinal study, and so conclusions cannot be drawn about lifetime trends, there is no pattern of decreasing PA levels across the age-span in this sample *until* later in life. Indeed, the trend appears to be one of gradually increasing levels of PA until more advanced older age (66+). Older age is associated with higher light PA and older subjects have significantly higher levels of light activity than younger subjects. Comparing the two main age groups, it does not appear that there is any clear, specific trade-off between this increase in light PA and a corresponding decrease in any other activity level in the older group. The main component of the 17 minute difference in daily light PA between older and younger groups appears to be a 9 minute longer bed duration in the younger group, but this difference is not significant.

A comparison of activity levels in more detailed age groups however reveals a more nuanced picture (see Figure 5.3). Together, there is a reduction of 40 minutes in light and moderate activity (LMPA) by Group 4 (66+, 257 minutes) compared with Group 3 (51-65, 297 minutes) and this is a significant reduction in aggregate light and moderate activity levels between the two oldest age groups. However, because both light and moderate PA increases steadily between Group 1 (18-35), Group 2 (36-50) and Group 3 (51-65), Group 4 (257 minutes) does not have significantly different LMPA from Group 1 (242 minutes). Vigorous PA accounts for very small amounts of daily time so that the same pattern is seen for the aggregate of all daily PA levels (LMVPA), namely Group 4 and Group 1 are both lower than Group 3, but Group 1 and Group 4 are no different. In short, whilst activity levels do decline in the oldest age group (66+ years), they remain broadly on a par with activity levels in the youngest group, although the reasons for the comparatively lower levels of PA in both the youngest and oldest age groups (compared with the two ‘middle-aged’ groups) may be quite different. For example, work or social commitments may constrain the youngest group from undertaking more PA, whereas physical limitations may place PA constraints on the oldest group.

The same pattern is followed in reverse with sedentary behaviour, namely a gradual reduction in sedentary time from Group 1 to Group 3 before an increase in Group 4, although none of the

differences reaches statistical significance; this comparative trend is to be expected given the strong negative relationship between PA levels and sedentary time generally. The net result is a mere 7 minutes difference between the sedentary time of Group 1 (18-35) and Group 4 (66+). Whilst these changes may not be statistically significant, they are consistent with a pattern of increasing light and moderate activity through detailed 15-year age groups 1 to 3 before, comparatively, PA levels reduce more substantially in Group 4.

*5.4.2. **New Finding:** Older Persons with More Available Time may find it Easier to Increase Levels of Light PA*

The comparison of activity levels across these detailed age groups reveals several interesting findings. First, and although this is not a longitudinal study, the finding that PA levels (as opposed to PA *performance*) do not decline until quite advanced older age (in this case, 66 plus), is not wholly consistent with earlier research (e.g. Hall, 2017). It is possible that this result simply reflects a demographic bias in this sample of under-active younger persons (professional, sedentary and free-time constrained) and over-active older persons (time-rich and engaged in PA-linked social pursuits), compared with the general population. However, whatever the reason for the difference in this finding, it seems to be the case that with progression through the age groups, (until the very oldest) subjects are becoming increasingly active, perhaps reflecting an increasing appreciation of staying active in later life and more free time in which to do so. In this respect, the hypothesis of a gradual decrease in PA levels with increasing age is unsupported and this may merit further investigation.

Second, comparison of the two main age groups shows a significant 17 minutes increase in light activity but a non-significant 2 minutes reduction in moderate activity. The more nuanced picture that emerges with more detailed age groups shows how both light and moderate activity increase across the first 3 age groups (in line with gradually reducing sedentary behaviour) before reducing in the oldest age group. This presents a quite different profile of PA across age-groups and suggests that PA comparisons between 'younger' and 'older' groups alone may be overly simplistic. Changes in the levels of PA over the lifespan may not be linear, particularly in predominantly sedentary working populations where older persons are actively encouraged to remain active in later life.

Third, and this is somewhat self-evident but nevertheless worth stating, it appears to be easier in older age to maintain higher levels of light PA, as opposed to moderate PA. Given some of the recent findings elsewhere on the cognitive benefits of, e.g., light housework in older age

(Lee, 2021), this is not an unimportant public health message and may bear some repetition. This is subject to one qualification; the present study shows that higher moderate activity (rather than higher light activity) may help Working Memory. Encouraging older persons to exchange some of their increased daily light PA for a higher moderate level of PA (e.g., by undertaking slightly more energetic household/garden work) could prove advantageous.

*5.4.3. **New Finding:** Different levels of PA may have Benefits for Working Memory in Younger and Older Persons*

The hypothesis was that, across different age groups, higher levels of PA might be associated with better memory domain performance, particularly in those memory domains strongly subserved by hippocampal function, in line with earlier research findings (e.g., Colcombe, 2006; Pereira, 2007; Erickson, 2011). However, previous research has focussed heavily on the benefits of PA and exercise to memory and cognitive function in older adults (e.g., Colcombe & Kramer, 2003) and only comparatively recently has this research extended to differentiate PA and exercise benefits to memory in younger subjects (e.g., Hayes, 2015). The findings in this study replicate those elsewhere for the benefit of PA and exercise in older subjects (Hayes, 2015; Lee, 2021). In particular, there is strong support for the proposition that, for tasks requiring greater cognitive effort (in this study, the Stroop test), the benefit of higher levels of PA is most easily discernible.

As has been found elsewhere (Hayes, 2015; Lee, 2021), the results in this study also differ between younger and older subjects, in some cases quite subtly, and in other cases quite substantially. One example of a subtle difference is that the association between higher levels of activity and better Working Memory appears to differ between younger and older subjects. For older subjects, the association between better Working Memory and higher activity appears to be largely confined to *moderate* levels of activity (Table 5.4) and does not extend to higher light activity or higher levels of more vigorous, sustained MVPA. For younger subjects however, the beneficial association appears to be largely confined to more vigorous, sustained MVPA (Table 5.4). Across all subjects, linear regression models for both Working Memory (meaning specifically Stroop Interference) tend to confirm that higher levels of moderate activity are the best PA predictor of better performance (Tables 5.5, 5.6 & 5.7 and Figure 5.5, 5.6 & 5.7).

*5.4.4. **Unexpected Finding:** Higher Levels of PA are Associated with Lower VEM Short Term Recall in Younger Subjects*

For an example of a more marked contrast between the younger and older groups, the findings here that, in the younger group, higher levels of activity are associated with *worse* VEM Short Term Recall are unexpected. Ordinarily, younger subjects perform better on both component elements of VEM Short Term Recall (e.g. see Larrabee, 1988 for Buschke's VSRT and Van der Elst, 2005 for the RAVLT) and younger subjects have been shown to have higher levels of PA generally (Hall, 2017), although, as discussed above, the findings in the present study are not wholly in line with this. For the younger group, the findings are reasonably strong and consistent across most activity levels; for example, higher aggregate daily PA (LMVPA) is similar to sustained MVPA (purposeful, intense activity) in its association with lower VEM Short Term Recall: LMVPA: Pearson's r=-.412, p=.002; sustained MVPA: Pearson's r=-.385, p=.005. In addition, correlations between higher activity and lower VEM Short Term Recall show a corresponding reverse pattern with sedentary time: e.g., moderate activity: Pearson's r=-.425, p=.002; sedentary time: Pearson's r=.419, p=.002; see Table 5.4. In short, in the younger group, more sedentary time and less PA are equivalently associated with better VEM Short Term Recall. However, this is not the case in the older group where higher activity levels are only beneficial (albeit to Working Memory and not VEM Short Term Recall); see Table 5.4.

Across all subjects (N=145), the contrast between the relationship of PA to Working Memory and to VEM Short Term Recall is most strongly illustrated in the different linear regression models for the two different memory domains (Tables 5.5 & Figure 5.5). Whereas lower age and higher activity levels together predict better Working Memory, lower age and *lower* activity levels together predict better VEM Short Term Recall. Higher education also helps to predict better Working Memory, alongside younger age and higher PA levels/lower sedentary time (Table 5.5).

5.4.5. Explaining the Unexpected Finding: This Requires Further Research

It is relatively easy to see why this unexpected finding has not been previously reported. VEM Short Term Recall is a new composite measure, revealed in the present study by PCA factor analysis. When the underlying tests to this PCA factor are examined, these do not show the same widespread associations between lower activity levels of all types and higher underlying test scores, as seen for the PCA factor score in Table 5.4. In fact, the only negative correlations

(for all subjects) are with higher Sustained MVPA and lower underlying short delayed recall. Again, Sustained MVPA is a special composite calculation made for the purposes of this study.

Although therefore it is possible to explain why this unusual result has not been seen before, it is harder to explain the reasons for it. There are several possibilities which can probably be discounted.

The Unexpected Result is an Aberration

This seems unlikely. Although Table 5.4 shows that there are no non-parametric correlations between lower activity levels and higher VEM Short Term Recall, the Pearson's correlations are strong and range across all activity levels, and composite activity levels, including sedentary time. The linear regression models in Table 5.5 also tend to suggest that the significant correlations are not an aberration.

The Unexpected Result is Largely Confined to the Younger Group and the Younger Group is Somehow Atypical

There are several reasons why this is unlikely. First, as seen in Chapter 2, younger subjects have better VEM Short Term Recall ($p=.004$) and better Working Memory than older subjects ($p<.0001$). Performance in both memory domains of the younger group is therefore not unusual. Second, the linear regression models which show the negative contribution of PA to better VEM Short Term Recall include all subjects, not just the younger group. Moreover, although not significant, the direction of the results for the older group alone, suggest that lower Sustained MVPA may be associated with higher VEM Short Term Recall more extensively than in younger persons only. Finally, for younger persons, the opposite applies for Working Memory; namely, higher PA levels are associated with better Working Memory performance.

The Unexpected Result is Attributable to some Abnormality in one of the Underlying Tests

Short delayed recall in both underlying tests (the RAVLT and Buschke's VSRT) shows an association between better performance and lower Sustained MVPA. Moreover, when detailed exploratory analysis is undertaken (not shown in Results), in the younger group, negative correlations apply between a large number of different scores in both underlying tests and different activity levels. This similar pattern arises moreover in two separate underlying tests of VEM that were carried out two weeks apart. In the older group, the correlations between underlying test scores and PA levels are generally only positive.

A clear explanation for these unexpected unusual results is not easy to formulate. One possible explanation might be that lower physical activity may be associated with lower psychological mood and these factors might together produce a heightened capacity for verbal episodic memory (see e.g., McManus, 2020). The results in this study show that higher Social Confidence is associated with higher levels of PA, and this PCA factor contains elements that capture social stress and anxiety (see Table 5.9 and Figure 5.9). However, an association between higher activity and lower psychological stress does not offer a simple explanation for an association between lower activity and higher VEM Short Term Recall. This might require a link (say) between higher stress and better VEM Short Term Recall, where performance is perhaps enhanced through higher arousal, but such a link is not readily apparent in the results of this study. Further research is required here.

5.4.6. ***New Finding:*** *Subjective PA Assessment tools are Limited to Differentiating Subjects at the Extremes but may be Less Sensitive to More Moderate Levels of PA and Less Useful in the Determination of Activity Levels in Older Subjects.*

This sample of subjects included a large number of older subjects (N=93), many of whom were retired or semi-retired and therefore no longer had full-time occupations requiring specific job-related physical activity. The younger group (N=52) largely included office workers and persons whose occupations were mainly sedentary. The GPPA (Physical Activity Policy, 2009) examines self-reported physical activity based on two main dimensions; first, occupational activity level and, secondly, weekly structured exercise. Based on self-assessments, the GPPA allocates subjects to one of four categories, being ‘active’, ‘moderately active’, ‘moderately inactive’ and ‘inactive’. Comparisons of actual activity levels were made with all four self-reported activity levels. In addition, two combined category groups were compared, being subjects who were either ‘active or moderately active’ or ‘inactive or moderately inactive’ under the GPPA classification. These two combined groups are referred to as ‘Active +’ and ‘Inactive +’.

The results indicated that Sustained MVPA is the most reliable differentiator between the two most extreme groups of the four GPPA categories (i.e. the ‘active’ and ‘inactive’ sub-groups) and between the two combined groups (i.e. ‘Active +’ and ‘Inactive +’); see Table 5.8 and Figure 5.8. (Vigorous level activity is a similar differentiator but daily minutes of vigorous PA are much lower than daily minutes of sustained MVPA). Unlike other more light to moderate activity levels, which show an uneven profile across the GPPA groupings, Sustained MVPA (and vigorous PA) shows a progressive decline across the four GPPA groupings.

Although therefore the ‘exercise’ and ‘occupational activity’ dimensions of the GPPA may be well-suited to distinguishing between groups who regularly exercise or who have strenuous, physical jobs, as demonstrated by the clear category differences in Sustained MVPA, they seem less well suited to differentiating between ‘more active’ and ‘less active’ older subjects who may have no job-related physical activity and who might not undertake specific, structured exercise. Some fine-tuning of the GPPA may therefore be required to include in the overall assessment daily levels of lighter activity, such as (e.g.) light or moderate housework, particularly in the light of recent findings for the beneficial effects of more light activity in older age in studies such as Lee, 2021. At present, the GPPA does not appear to take such matters sufficiently into account. This finding is consistent with an earlier study (Ahmad, 2015) which found that, although the GPPA is reasonably reliable, it does not correspond well to activity levels in older adults measured by accelerometery.

5.4.7. Limitations

There are some limitations that are specific to this chapter on PA. First, this is a cross-sectional study and conclusions about PA levels across age groups and the effect of PA on different memory domains across the lifespan probably demands longitudinal assessment. Second, as described in Chapter 2, a number of older subjects in this study were recruited through the University of the Third Age (U3A), including through U3A ‘keep fit’ and other classes. It is highly likely therefore that this sample of older persons may represent a group that is considerably more physically active than a typical representative sample of such an age group. In addition, many of the younger subjects in this subject were professional persons in largely sedentary occupations. It is possible that, as such, they may be more time-constrained than (say) a student population in being able to pursue PA and higher levels of exercise. Results here may not generalise more widely to (say) a younger, more active, sample or an older, less active one.

5.5. Summary of Chapter 5

PA levels and sedentary behaviour are relatively similar across a wide age range in a sample of healthy, active subjects (age 21-91). PA levels actually increase in progressively older age groups (i.e. groups with, broadly, a 15 year span), before declining in a sub-group of more advanced age subjects (66+ years old). Much older adults appear to find it easier to maintain levels of light activity, than more effortful levels of PA.

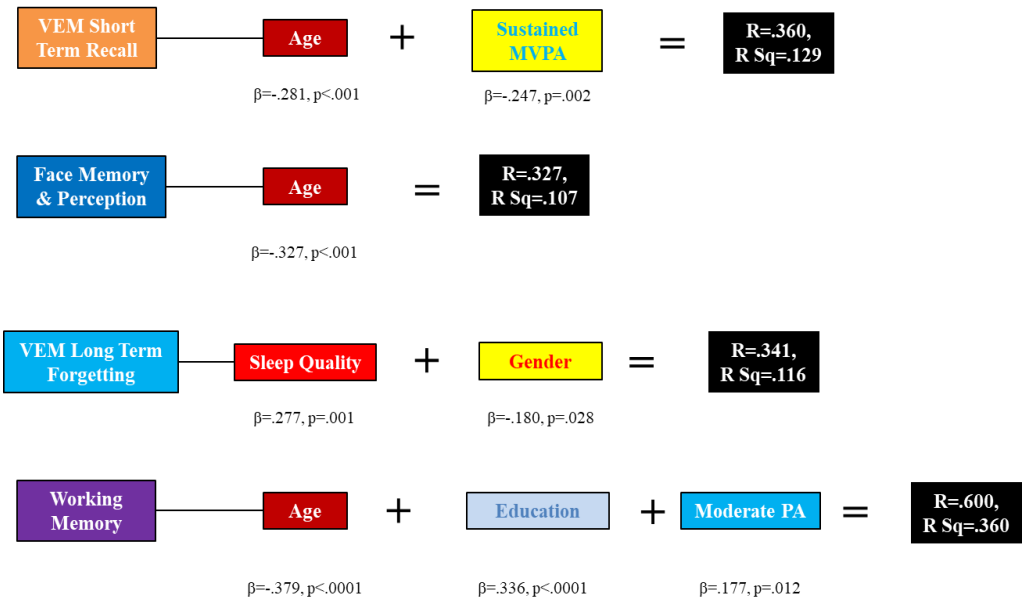
In older subjects, higher levels of quite *moderate* PA are associated with better Working Memory, although the same result is achieved in younger subjects by more *sustained moderate and vigorous* activity. So far as is known, this distinction has not been shown previously. Working Memory benefits relate specifically to better performance on the Stroop test. Across all subjects, younger age, higher education and higher levels of moderate PA together predict better Stroop performance (i.e. potentially better selective attention and goal maintenance). An equivalent result is not achieved either by lighter or more strenuous PA levels. This may mean that exchanging some of the increased light PA in later life for slightly more moderate levels of PA may afford some memory benefits to older subjects. This is unlikely to be the case for younger subjects because they have lower levels of light PA and their Working Memory may only be improved by more vigorous, sustained PA.

An unexpected finding is that higher levels of moderate PA is also associated with *worse* VEM Short Term Recall, and in linear regression, younger age and *less* physical activity predicts better performance in VEM Short Term Recall. A simple explanation for this unusual result is elusive.

Persons who self-report being more active generally have higher levels of sustained PA. However, although standard PA questionnaires may be good at differentiating those who undertake purposeful exercise from those who do not, they are less well-able to identify those who undertake more light PA. Given the recently reported benefits of more light activity in older subjects (see e.g., Lee, 2021), this is a deficiency in standard self-report measures of beneficial activity levels in older subjects, specifically, the NHS GPPA questionnaire (Physical Activity Policy, 2009).

The updated regression models are shown in Figure 5.9.

Figure 5.9: Updated Regression Models for Chapter 2, 3, 4, & 5 Variables



Note: Although different regression models for VEM Short Term Recall and Working Memory are shown in Figure 5.5, only the best models are shown for each of these memory domains in these overall Updated Regression Models

The next chapter (Chapter 6) considers the effects of social networks and psychological health on memory domain performance. Some results have already been highlighted in this chapter (e.g. the relationship between both higher PA and higher Social Confidence). Psychological health factors will be examined further in Chapter 6, and re-introducing sleep as another important factor in the complex relationship between psychological health and memory performance.

CHAPTER 6: SOCIAL NETWORKS AND PSYCHOLOGICAL HEALTH

6.1. INTRODUCTION

The previous chapter (Chapter 5) examined the relationship between physical activity (PA) levels and memory domain performance, highlighting age-related PA changes, and how different PA levels in different age groups may afford equivalent or different memory domain benefits. Some results in Chapter 5 showed evidence of relationships between psychological health and PA levels, as well as some evidence of the effect of psychological health on memory domain performance. Those relationships will be examined further in this chapter and, in particular, will be extended to include the relationship between psychological health and sleep.

6.1.1. Purpose of this Chapter: How do Social Networks and Psychological Health influence Memory Domain Performance?

The main purpose of this Chapter 6 is to examine the effect, if any, of social networks and psychological health on memory domain performance in different age groups. This Chapter examines how social networks and psychological health are related to each other and how this relationship might help to explain the relationship between social networks and healthy cognitive ageing (see Chapter 1). As stated already, this is not a longitudinal study, so it is not possible, for example, to examine how size of social networks or psychological health may change in the course of normal ageing.

6.1.2. Exploratory Principal Component Analysis (PCA) has been Used to Identify Psychological Health Constructs

Chapter 2 set out age-related results for four memory domain factors, which showed that younger age is associated with better performance in three factors: VEM Short Term Recall, Face Memory & Perception and Working Memory. Younger age is not associated with better performance in VEM Long Term Forgetting, although as seen in Chapter 3, good sleepers perform better than poor sleepers. Chapter 2 also explained how Principal Component Analysis (PCA) was used to organise multiple scores from different questionnaires into two complementary sets of psychological health factors. Set 1 comprises 3 factors labelled Positive Social Experience, Social Confidence and Social Connectedness; Set 2 comprises 2 factors Negative Social Experience and Social Fearfulness. Although the two sets of factors were developed separately, there is a strong cross-correlation between Positive Social Experience and Negative Social Experience and between Social Confidence and Social Fearfulness which represent positive/negative ‘mirror image’ constructs. Social Connectedness stands apart as a

measure of social network connections. The underlying questionnaires included in these five PCA factors are further described in Methods (below) and the specific questionnaire elements included in each PCA factor are shown in Table 2.9 in Chapter 2. The use of exploratory factor analysis to reduce multiple questionnaire scores into factor dimensions of psychological health is a unique approach of the present study. It has been further extended in this Chapter to include factor analysis of one specific questionnaire, the SF36 Short Form Health Assessment (Ware Jr & Sherbourne, 1992; Framework, 1992; 'the SF36') which is a widely-used and reliable questionnaire (Gandek, 1998; Brazier, 1992; Hayes, 1995; Jenkinson, 1993). In the present study, the 8 commonly-reported health measures of the SF36 have been reduced to two PCA factor domains, as described further below.

6.1.3. The Relationship between Sleep Quality and Psychological Health Factors is Explored in this Chapter

In this Chapter, psychological health factors have also been examined in the way they relate to sleep quality, as well as normal ageing. Some earlier studies have linked the results of specific psychological health questionnaires to Pittsburgh Sleep Questionnaire (PSQ; Buysse, 1989) sleep quality (e.g. Rezaei, 2018). In one study (Driscoll, 2008), it was found that in older subjects (N=64, M=79) better PSQI scores were associated with both better SF36 physical health components ($r=-.26$, $p<.05$) and better SF36 psychological components ($r=.30$, $p<.05$) although these results became non-significant when an α-level value of .01 was imposed to control for Type I errors. In another study (Lo & Lee, 2012) differences were found between PSQ good and poor sleepers in all 8 separate measures of the SF36 health questionnaire, and in a recent review (Sella, 2021), self-reported good sleep quality was found to be associated with better quality of life generally in older subjects, suggesting, in the authors' view, a need for further research in this area. This study is the first to examine sleep quality in relation to a broad range of psychological health measures based on multiple questionnaire responses and using factor analysis to reveal new aspects of this relationship. The results in the present study reveal where good and poor sleepers differ in matters of psychological health, but just as importantly, where they do not. In addition, factor analysis has enabled the identification of psychological health measures that may promote better VEM Long Term Forgetting, alongside sleep quality, as seen in Chapter 3.

This Chapter begins by explaining previous research on social networks and psychological health. This forms the background against which the interaction between age, psychological health and memory domain performance will then be analysed. Finally, the relationship

between sleep quality and psychological health is also considered. The aim is to understand what role, if any, psychological health plays in healthy cognitive ageing and how psychological health relates to some of the factors already considered, such as sleep and physical activity.

6.1.4. Good Cognitive Health in Older Age has been Associated with Larger Social Networks

Good cognitive health in older age has been extensively linked to the size of social networks (Krueger, 2009; Stevens & Van Tilburg, 2011; Holtzman, 2004; Hughes, 2008; Seeman, 2001; Giles, 2012; Cornwell & Laumann, 2015). Social network size may be related to higher cognitive or neural reserve (Bennett, 2006; Stern, 2002). Older people who are well-integrated socially may have more resilience against stress (De Jong Gierveld, 2016) and a larger social network, including more discretionary relationships with friends and confidants, may be a protective factor against risk of earlier mortality (Giles, 2005) and may improve physical health (Cohen & Janicki-Deverts, 2009). One study examined the effect of social networks on the relation between dementia pathology and cognitive function and found that, even for more severe pathology, cognitive function was still higher for those with larger social networks (Bennett, 2006).

6.1.5. Larger Friendship Networks may be More Important to Good Cognitive Health than Larger Family Networks

There are some qualifications to be made about the influence of social networks. First, size of network may not necessarily be the only factor in gauging their beneficial effect (Glass, 1997), and second, the type of network (e.g. friendship as opposed to family) may also be important (Cornwell, 2008; Ellwardt, 2015). Recently studies have focused on the complexity of older individuals' social networks (as opposed to size alone) (e.g., Ellwardt, 2015; Litwin, 2015; Cornwell & Laumann, 2015). A larger homogenous network may afford different benefits from a smaller, more heterogenous one, and persons with large extended families do not necessarily have matching large friendship networks; one study (Giles, 2012) found that people with larger social networks of friends had better episodic memory than those with smaller networks, but this did *not* extend to larger networks comprising children, relatives or confidants. The authors concluded that "*the mechanisms through which different types of social network affect cognitive function* remain unclear" (Giles, 2012, at page 5, italics added).

The present study uses the Lubben Social Networks questionnaire (Lubben, 2006) which measures social networks across two sub-scales of 'Family' and 'Friendship' networks (see further under Methods below). It will be assumed, based on the earlier research described

above, that larger social networks, and especially larger *friendship* networks, will also tend to be more complex social networks. Accordingly, references to 'larger social networks' will, except where otherwise stated, be taken to mean also more complex networks. In the analysis of results, the Social Connectedness PCA factor is a composite of both family and friendship measures, and so 'Lubben' Family and Friendship networks will also be analysed separately, wherever appropriate.

6.1.6. Previous Research shows that Older People may enjoy more Positive Psychological Health but this is counter-balanced by the Risk of Greater Loneliness

The well-established associations between smaller or less complex social networks and older age could imply that older age is characterised by social withdrawal and consequentially lower psychological mood and greater unhappiness. However, evidence tends to suggest otherwise. Although the meaning of happiness may change across the lifespan (Mogilner, 2011), ordinarily, older age is strongly associated with better psychological health and wellbeing, higher sociability and lower levels of negative social experience and social fearfulness (Ryff, 1989; Bishop, 2006; Cornwell, 2008; Oerlemans, 2011; Olds, 2016).

However, counterbalancing these positive aspects of psychological health in older age, individuals who are more socially isolated risk greater loneliness (Van Tilburg, 1990; 1998; Bassuk, 1999) and levels of loneliness increase with age (Dahlberg, 2015; Aartsen & Jylha, 2011, Cohen-Mansfield, 2009) and negatively affect quality of life (Victor, 2000; 2005; Cacioppo, 2009; Arslantas, 2014). Loneliness in old age is associated with dementia risk (Fratiglioni, 2004; Bennett, 2006; Rafnsson, 2020) and people who are lifelong single have 42% increased risk of dementia compared to married people (Sommerlad, 2018). Loneliness is strongly related to stress and may be as much of a health risk as, for example, smoking or obesity (Singer, 2018; Campagne, 2019). Social support and physical activity have been found to alleviate the stress caused by loneliness (Kwag, 2011) and, unsurprisingly therefore, the link between stress and loneliness has been exacerbated by the Covid 19 pandemic (Donovan & Blazer, 2020). It is expected therefore that higher loneliness in this sample may be associated with older age and smaller social networks, lower sociability and poorer psychological health. Together these factors could contribute to worse memory domain performance.

6.1.7. Sleep Quality and 'Everyday' Psychological Mood is less well explored than Problematic Areas of Sleep and Psychological Health, such as Insomnia and Depression

Whilst some earlier research has reported associations between sleep and psychological problems (e.g. between insomnia and depression; Buysse, 2008), there appears to be much less research on potential links between sleep quality and 'everyday' psychological mood, although in a longitudinal study, loneliness has been found to predict sleep quality (McHugh & Lawlor, 2013) which the authors suggested may be attributable to the stress caused by loneliness. In a recent cross-sectional study of Iranian medical students (Rezaei, 2018), the Pittsburgh Sleep Questionnaire (PSQ; Buysse, 1989) and the DASS 21 distress questionnaire (Lovibond & Lovibond, 1995) were used to assess sleep quality and psychological health respectively. The authors (who stated at page 279 that "no previous study has examined the relationship between psychological distress and sleep quality using both DASS 21 and PSQI") found that students with better psychological mood and lower distress also had lower (better) PSQI scores. The present study has also used the PSQ, the DASS 21 questionnaire and the UCLA Loneliness scale (see under Methods below), but has also gone further into examining the link between psychological health and sleep quality by including a wider range of psychological health questionnaires and composite psychological health measures derived from factor analysis. It has been previously shown that sleep deprivation (an aspect of poor sleep quality) may influence negative salience so that negative memories are preferentially reinforced (Walker & Stickgold, 2006). This is the first study to examine how self-reported sleep quality and psychological health (e.g., 'Positive' or 'Negative' Social Experience) may together affect long-term memory.

6.1.8. Hypotheses

It is hypothesised that, in line with earlier research, older age may be associated with better psychological mood but perhaps also with lower sociability, smaller social networks and higher loneliness. These matters may affect performance in memory domains and, in particular, better psychological mood and larger social networks may predict better memory domain performance. In line with findings elsewhere (e.g., Rezaei, 2018; Sella, 2021; Lo & Lee; 2012; Driscoll, 2008), it is also hypothesised that poorer sleep may be associated with lower psychological mood.

6.2. METHODS

6.2.1. General Approach: Exploratory PCA Factor Analysis has been used to Reduce Questionnaire Scores into Five Psychological Health Factors

Table 2.9 in Chapter 2 shows the five separate social psychological health factors and the underlying questionnaires that comprise those factors. The factors 'Positive Social Experience', 'Social Confidence' and 'Social Connectedness' are derived from a single PCA factor analysis (and therefore have Pearson correlations of zero as between each other) and the factors 'Negative Social Experience' and 'Social Fearfulness' are derived from a second separate PCA factor analysis (and also have a Pearson correlation of zero with each other). As described in Chapter 2, two separate exploratory PCA factor analyses were required because of the limitations of case to variable ratios (10:1) due to the number of questionnaire scores and sample size (N=140). Before proceeding with exploratory factor analysis, questionnaire scores were first divided between questionnaires relating more to aspects of 'Sociability' and questionnaires relating more to aspects of 'Psychological Mood'. Some questionnaire scores were included in both PCA factor analyses (e.g. the Liebowitz Social Anxiety questionnaire and the UCLA loneliness scale) and therefore appear in both factor sets (see Table 2.9). 'Social Connectedness' comprises both elements of the Lubben social networks questionnaire; the Family subscale and the Friendship subscale.

6.2.2. The PCA Factor Psychological Health Factors divide into two Mirror-Image Pairs of Factors (comprising 'Psychological Mood' and 'Sociability' factors) and a Wholly Separate Factor, Social Connectedness

Factor analysis produced two separate sets of factors based on the questionnaire responses (see Table 2.9 in Chapter 2). The first set comprises 'positive' psychological health factors (labelled 'Positive Social Experience', Social Confidence' and 'Social Connectedness'); in this set of PCA factors, higher scores denote higher levels of sociability or social functioning. The second set of PCA factors comprises 'negative' psychological health factors (labelled 'Negative Social Experience' and 'Social Fearfulness'); in this set of PCA factors, higher scores denote higher levels of negative psychological mood or functioning.

As there is some overlap in the underlying questionnaires in the first and second sets of factors, there is a very strong negative association across the two factor sets between Positive Social Experience and Negative Social Experience (Pearson's $r=-.826$, $p<.0001$) and also between Social Confidence and Social Fearfulness (Pearson's $r=-.880$, $p<.0001$) (see Table 2.10 in Chapter 2). (As a reminder, factors in the same set have a zero correlation). The strong

association between ‘Social Confidence’ and ‘Social Fearfulness’ is to be expected as the Liebowitz questionnaire score is common to both factors. The Diener SPANE (Positive Affect) score and the UCLA Loneliness Scale score is common to both Positive Social Experience and Negative Social Experience. The two highly correlated groupings might therefore be conveniently labelled as ‘Psychological Mood’ factors (i.e. PCA Factors 1A and 1B, Positive and Negative Social Experience) and ‘Sociability’ factors (i.e. PCA Factors 2A and 2B, Social Confidence and Social Fearfulness).

Although there is a ‘mirror-image’ of pairs of factors in the two sets of PCA social psychological factors, the linkage does not extend between the components of the mirror image pairs. Accordingly, Positive Social Experience (Set 1) and Social Fearfulness (Set 2) are unrelated (Pearson’s r=-.011, p=.9) and there is only a very weak marginal relationship between higher Negative Social Experience (Set 2) and lower Social Confidence (Set 1) (Pearson’s r=-.156, p=.07). This tends to support the view that the ‘Psychological Mood’ construct (PCA factors 1A and 1B) and the ‘Sociability’ construct (PCA factors 2A and 2B) are separate, independent constructs.

The fifth PCA factor, Social Connectedness, is separate from the mirror image pairs, although as a measure of social networks, it is perhaps more of a Sociability than Psychological Mood measure. The correlation between Social Connectedness and Negative Social Experience (Pearson’s r=-.267, p=.002; see Table 2.10) is underpinned by separate, negative correlations between both elements of the Lubben questionnaire (Family Networks, Pearson’s r=-.278, p=.001; Friendship Networks, Pearson’s r=-.337, p<.0001) and Negative Social Experience. Social Fearfulness shows a significant, *negative* correlation with Friendship Networks (Pearson’s r=-.192, p=.024) but a non-significant positive correlation with Family Networks (Pearson’s r=.145, p=.09). This illustrates how the underlying dimensions of the Social Connectedness factor may work in quite different ways (and see 6.1.5 above for the potentially different effects of larger friendship networks, as opposed to family networks).

6.2.3. Details of the Underlying Questionnaires are Provided in relation to the PCA Psychological Factors where they appear as Component Scores

The 15 questionnaires used in the assessment of psychological health and wellbeing are listed in Appendix 4. The underlying questionnaires for which scores and results have been reported in the Results section of this Chapter 6, both in the PCA factor scores and for the underlying questionnaires themselves, are as follows:

6.3. PCA Factor 1A: Positive Social Experience

6.3.1. Diener Scale of Positive and Negative Experience (Diener SPANE)

The Diener SPANE (Diener, 2009) assesses 'positive' and 'negative' experience by asking subjects to rate, on a 1-5 Likert scale, how often (from 'very rarely' to 'very often') they have experienced each of 6 positive and 6 negative feelings over the previous 4 weeks (e.g. happy, sad, afraid, joyful, angry, contented). The range for both positive (P) and negative (N) experience is on a scale of 6 to 30.

6.3.2. Diener Satisfaction with Life Scale

The Diener Satisfaction with Life Scale (Diener, 1985) comprises 5 statements concerning the respondent's satisfaction with life. Each statement is graded on a Likert scale of 1-7 (strongly agree, agree, slightly agree, neither agree nor disagree, slightly disagree, disagree and strongly disagree). This questionnaire produces a score (between 5 and 35) and a scale rating, also on a scale of 1-7 (extremely satisfied, satisfied, slightly satisfied, neutral, slightly dissatisfied, dissatisfied, extremely dissatisfied). In a review, the Diener Satisfaction with Life scale was found to be a good scale for assessment of emotional well-being (Pavot, 1991; Pavot & Diener, 2009).

6.3.3. Diener Flourishing Scale

The Diener Flourishing Scale (Diener, 2010) comprises 8 statements which are graded on the same Likert scale of 1-7 as the Diener Satisfaction with Life Scale. The score range is between 8 and 56 (low to high flourishing).

6.3.4. SF-36 Short Form General Health Assessment

The SF-36 Short Form General Health Assessment (Ware Jr & Sherbourne, 1992) ('the SF36') is a short-form health survey comprising 36 questions that are designed to provide a score in eight different health domains. These are: (1) physical functioning (2) limitations due to physical health problems (3) emotional wellbeing (4) limitations due to emotional problems (5) pain (6) energy and fatigue (7) social functioning and (8) general health. High scores denote better health in each of the categories so, for example, a higher score in category 6 denotes higher energy and lower fatigue. The SF36 is widely-used with good reliability (Gandek, 1998; Brazier, 1992; Hayes, 1995; Jenkinson, 1993).

As further described in Results below, PCA factor analysis has also been used to reduce the 8 separate SF36 component scores to two reliable factors, labelled 'SF36 Psychological' and 'SF36 Physical'. Examples of the questions in these factors are as follows:

SF 36 Psychological

Emotional Wellbeing

How much of the time during the past 4 weeks

- Have you felt so down in the dumps that nothing could cheer you up
- Have you been a happy person

Energy and Fatigue

How much of the time during the past 4 weeks

- Did you have a lot of energy
- Did you feel worn out

Limitations Due to Emotional Problems

During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)

- Cut down the amount of time you spent on work or other activities

Social Functioning

During the past 4 weeks, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbours or groups

SF36 Physical

Physical Functioning

The following items are about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much

- Moderate activities, such as moving a table, pushing a vacuum cleaner, bowling or playing golf
- Lifting or carrying groceries
- Climbing several flights of stairs

Limitations Due to Physical Health Problems

During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of your physical health?

- Had difficulty performing the work or other activities (for example, it took extra effort)

Each of the questions in the SF36 has a range of answers, the scores on which differ according to the question and response option. The range is always 0-100 (low health-high health).

6.3.5. The UCLA Loneliness Scale

The UCLA Loneliness Scale (Russell, 1980) aims to assess loneliness through 20 questions including the following

- Question 5: I feel part of a group of friends
- Question 10: There are people I feel close to
- Question 19: There are people I can talk to

Each question is scored on a Likert scale of 1 to 4, with a score range of 20 to 80 (low to high loneliness).

6.4. PCA Factor 2A: Social Confidence

6.4.1. Liebowitz Social Anxiety Scale

The Liebowitz Social Anxiety Scale (Heimberg, 1999) assesses social anxiety and fearfulness for each of 24 defined situations on two dimensions; first, how much the situation is feared (none, mild, moderate, severe) and second, how often the situation is avoided (never, occasionally, often, usually). Examples of the situations are:

- Acting, performing or speaking in front of an audience
- Calling someone you don't know very well
- Being the centre of attention

Each of the sub-scales, fear and avoidance, have a range of 24 to 96 ('low' to 'high' social fear and anxiety).

6.4.2. The Social Situation Questionnaire

This questionnaire (included in full in Appendix 5) was developed by University of Durham researchers and aims to assess a subject's 'sociability' by asking about their propensity for social approach and for developing and maintaining friendship networks. Example questions include:

- Question 2: I find it easy to meet new people
- Question 5: I have friends outside of family members that I see on at least a fortnightly basis
- Question 12: I enjoy socialising outside of my home environment

Each answer is scored on a Likert scale of 1 to 5 from ‘strongly agree’ to ‘strongly disagree’. The score range is 16 (lowest, bad) to 80 (highest, good).

6.5. PCA Factor 3: Social Connectedness

6.5.1. The Lubben Social Networks Questionnaire

The Lubben Social Networks questionnaire (Lubben, 2006) determines the size of a person’s social network on two separate sub-scales for family and friendship networks. Scores on each sub-scale are determined by the number of persons (family or friends) who meet certain tests for the subject (e.g., ‘how many relatives do you feel close to such that you could call on them for help?’). Scores are determined on a Likert scale of 0-5 for each of 3 questions for each sub-scale, giving a score range for both family and friendship scales of 0 to 15.

6.6. PCA Factor 1B: Negative Social Experience

6.6.1. DASS 21

The DASS 21 (Lovibond & Lovibond, 1995) is a short-form measurement standing for ‘Depression Anxiety Stress Scale’ and is based on responses to 21 questions about feelings in the previous week and a single score (range 0-63). The DASS 21 Distress questionnaire score is the basis for a ‘severity rating’ on three measures of distress: stress, anxiety and depression. For each of the three measures, there are 5 levels of severity; ‘normal’, ‘mild’, ‘moderate’, ‘severe’ and ‘extremely severe’. Scores are multiplied by 2 for the purposes of assessment on the severity scales (i.e., in a range of 0-126). The scales are different for each of the three measures. For example, an ‘extremely severe’ rating for anxiety is a (doubled) score of 20 or higher whereas an ‘extremely severe’ rating for stress is a (doubled) score of 34 or higher.

Example questions include:

- Question 10: I felt I had nothing to look forward to
- Question 12: I found it difficult to relax
- Question 18: I felt that I was rather touchy

6.6.2. Zung Anxiety Scale

The Zung Anxiety Scale (Zung, 1971) is a self-rating questionnaire for anxiety and mood disorders. Despite being 50 years old, the questionnaire is still used extensively in clinical practice (Dunstan & Scott, 2018; 2020). There are 20 statements which are rated on a 5 point

Likert scale, from ‘strongly disagree’ to ‘strongly agree’. The score range is from 20 (low) to 100 (high) anxiety. Example questions include:

- Question 3: I get upset easily or feel panicky
- Question 8: I feel weak and get tired easily
- Question 20: I have nightmares

6.7. PCA Factor 2B: Social Fearfulness

6.7.1. Brief Fear of Negative Evaluation (BFNE)

The BFNE (Carleton, 2007) measures subjects’ social fearfulness. Example questions include:

- Question 3: I am frequently afraid of other people noticing my shortcomings
- Question 5: I am afraid that others will not approve of me
- Question 6: I am afraid that other people will find fault with me

Each answer is scored on a Likert scale of 1 to 5 depending upon how ‘characteristic of me’ the subject determines each statement to be. The score range is from 12 (low fear of negative evaluation) to 60 (high fear of negative evaluation).

As explained in Chapter 2, the labels ascribed to the two PCA factors in each of the Psychological Mood and Sociability domains are umbrella terms of convenience rather than a technical summary of the underlying questionnaire components. For example, the PCA factor Negative Social Experience includes component scores for the Zung Anxiety scale, the DASS 21 questionnaire and UCLA Loneliness scale. Each questionnaire assesses different aspects of more negative social experience (anxiety, distress, loneliness) and the factor label is therefore used as a convenient summary for these very different components.

6.8. Other Questionnaires

In addition, this Chapter 6 also features two questionnaires that were not included in the PCA exploratory factor analyses carried out for psychological health scores.

First, the Pittsburgh Sleep Questionnaire (the ‘PSQ’, Buysse, 1989) has been described in detail in Chapter 3 (Sleep) above.

Second, the Spatial Abilities questionnaire is another questionnaire developed by University of Durham researchers and included in full in the Appendix 6. The aim of the questionnaire is for the subject to self-report their spatial abilities and practices in everyday life. There are 15

performance questions which are each score on a Likert scale of 1-5 (‘strongly agree’, ‘agree’, ‘undecided’, ‘disagree’ and ‘strongly disagree’). There are also 15 ‘change’ questions which ask whether spatial ability performance has changed in the last year on a Likert scale of 1-3 (‘better’, ‘same’ or ‘worse’). Example questions include:

- Question 7a: I find it easy to remember precisely where the car is parked
- Question 10a: It is difficult for me to find my bearings in a new town/city
- Question 11a: As a passenger in a car, I usually have to take the same route many times to remember it

Results for the Spatial Abilities questionnaire are not reported in detail in the present study.

6.9. RESULTS

6.9.1. Previous Finding Not Replicated: Larger Social Networks do not appear to have any Direct Relationship with Better Memory Domain Performance

One specific measure of sociability used in this study is the Social Situation questionnaire (see Methods above). This questionnaire measures both current predisposition to, as well as personal 'trend' in, sociability. These two components of the Social Situation questionnaire are included in the Social Confidence PCA factor score (see Table 2.9 in Chapter 2). Current sociability is particularly strongly correlated with size of Friendship Networks (Pearson's r=.547, p<.0001) and also with the Social Connectedness factor score (Pearson's r=.478, p<.0001). Current sociability and trend in sociability are however only moderately associated with larger Family Networks (Pearson's r=.167, p=.048 and Pearson's r=.175, p=.039 respectively). The correlations between the Social Situation score (current sociability) and both Family and Friendship networks are shown in Figure 6.1.

Figure 6.1: Higher Sociability is strongly associated with Larger Friendship Networks

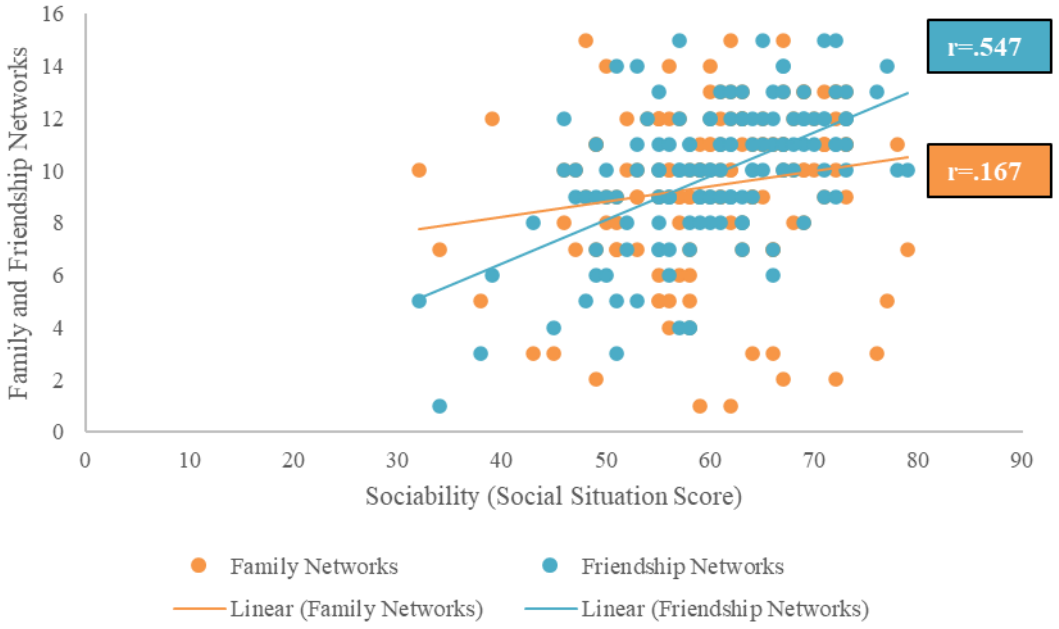


Figure 6.1 shows correlations between higher sociability (scores on the Social Situation questionnaire for current sociability) and larger social networks. Larger family networks are only moderately associated with higher sociability (Pearson's r=.167, p=.048) but larger friendship networks are strongly associated with higher sociability (Pearson's r=.547, p<.0001). These two measures of social networks are comprised in the PCA factor score for Social Connectedness which is itself also strongly correlated with higher current sociability as measured by the Social Situation Questionnaire (Pearson's r=.478, p<.0001).

Table 6.1: Social Connectedness is not associated with Age

Correlations with Age	r	p	r_s	p
Social Connectedness	-.068	.43	-.041	.64
Lubben Family Networks	-.012	.89	-.007	.94
Lubben Friendship Networks	.053	.53	.078	.36
Lubben Total Networks	.023	.79	.051	.55

Table 6.1 shows that there is no association (either using Pearson's r or Spearman's r_s correlations) between age and the PCA factor score for Social Connectedness or with the underlying scores for the Lubben Family and Lubben Friendship Networks.

Table 6.2: Neither Sociability nor Social Connectedness are associated with Memory Domain Performance

Sociability/ Social Connectedness	VEM Short Term Recall		Face Memory & Perception		VEM Long Term Forgetting		Working Memory	
	r	p	r	p	r	p	r	p
Social Situation Score	-.152	.07	-.067	.43	-.092	.28	-.051	.55
Family Networks	.022	.80	.059	.49	-.033	.70	.017	.85
Friendship Networks	-.099	.24	-.096	.26	.015	.86	-.058	.49
Social Connectedness	.010	.91	.040	.64	.008	.93	.015	.86
	r_s	p	r_s	p	r_s	p	r_s	p
Social Situation Score	-.170	.045	-.079	.35	-.114	.18	-.093	.28
Family Networks	.010	.91	.067	.43	-.051	.55	-.034	.69
Friendship Networks	-.091	.28	-.078	.36	.038	.65	-.053	.53
Social Connectedness	-.006	.94	.063	.47	.021	.81	-.013	.88

Table 6.2 shows that there are no significant positive correlations (Pearson's r or Spearman's r_s) between higher Sociability or larger Social Networks and better memory domain performance. Higher social situation score is weakly associated with worse VEM Short Term Recall (Spearman's r_s=-.170, p=.045) a negative trend seen in the previous chapter (Chapter 5) between certain levels of higher physical activity and lower VEM Short Term Recall. Orange shading denotes significant correlations.

Larger social networks, and in particular larger Friendship Networks, are therefore strongly associated with higher sociability, as measured by the Social Situation questionnaire. Older age is moderately associated in this study with higher Social Situation score (Pearson's r=.217, p=.010, Spearman's rs=.259, p=.002). However, there is no association between older age and size of social networks; see Table 6.1.

Table 6.2 shows that there are no significant positive correlations between either higher Social Situation score or larger social networks and any better performance in any of the four memory domain factors. Accordingly, there is no clear support in the present study for any relationship between larger social networks (or higher sociability) and better cognitive performance, as previously seen elsewhere (e.g., Cornwell & Waite, 2009; Giles, 2012).

*6.9.2. **Unexpected Finding:** Subjects with Higher Positive Social Experience and Lower Negative Social Experience have Lower (better) VEM Long Term Forgetting but there is a Diverging Pattern of Association with VEM Short Term Recall*

Table 6.3 shows Pearson's r and Spearman's r_s correlations between the other four PCA psychological health factors (i.e., apart from Social Connectedness) and performance in PCA memory domain factors. Notably, higher Positive Social Experience is associated with lower (better) VEM Long Term Forgetting (Pearson's r=-.220, p=.010, Spearman's r_s=-.266, p=.002) and higher Negative Social Experience is associated with higher (worse) VEM Long Term Forgetting (Pearson's r=.244, p=.004, Spearman's rs=.258, p=.002). These correlations are illustrated in Figure 6.2.

Table 6.3 also shows that worse VEM Short Term Recall is associated with higher Positive Social Experience and lower Negative Social Experience (i.e., the reverse pattern to VEM Long Term Forgetting) although these diverging correlations are only very moderate in comparison with those for VEM Long Term Forgetting.

Table 6.3: Psychological Health Factors show diverging associations with VEM Short Term Recall and VEM Long Term Forgetting

PCA Factor Memory Domains	VEM Short Term Recall		Face Memory & Perception		VEM Long Term Forgetting		Working Memory	
	r	p	r	p	r	p	r	p
Positive Social Experience	-.172	.044	-.151	.08	-.220	.010	-.144	.09
Social Confidence	-.176	.039	-.071	.41	.048	.58	-.016	.85
Negative Social Experience	.183	.032	.120	.16	.244	.004	.090	.29
Social Fearfulness	.193	.024	.091	.29	-.118	.167	.109	.20
	r_s	p	r_s	p	r_s	p	r_s	p
Positive Social Experience	-.169	.047	-.169	.048	-.266	.002	-.200	.019
Social Confidence	-.180	.035	-.083	.33	.008	.92	-.042	.63
Negative Social Experience	.190	.026	.139	.10	.258	.002	.143	.09
Social Fearfulness	.237	.005	.105	.22	-.084	.33	.115	.18

Table 6.3 shows Pearson's r and Spearman's r_s correlations between PCA psychological health factors and performance in PCA memory domain factors. Correlations with better VEM Short Term Recall show an unexpected pattern with lower Psychological Mood and lower Sociability, but contrastingly better Psychological Mood is associated with lower VEM Long Term Forgetting (see text for further detail.) Orange shading denotes significant results.

Figure 6.2 Better VEM Long Term Forgetting is correlated with higher Positive Social Experience and lower Negative Social Experience (or better Psychological Mood)

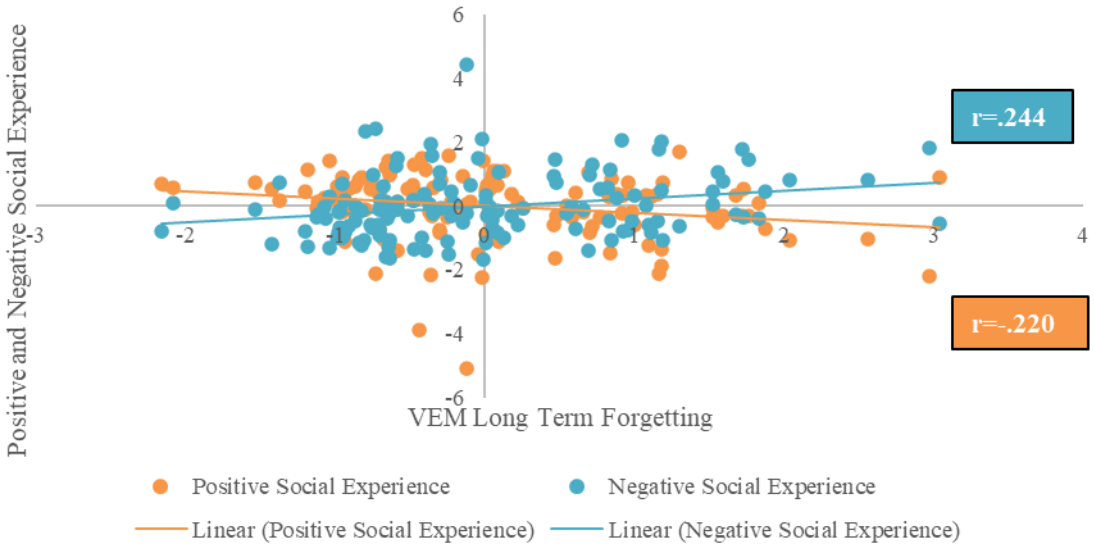


Figure 6.2 shows that higher (worse) VEM Long Term Forgetting is strongly associated with higher Negative Social Experience (Pearson's r=.244, p=.004). Conversely, lower (better) VEM Long Term Forgetting is associated with higher Positive Social Experience (Pearson's r=-.220, p=.01). There is therefore a clear relationship between lower (better) VEM Long Term Forgetting and better Psychological Mood. Neither Social Confidence nor Social Fearfulness are associated with VEM Long Term Forgetting. See Table 6.3 for further details.

*6.9.3. A **Replicated Finding**: Subjects with Worse Sleep Quality have Higher DASS 21 Distress*

In a recent study (Rezaei, 2018), it was seen that good sleepers (as measured by the PSQI) had lower levels of DASS 21 distress than poor sleepers. Figure 6.3 shows how, consistent with this earlier finding, a higher (worse) PSQI score is associated with a higher (worse) DASS 21 score (Pearson's r=.249, p=.003, Spearman's r_s=.237, p=.005). For comparison purposes with earlier findings on sleep quality and loneliness (McHugh & Lawlor, 2013; see above), Figure 6.3 also shows how a higher (worse) PSQI score is even more strongly associated with higher loneliness (Pearson's r=.317, p=.0001, Spearman's rs=.361, p<.0001).

Figure 6.3: Worse Sleep Quality (a higher PSQI score) is associated with higher DASS 21 distress and higher Loneliness

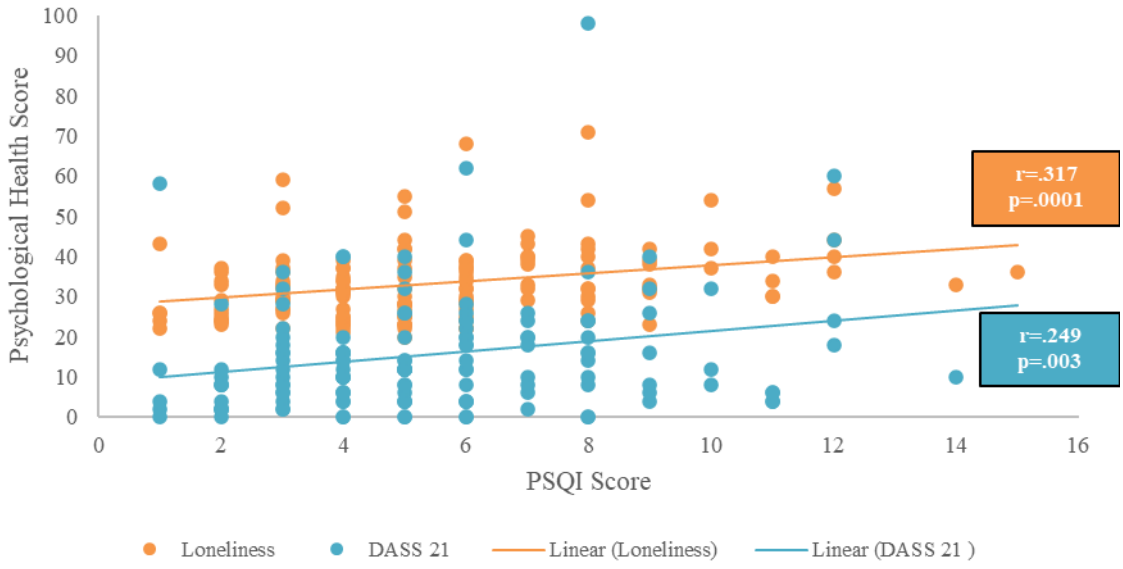


Figure 6.3 shows that a higher (worse) PSQI score is associated with a higher DASS 21 distress score (in line with Rezaei, 2018) and with higher loneliness, as measured by the UCLA Loneliness Scale. The scores for DASS 21 distress represented in Figure 6.3 are those which are used to calculate ratings on the DASS stress, anxiety and depression scales (i.e. the doubled DASS 21 score) in order for more straightforward comparison with scores on the UCLA Loneliness scale.

Table 6.4: Better Psychological Health is associated with Older Age but in a more limited way with Better Sleep Quality (a lower PSQI Score)

	Correlations with PSQI Score (r)		Correlations with PSQI Score (r_s)		Correlations with Age (r)		Correlations with Age (r_s)	
	r	p	r_s	p	r	p	r_s	p
'Psychological Mood' PCA Factors								
Positive Social Experience	-.347	<.0001	-.395	<.0001	.291	.001	.261	.002
Negative Social Experience	.373	<.0001	.422	<.0001	-.247	.004	-.213	.012
'Sociability' PCA Factors								
Social Confidence	-.178	.037	-.110	.20	.178	.037	.199	.019
Social Fearfulness	.157	.07	.083	.33	-.269	.001	-.282	.001

Table 6.4: This table shows Pearson's r and Spearman's r_s correlations between age, PSQI scores and the PCA psychological health factors. Older age is strongly associated with better Positive Social Experience, lower Negative Social Experience and lower Social Fearfulness and more moderately with better Social Confidence. Positive and Negative Social Experience ('Psychological Mood') are strongly associated with PSQI score but the PCA factors Social Confidence and Social Fearfulness ('Sociability') are not. There is only a moderate association between higher Social Confidence and a lower/better PSQI score. Orange shading denotes significant results.

*6.9.4. A **Main New Finding (1)**: Subjects with Better Sleep Quality have Higher Positive Social Experience and Lower Negative Social Experience*

Table 6.4 shows correlations between both PSQI score and age and the PCA Psychological health factor scores for Psychological Mood and Sociability. Older age is associated with higher Positive Social Experience (Pearson's r=.291, p=.001), lower Negative Social Experience (Pearson's r=-.247, p=.004), higher Social Confidence (Pearson's r=.178, p=.037) and lower Social Fearfulness (Pearson's r=-.269, p=.001); i.e. older age is associated with better Psychological Mood and better Sociability.

Table 6.4 also shows that there are strong correlations between both Positive and Negative Social Experience (i.e. Psychological Mood) and the PSQI score. The strongest of these correlations is between a higher (worse) PSQI score and higher Negative Social Experience (Pearson's r=.373, p<.0001, Spearman's rs=.422, p<.0001). Howerver, the negative correlation between higher (worse) PSQI score and lower Positive Social Experience is also strong (Pearson's r=-.347, p<.0001, Spearman's rs=-.395, p<.0001). These higher correlations than are evident for DASS 21 alone suggest that the association between low Psychological Mood and worse PSQ sleep extends beyond the DASS 21 scale shown previously (Rezaei, 2018).

*6.9.5. A **Main New Finding (2)**: Older Age is Strongly Associated with Better 'Psychological Mood' and 'Sociability' but Better PSQI Score is Strongly Associated Only with Better Psychological Mood*

By contrast, Table 6.4 also shows that there are no strong correlations between PSQI score and either of the 'Sociability' PCA factors, Social Confidence or Social Fearfulness. The difference in the pattern of psychological health correlations with age and PSQI score respectively is shown in comparing correlations in Table 6.4. Strong *age* correlations extend across all PCA psychological health factor scores, but are limited to Positive and Negative Social Experience with the PSQI. Although a worse PSQI score is very moderately associated with lower Social Confidence (Pearson's r=-.178, p=.037), this association does not appear in the non-parametric test (Spearman's r=-110, p=.20).

The comparison between age and PSQI score in Psychological Mood and Sociability factors is illustrated in Figure 6.4.

The divergence in the relationship between the PSQI and 'Psychological Mood' versus 'Sociability' is further emphasised by the comparisons between good and poor sleepers shown in Figure 6.5 where the significant correlations are reflected in strong differences between good and poor sleepers (only) in Positive and Negative Social Experience. Good and poor sleepers noticeably do not differ in Social Confidence, Social Fearfulness or Social Connectedness.

The differences in the correlations with PSQI scores between Positive and Negative Social Experience on the one hand and Social Confidence and Fearfulness on the other strongly suggests that *only some* scores from the underlying standard psychological health questionnaires appear to be associated with PSQ sleep quality. Further exploratory analysis was carried out to determine more precisely those psychological health measures which are (and those which are not) associated with better sleep, and which may in turn affect VEM Long Term Forgetting.

Figure 6.4: Older age is associated with better Psychological Mood and higher Sociability but Better Sleep is only strongly associated with better Psychological Mood

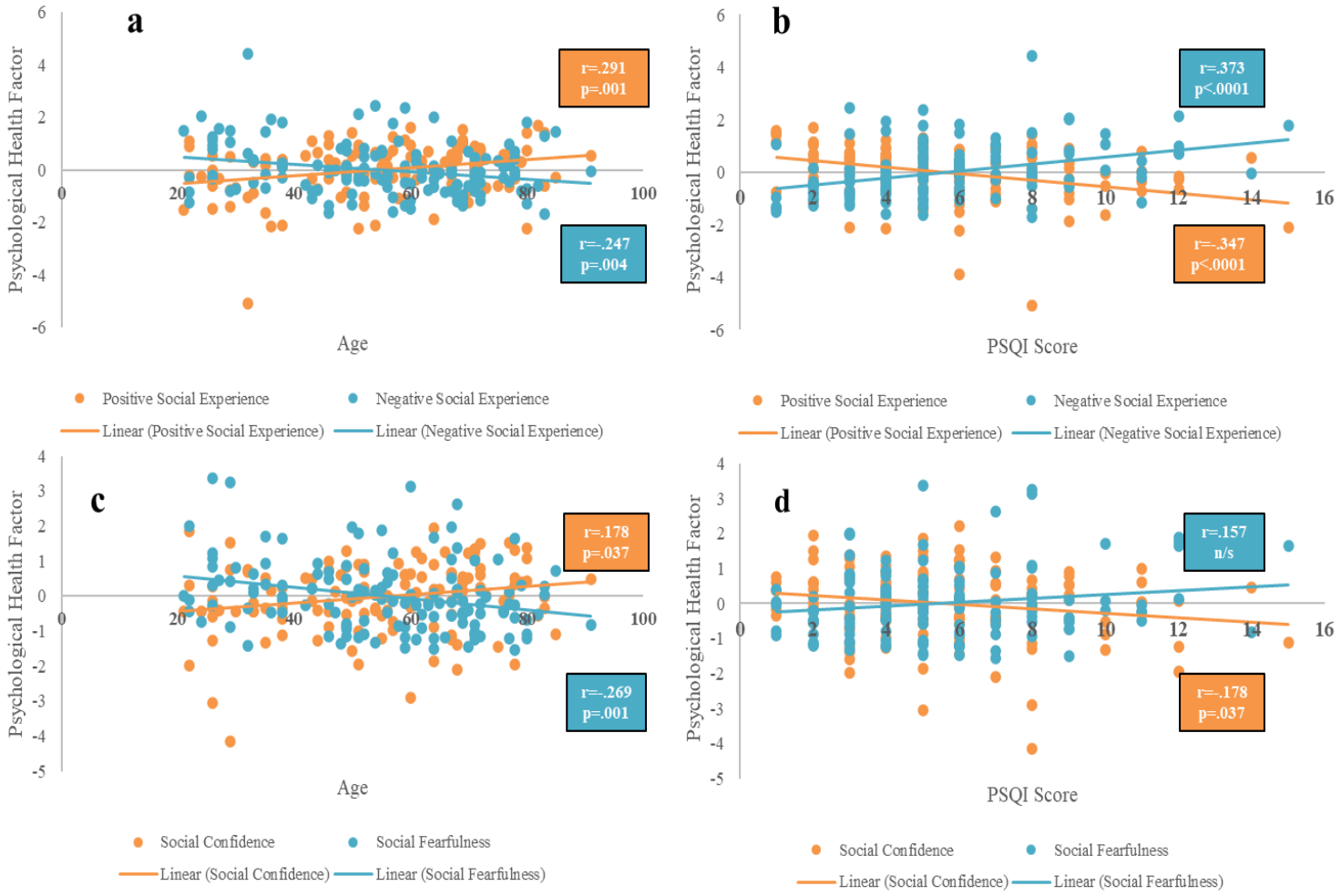


Figure 6.4 a and b show Pearson's r correlations between Positive and Negative Social Experience and both age and PSQI Score. Higher Positive Social Experience is associated with a lower PSQI score or better sleep (r=-.347, p<.0001) and older age (r=.291, p=.001) whereas higher Negative Social Experience is associated with a higher PSQI score or worse sleep (r=.373, p<.0001) and younger age (r=-.247, p=.004). **Figure 6.4 c and d** show Pearson's r correlations between Social Confidence, Social Fearfulness and both age and PSQI Score: Higher Social Confidence is only moderately associated with lower PSQI score or better sleep (r=-.178, p=.037) and with older age (r=.178, p=.037). There is no evidence of an association between higher Social Fearfulness and higher PSQI score or worse sleep, but younger age is strongly associated with higher Social Fearfulness (r=-.269, p=.001).

Figure 6.5: Good Sleepers have higher Positive and lower Negative Social Experience (Psychological Mood) PCA factor scores than Poor Sleepers. Good and Poor Sleepers do not differ in Social Confidence, Fearfulness or Connectedness (Sociability) PCA factor scores

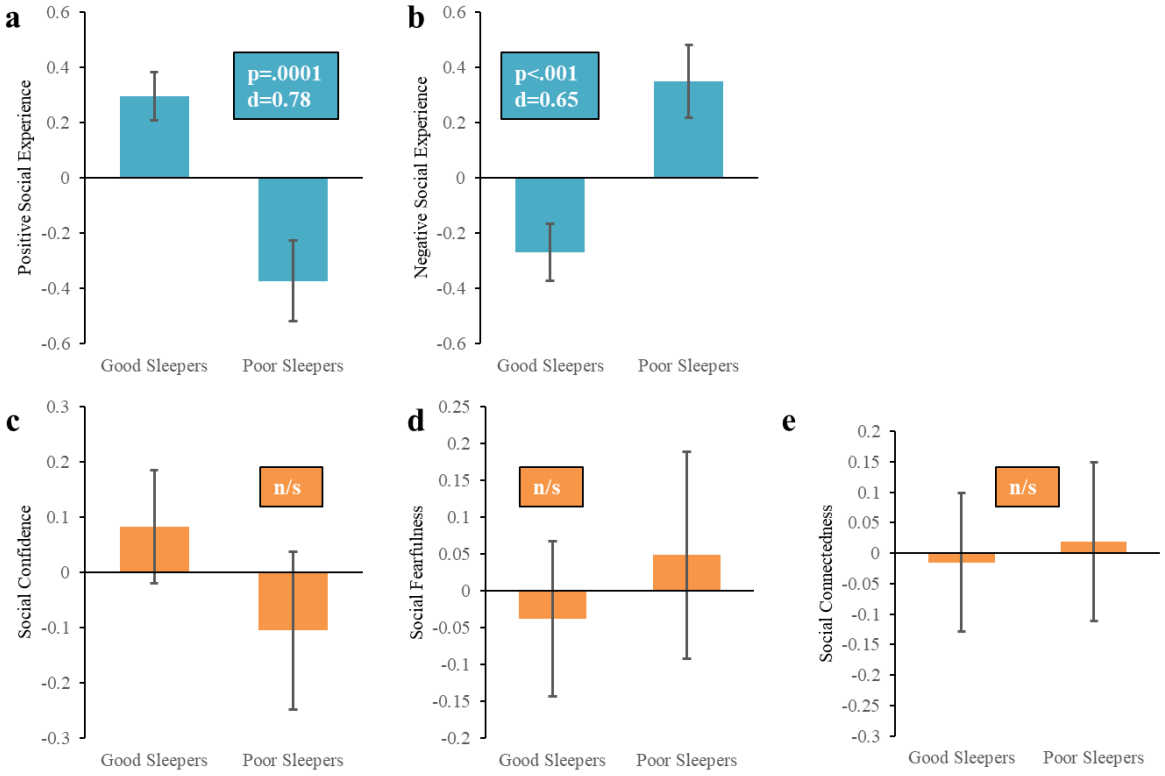


Figure 6.5 compares good and poor sleepers in the Psychological Mood PCA factors, Positive & Negative Social Experience and in the Sociability PCA factors, Social Confidence, Social Fearfulness and Social Connectedness. **a** & **b**: Psychological Mood. **a**. Good sleepers have higher Positive Social Experience than poor sleepers; $t_{101.181}$=3.940, p=.0001, Cohen's d=0.78. **b**. Good sleepers also have lower Negative Social Experience than poor sleepers; t_{136}=-3.764, p<.001, Cohen's d=0.65. **c**, **d** & **e**: Sociability. **c**. Good sleepers and poor sleepers do not score differently on Social Confidence; t_{136}=1.099, p=.27. **d**. Good sleepers also score no differently from poor sleepers on Social Fearfulness; t_{136}=-.501, p=.62. **e**. Good sleepers and poor sleepers do not score differently on Social Connectedness; t_{136}=-.196, p=.85. Error bars show +/- one s.e.m.

*6.9.6. A **Main New Finding (3):** Good and Poor Sleepers do not differ on Negative Affect, Fear of Negative Evaluation or Social Fear and do not differ in Social Situation score or in Size of Social Networks*

Table 6.5 shows where good and poor sleepers differ on the underlying psychological health questionnaire scores. It can be seen that good and poor sleepers *do not differ* on negative affect (Diener SPANE Negative Affect), fear of negative evaluation (BFNE) or social fear (Liebowitz

Table 6.5: Good Sleepers and Poor Sleepers differ across a range of Psychological health assessment measures but these measures are not generally correlated with VEM Long Term Forgetting

Psychological Measure	Good Sleepers	Poor Sleepers	Difference	Sig	Cohen's d	Correlation with VEM Long Term Forgetting (Pearson's r)	
Age	52.91 (16.74)	59.03 (17.07)	t_{138}=-2.127	.035	0.36	r	p
Diener Satisfaction With Life Scale	27.53 (5.59)	24.7 (6.59)	t_{138}=2.768	.006	0.47	-.097	.25
Diener Positive Affect	23.96 (3.57)	21.87 (4.4)	t_{138}=3.107	.002	0.53	-.205	.015
Diener Negative Affect	13.11 (4.16)	14.46 (4.19)	t_{138}=-1.892	.061	N/A	.064	.45
Diener Flourishing Scale	47.41 (5.33)	43.92 (7.8)	t_{137}=3.128	.002	0.53	-.031	.71
Zung Anxiety	35.29 (8.79)	42.49 (9.3)	t_{138}=-4.687	<.0001	0.80	.073	.39
DASS 21	6.47 (5.7)	9.64 (8.76)	$t_{97.667}$=-2.455	.016	0.50	.054	.52
Brief Fear of Negative Evaluation	28.39 (11.79)	27.15 (12.25)	t_{138}=.609	.54	N/A	-.006	.94
UCLA Loneliness Scale	30.91 (7.93)	36.28 (9.6)	t_{138}=-3.622	<.001	0.62	.094	.27
Social Situation (Sociability)	61.04 (8.55)	59.11 (9.08)	t_{138}=1.284	.20	N/A	-.092	.28
Lubben Family Networks	9.62 (3)	9.15 (3.1)	t_{138}=.909	.36	N/A	-.033	.70
Lubben Friendship Networks	9.82 (2.7)	9.82 (2.7)	t_{138}=.007	.99	N/A	.015	.86
Liebowitz Social Fear	40.24 (11.35)	41.36 (11.1)	t_{137}=-.561	.58	N/A	-.090	.29
Liebowitz Social Avoidance	33.91 (8.78)	38.43 (11.07)	t_{137}=-2.682	.008	0.46	.005	.96

Table 6.5 shows the differences between PSQ good and poor sleepers in some of the underlying psychological health questionnaires. The DASS 21 difference replicates that seen in Rezaei, 2018 but Table 6.5 also shows that the differences between good and poor sleepers extend beyond that single measure of psychological distress and can be seen in many other different measures of psychological health. Orange shading denotes significant differences between good and poor sleepers. Table 6.5 also shows Pearson's r correlations between the psychological measures and VEM Long Term Forgetting. The only moderate correlation is between higher Diener SPANE Positive Affect and lower VEM Long Term Forgetting (Pearson's r=-.205, p=.015; Spearman's r_s=-.242, p=.004). Orange shading denotes significant correlations. All other non-parametric correlations (not separately shown) are non-significant.

Fear Sub-scale). Also, good and poor sleepers do not differ on sociability (as determined by the Social Situation questionnaire score) or in the size of their Family or Friendship Networks. The pattern of differences (and absence of differences) suggests that while poor sleep is associated with lower Psychological Mood (as previously found by e.g., Rezaei, 2018 and McHugh & Lawlor, 2013), this does not extend into areas of Sociability, or (seemingly) social behaviour and functioning.

This finding is both new and unexpected. Moreover, although good and poor sleepers differ in Psychological Mood but not in Sociability, the correlations between these underlying questionnaire scores for Psychological Mood and Sociability are extensively strong. For example, higher UCLA loneliness score (a component of Positive Social Experience) and Lubben Friendship Networks (a component of Social Connectedness) are strongly negatively associated (Pearson's r=-.569, p<.0001; Spearman's r_s=-.440, p<.0001), even though Positive Social Experience and Social Connectedness factor scores in the same set have a correlation of zero. However, *within* the separate good and poor sleeper sub-groups, these strong associations between Psychological Mood and Sociability underlying scores remain strong. For example, UCLA loneliness/Friendship Networks correlations are: good sleepers: Pearson's r=-.615, p<.0001, Spearman's r_s=-.452, p<.0001; poor sleepers: Pearson's r=-.578, p<.0001, Spearman's r_s=-.499, p<.0001; and for UCLA loneliness/Social Situation score: good sleepers: Pearson's r=-.587, p<.0001, Spearman's r_s=-.506, p<.0001; poor sleepers: Pearson's r=-.564, p<.0001, Spearman's r_s=-.547, p<.0001. Supplementary Table 6.2 shows further examples.

Table 6.5 also shows the (absence of) associations between the underlying psychological health measures and VEM Long Term Forgetting. With the single exception of the score for Diener SPANE Positive Affect, where higher positive scores are moderately associated with better/lower VEM Long Term Forgetting (Pearson's r=-.205, p=.015; Spearman's r_s=-.242, p=.004), *none* of the underlying psychological health measures (where good and poor sleepers may or may not differ) is associated with higher or lower VEM Long Term Forgetting. Comparing this absence of correlations in the underlying questionnaire scores with VEM Long Term Forgetting with the strong correlations shown in Figure 6.2 between better VEM Long Term Forgetting and Positive and Negative Social Experience appears unusual because Positive and Negative Social Experience together comprise seven of these underlying scores (see Table 2.9 in Chapter 2). Positive and Negative Social Experience also comprise 4 of the 8 measures from the SF36 Short Form Health questionnaire. Supplementary Table 6.3 shows a detailed comparison between individual questionnaire scores and the 8 separate components of the SF36. As a result, exploratory PCA factor analysis was also undertaken on the SF36 Short Form Health Assessment in order to determine whether there were any other composite psychological health factor measures which might be associated with PSQ sleep quality, and also with VEM Long Term Forgetting.

*6.9.7. A **Main New Finding (4)**: PCA Factor Analysis Reliably Divides the SF36 Short Form Health Assessment between Psychological and Physical Health Factors*

PCA exploratory factor analysis revealed that the 8 separate health measures comprised in the SF36 that are traditionally reported separately (see, e.g., Jenkinson, 1993) generated a strong two factor solution with distinct and separate psychological and physical factors, and this is shown in Table 6.6. Reliability analysis shows that the two factor solution is robust (Cronbach's α =.782). Further statistical support for the PCA factor analysis of the SF36 (communalities, ant-image correlations and scree plot) is provided in Supplementary Table and Figure 6.2.

Table 6.6: The SF36 Short Form Health Survey can be divided between Psychological and Physical Health Constructs

SF36 PCA Factor 1 SF36 Psychological		**SF36 PCA Factor 2 SF36 Physical**	
SF36 Emotional Well-Being	.866	SF36 Physical Functioning	.815
SF36 Energy & Fatigue	.789	SF36 Limits (Physical)	.756
SF36 Limits (Emotional)	.746	SF36 Pain	.677
SF36 Social Functioning	.703		
SF36 General Health	.571		
Eigenvalue	3.253		1.621
% of Variance	40.67		20.26
Cumulative Variance %	40.67		60.93

SF36 PCA Factor 1 SF36 Psychological			**SF 36 PCA Factor 2 SF36 Physical**		
	CITC	CAIID		CITC	CAIID
Limits (Emotional)	.545	.792	Physical Functioning	.529	.487
Energy & Fatigue	.663	.708	Limits (Physical)	.500	.516
Emotional Wellbeing	.661	.725	Pain	.391	.630
Social Functioning	.605	.736			
General Health	.364	.759			
Cronbach's α	**.782**			**.646**	
Standardized Cronbach's α	**.815**			**.661**	

Table 6.6 shows a two factor solution for the 8 health measures of the SF36 Short Form Health Questionnaire. Principal Component Analysis or PCA was used as the extraction method and Varimax with Kaiser Normalization as the rotation method. The top half of Table 6.6 shows the rotated component matrix scores. PCA suggests a two factor solution (see Supplementary Table and Figure 6.2 for further confirmatory analysis). Coefficients have been suppressed below 0.512. The Kaiser-Meyer-Olkin measure of sampling adequacy is .760 which suggests a strong factor solution. Bartlett's test of sphericity is <.0001 and the determinant is 0.073 which means that there is no evidence of multicollinearity or singularity in the data. The bottom half of Table 6.6 also shows the reliability analysis for each of the two factors (labelled 'SF36 Psychological' and 'SF36 Physical') and shows Cronbach's a and Cronbach's a based on standardized items (Standardized Cronbach's a) for each of the two separate factors, together with Corrected Item-Total Correlation (CITC) and Cronbach's Alpha If Item Deleted (CAIID). For PCA Factor 1, the SF36 Psychological factor, Cronbach's a might be improved by removing the score for Limits (Emotional) but this would only make a small improvement (.010) and overall Cronbach's a is reasonable if the item remains.

Table 6.7 shows correlations between the two SF36 PCA factors (here labelled 'SF36 Psychological' and 'SF36 Physical') and age and performance in the four memory domain

Table 6.7: Psychological and Physical health are differentially associated with Memory Domain Performance

	Age		VEM Short Term Recall		Face Memory & Perception		VEM Long Term Forgetting		Working Memory	
	r	p	r	p	r	p	r	p	r	p
SF36 Psychological	.406	<.0001	-.204	.016	-.127	.13	-.254	.003	-.114	.18
SF36 Physical	-.386	<.0001	.082	.33	.165	.053	-.135	.11	.318	.0001
	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p
SF36 Psychological	.391	<.0001	-.186	.029	-.166	.050	-.289	.001	-.150	.078
SF36 Physical	-.418	<.0001	.096	.26	.133	.12	-.080	.35	.173	.041

Table 6.7 shows Pearson's r and Spearman's r_s correlations between the two SF36 PCA factors, SF36 Psychological and SF36 Physical, and both age and performance in memory domain factors. Older age is strongly associated with better SF36 Psychological scores but younger age is strongly associated with better SF36 Physical scores. Higher SF36 Psychological scores are associated with *worse* VEM Short Term Recall but with *better* VEM Long Term Forgetting. Better SF36 Physical scores are associated with better Working Memory. Orange shading denotes significant associations.

factors. A number of dissociations arise. First, older age is strongly associated with *higher* SF36 Psychological scores (Pearson's r=.406, p<.0001) but *lower* SF36 Physical scores (Pearson's r=-.386, p<.0001). This indicates that the two SF36 factors represent very different measures. Second, higher (better) SF36 Psychological scores are moderately negatively correlated with lower/worse VEM Short Term Recall (Pearson's r=-.204, p=.016), but more strongly with lower/better VEM Long Term Forgetting (Pearson's r=-.254, p=.003). In contrast, performance in neither VEM domain is associated with SF36 Physical scores. Third, better SF36 Physical scores are associated with better Working Memory (Pearson's r=.318, p=.0001).

The negative correlations between better VEM Short Term Recall and worse SF36 Psychological scores resemble the unusual pattern of negative correlations between psychological health factors and VEM Short Term Recall seen in Table 6.3. However, further analysis revealed that, alongside younger age, worse SF36 Psychological scores did not contribute to predicting better performance in VEM Short Term Recall using linear regression (R=.291, R Sq=.085; Age: β=-.227, p=.013; SF36 Psychological score: β=-.112, p=.22). For this reason, and due to the modest nature of the correlations, this negative relationship between SF36 Psychological and VEM Short Term Recall was not considered further.

*6.9.8. A **Main New Finding (5):** Older Persons and Good Sleepers have better SF36 Psychological Health, whereas Younger Persons and Good Sleepers have better SF36 Physical Health*

Figure 6.6: Older Persons and Good Sleepers have better SF36 Psychological health, whereas Younger Persons and Good Sleepers have better SF36 Physical health

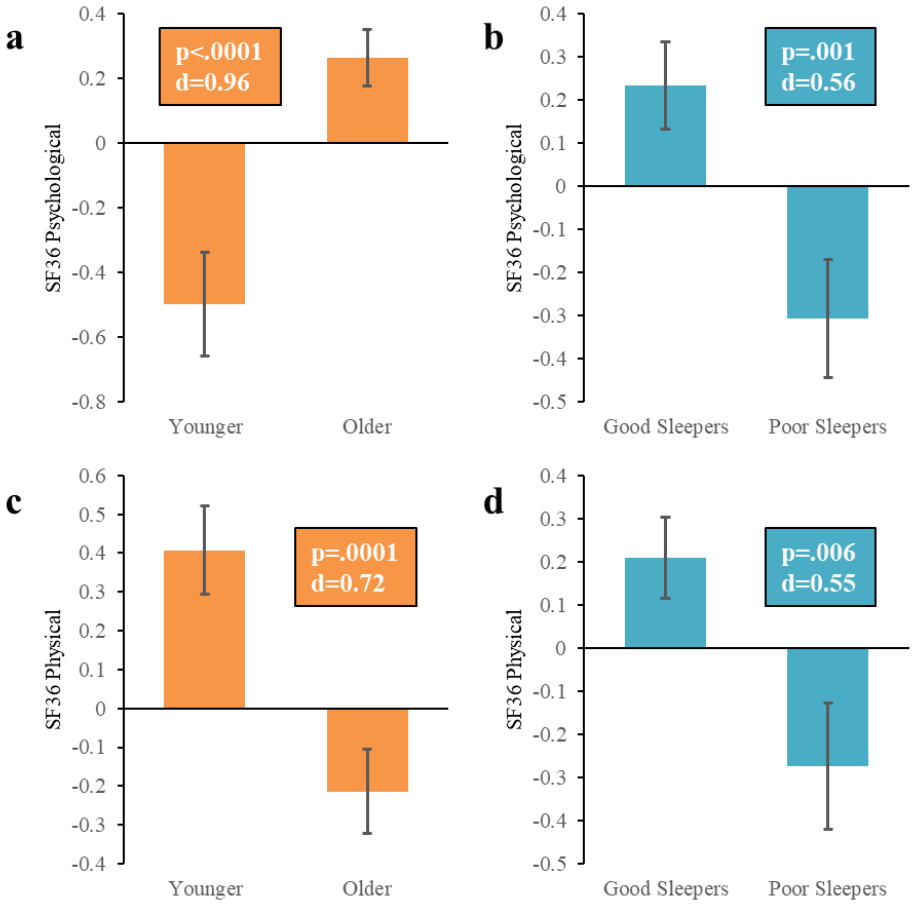


Figure 6.6 shows the differences between younger and older subjects and between good and poor sleepers in PCA factor scores for SF36 Psychological and SF36 Physical. **a**. Older subjects score higher than younger subjects on SF36 Psychological; $t_{75.112}$=-4.163, p<.0001, Cohen's d=0.96. **b**. Good sleepers score higher than poor sleepers on SF36 Psychological; t_{137}=3.629, p=.001, Cohen's d=0.56. **c**. Younger subjects score higher than older subjects on SF36 Physical; $t_{119.447}$=3.948, p=.0001, Cohen's d=0.72. **d**. Good sleepers score higher than poor sleepers on SF36 Physical; $t_{103.761}$=2.781, p=.006, Cohen's d=0.55. Error bars show +/- one s.e.m. It should be noted that whilst the differences between good and poor sleepers in SF36 Psychological reflect strong correlations between PSQI score and SF36 Psychological (Pearson's r=-.375, p<.0001; Spearman's r_s=-.387, p<.0001), there are no strong correlations between actual PSQI score and SF36 Physical (Pearson's r=-.131, p=.12; Spearman's r_s=-.156, p=.067).

Figure 6.6 illustrates a dissociation between younger and older subjects in SF36 Psychological and SF36 Physical scores, although importantly, being a good sleeper means a better score in

both SF36 Psychological *and* SF36 Physical domains. These comparisons suggest that the differences between PSQ good and poor sleepers may even extend *beyond* Psychological Mood to include 'quality of life' concerns such as self-assessed physical functioning and physical health. (Good and poor sleepers do not differ on any accelerometery measures of physical activity). However, against this, it should be noted that while better SF36 Psychological is strongly correlated with a lower (better) PSQI score (Pearson's r=-.375, p<.0001; Spearman's r_s=-.387, p<.0001), better SF36 Physical is not (Pearson's r= -.131, p=.12; Spearman's r_s=-.156, p=.067).

*6.9.9. A **Main New Finding (6)**: Worse SF36 Psychological health is associated with higher (worse) VEM Long Term Forgetting*

Figure 6.7 illustrates correlations between VEM Long Term Forgetting and age, PSQI score and SF36 factor scores. As explained in Chapter 3, higher (worse) PSQI score is associated with higher (worse) VEM Long Term Forgetting (Pearson's r=.283, p=.001; Spearman's r_s=.312, p=.0002), see Figure 6.7b, although age is not correlated with VEM Long Term Forgetting (Figure 6.7a). In addition, higher (worse) VEM Long Term Forgetting is associated with a lower (worse) SF36 Psychological factor score (Pearson's r=-.254, p=.003; Spearman's r_s=-.289, p=.001), but is not associated with SF36 Physical factor score (Pearson's r=-.135, p=.11) (Figure 6.7c).

Accordingly, although PSQI score is associated with a number of different underlying and composite psychological health scores, resulting in large differences between good and poor sleepers in some of these measures, correlations between psychological health scores and VEM Long Term Forgetting appear to be much more limited (see Table 6.5). In short, the relationship between psychological health and VEM Long Term Forgetting is mainly seen in the composite factor scores for Positive and Negative Social Experience (Figure 6.2) and SF36 Psychological (Figure 6.7c).

Figure 6.7: VEM Long Term Forgetting is correlated with PSQI score and SF36 Psychological factor score but not with Age or SF36 Physical factor score

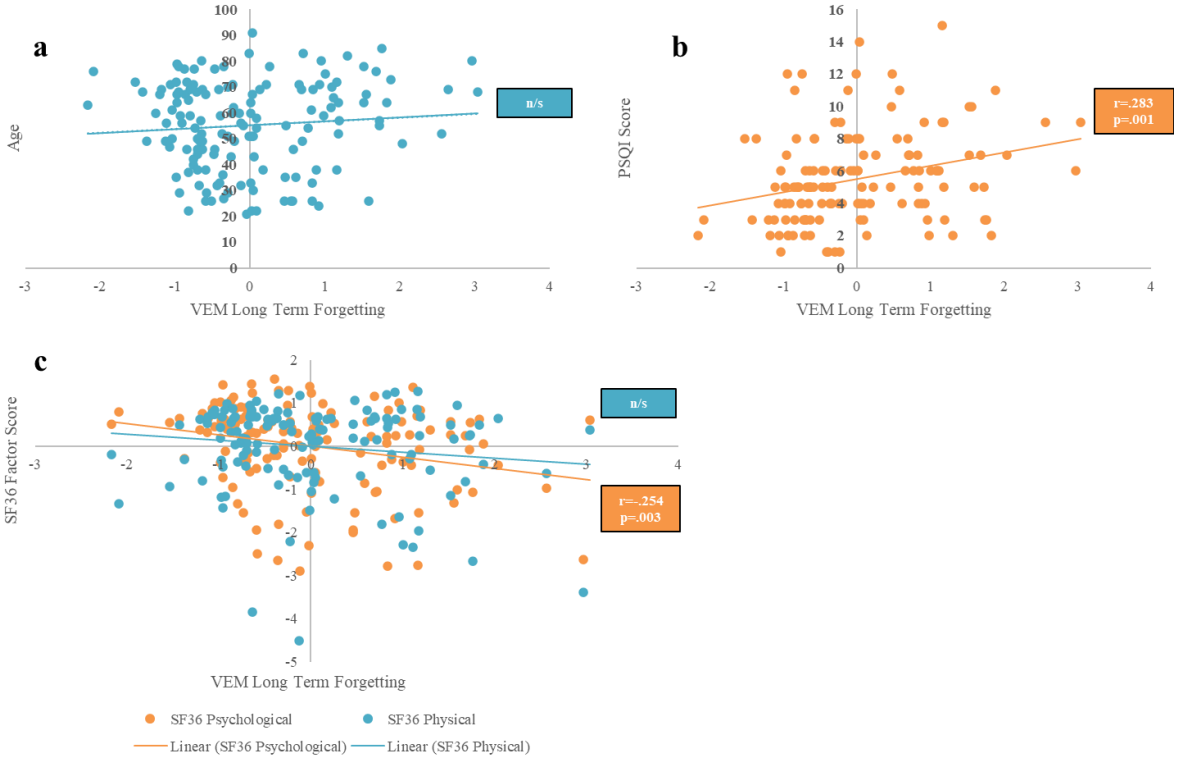


Figure 6.7 shows that (**a**) younger age is not associated with better VEM Long Term Forgetting (see chapter 2 for details) but (**b**) a higher (worse) PSQI score is associated with worse (higher) VEM Long Term Forgetting (Pearson's r=.283, p=.001) (see chapter 3 for details). (**c**) In addition, a higher SF36 Psychological factor score is associated with better (lower) VEM Long Term Forgetting, but there is no such association with the factor score for SF36 Physical.

*6.9.10. **A Main New Finding (7):** Better VEM Long Term Forgetting is co-predicted by Good Sleep and better Psychological health*

Figure 6.8 shows that, separately, both PSQ good sleep (β=.317, p=.0001) and SF36 Psychological health (β=.278, p=.001) predict lower/better VEM Long Term Forgetting in linear regression. However, the strongest regression model is when both variables are used together as co-predictors using the Enter method (R=.368).

Figure 6.8: Better VEM Long Term Forgetting is co-predicted by Good Sleep and Better Psychological health

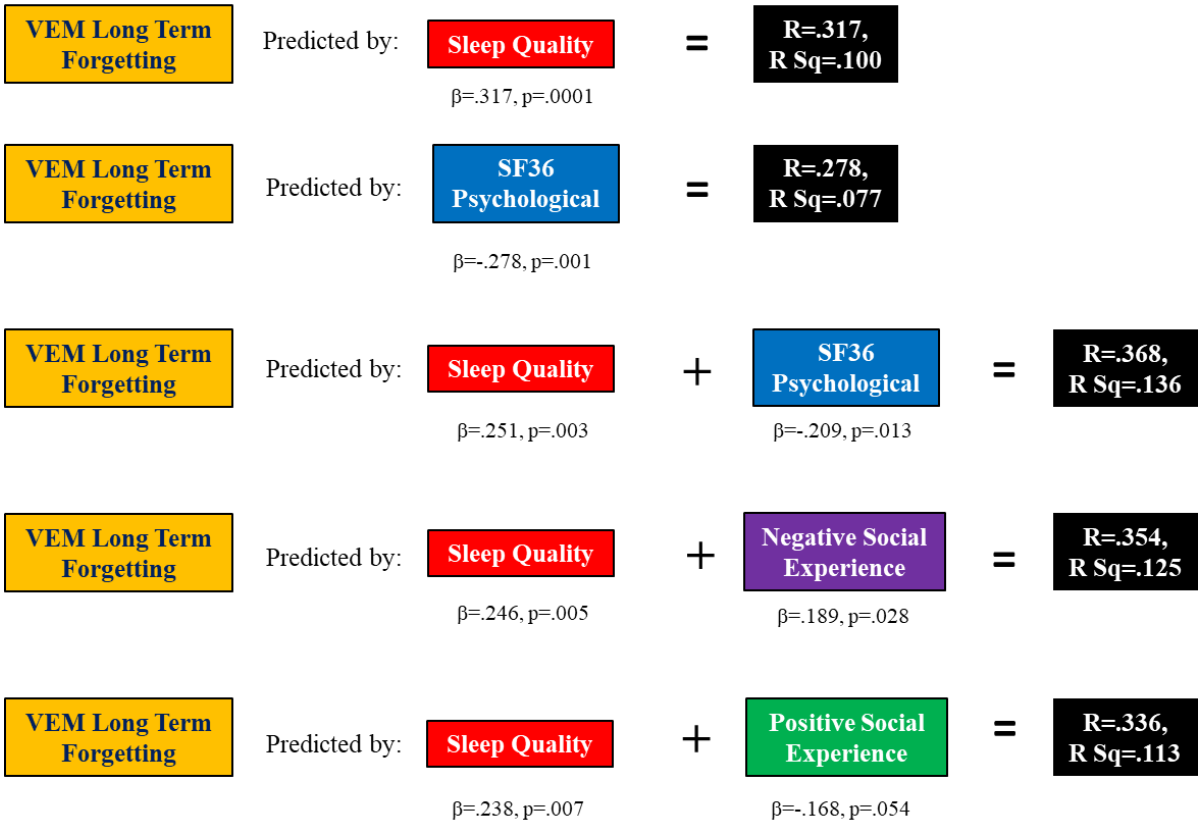


Figure 6.8 shows linear regression models using the Enter method for predicting VEM Long Term Forgetting. In all cases, one outlier has been excluded (subject scored 0/12 and 0/11 in free and cued recall respectively after two weeks). Both SF36 Psychological and Negative Social Experience make significant contributions to predicting VEM Long Term Forgetting alongside PSQ sleep quality. Positive Social Experience makes a marginal contribution alongside PSQ sleep quality, as does Diener SPANE positive affect score (β=-.161, p=.057), not shown above. When SF36 Psychological, Negative Social Experience and Positive Experience are together used as predictors alongside PSQ sleep quality using the Stepwise method, only SF36 Psychological is retained. The Stepwise model then becomes R=.366, R Sq=.134; PSQ sleep quality: β=.241, p=.005; SF36 Psychological: β=-.216, p=.011. This is substantially similar to the Enter method model shown in Figure 6.8 using Sleep Quality and SF36 Psychological as predictor variables.

In addition, Figure 6.8 shows that VEM Long Term Forgetting is also predicted by both PSQ good sleep (β=.246, p=.007) and Negative Social Experience (β=.189, p=.028) and, overall, this model (R=.354) is reasonably similar to that for PSQ sleep quality and SF36 Psychological (R=.368). Positive Social Experience makes a marginally significant contribution (β=-.168, p=.054) alongside PSQ sleep quality (β=.246, p=.005) but this model is somewhat weaker (R=.336) than the alternative models using SF36 Psychological or Negative Social Experience.

If all 3 composite psychological health variables (SF36 Psychological, Negative Social Experience and Positive Social Experience) are entered as co-predictors alongside PSQ sleep quality using the Stepwise method of linear regression, only SF36 Psychological is retained as a significant co-predictor. In this case the model is: R=.366, R Sq=.134; PSQ sleep quality: β=.241, p=.005; SF36 Psychological: β=-.216, p=.011 (i.e., it is substantially the same as the Enter method model using sleep quality and SF36 Psychological only as predictor variables). In all regression models, one outlier was identified by casewise diagnostics and excluded; this subject failed to recall any words after two weeks in both free (0/12) and cued (0/11) recall components of long-term recall. In conclusion, it appears therefore that, examining all of the composite measures of psychological health, a better SF36 Psychological factor score is the best co-predictor, alongside good sleep quality, of lower VEM Long Term Forgetting.

6.10. DISCUSSION

6.10.1. 'Psychological Mood' and 'Sociability' Constructs are derived from Exploratory Principal Component Analysis (PCA) of the Psychological Health Questionnaires

Chapter 2 explains how exploratory PCA factor analysis was used to reduce the number of psychological health questionnaire scores into five separate PCA factors; see Table 2.9. Examining the underlying component questionnaires to the PCA factors suggests that factors 1A and 1B (Positive Social Experience and Negative Social Experience) are concerned with areas of 'Psychological Mood' such as satisfaction with life, positive and negative affect, feelings of anxiety and distress (see Table 2.9). PCA factors 2A and 2B (Social Confidence and Social Fearfulness) have component questionnaire scores which appear to be more concerned with aspects of 'Sociability', including the level of social engagement and feelings of anxiety or fear in social situations (see Table 2.9). The high correlations between factors 1A and 1B and factors 2A and 2B respectively suggest that these factors are essentially 'mirror image' factors. For these reasons, this pair of mirror image factors have been treated as representing two separate psychological health constructs labelled for convenience in the present study as Psychological Mood and Sociability. The separation of these psychological PCA factor pairs into different constructs is supported by the fact that both Positive and Negative Social Experience are strongly associated with PSQI score, whereas Social Confidence and Social Fearfulness are not (see Table 6.4 and Figure 6.4). Also, good and poor sleepers differ on both Positive and Negative Social Experience, but do not differ on either Social Confidence or Social Fearfulness (see Figure 6.5).

6.10.2. There is No Evidence for any Substantial Decline in Social Connectedness in Older Age

Earlier studies have suggested a decline in social networks in older age (e.g. Carstensen, 1992; Wrzus, 2013; English & Carstensen, 2014). It was therefore hypothesised that older age might see a reduction in size of social networks, particularly friendship networks, but this is not the case. Neither Family nor Friendship Network size is correlated with age (see Table 6.1) and there are no differences in social networks between younger and older groups. These findings could represent Type II errors. Consistent with this, older age is also not associated with greater loneliness in this sample.

6.10.3. There is no evidence for any Relationship between larger Social Networks and Better Memory Domain Performance

Older age is not then associated with differently sized social networks (Table 6.1) but, as seen in Chapter 2, older age is strongly associated with lower performance in VEM Short Term Recall, Face Memory & Perception and Working Memory. However, neither the score on the University of Durham Social Situation questionnaire nor any measure of social networks has any appreciable direct relationship with better memory domain performance (see Table 6.2). The failure in the present study to replicate findings in earlier studies of an association between larger social networks and better cognition (e.g. Cornwell & Waite, 2009; Giles, 2012) may be attributable to methodology and/or demographics of this sample population. In particular, the present study was only cross-sectional and was not able to examine the effect of preserved or declining social networks on memory domain performance over time. In addition, the sample population in the present study may have had larger social networks than is typical for a different, similarly aged population sample.

*6.10.4. **Unexpected Finding:** Subjects with Higher Positive Social Experience and Lower Negative Social Experience have Lower (better) VEM Long Term Forgetting*

Although the PCA Psychological factor score for Social Connectedness failed to reveal any association with memory domain performance, other PCA psychological health factor scores did do so. The somewhat moderate correlations between PCA psychological health factors and VEM Short Term Recall (see Table 6.3) are not considered further here (specifically because they did not help to predict performance in VEM Short Term Recall). However, the stronger correlations between higher Positive Social Experience and lower Negative Social Experience (or together, better Psychological Mood) and lower VEM Long Term Forgetting signposted a relationship between psychological health and VEM Long Term Forgetting that was not easily seen in the underlying questionnaire scores only (see Table 6.5). In this respect, exploratory factor analysis has facilitated examination of the relationship between age, sleep quality, psychological health and long-term forgetting.

*6.10.5. **Replicated Finding:** Good Sleepers have Lower DASS 21 distress than Poor Sleepers*

Differences between PSQ good and poor sleepers have previously been found in DASS 21 distress (Rezaei, 2018). The present study replicates those findings; good sleepers have lower DASS 21 distress scores than poor sleepers; $t_{97.667}$=-2.455, p=.016, Cohen's d=0.50. A higher (worse) DASS 21 distress score is also associated with a higher (worse) PSQI score (Pearson's

r=.249, p=.003); see Figure 6.3. In addition, higher (worse) PSQI score is also shown to be strongly correlated with higher loneliness (Pearson's r=.317, p=.0001) which is consistent with findings elsewhere (e.g., McHugh & Lawlor, 2013). However, a more substantial extension to the findings in Rezaei, 2018 is seen in examining the relationship between PSQ sleep quality and the psychological health factors derived from PCA factor analysis; see Table 6.4.

*6.10.6. **Main New Finding**: Subjects with Better Sleep Quality have Higher Positive Social Experience and Lower Negative Social Experience (or better Psychological Mood) but do not Differ in Sociability*

Three main new related findings are described in sections 6.9.4 to 6.9.6 above.

Higher (worse) PSQI sleep quality is strongly associated with both lower Positive Social Experience and higher Negative Social Experience (both p<.0001; see Table 6.4). However, both Table 6.4 and Figures 6.4 and 6.5 reveal an important dissociation. This strong relationship between Psychological Mood PCA factors and PSQ sleep quality is not repeated in any association between PSQ sleep quality and Sociability PCA factors. Exploratory analysis of the underlying questionnaire scores confirmed the overview afforded by PCA factor analysis (see Table 6.5) so that good and poor sleepers differed extensively in questionnaire scores underlying Psychological Mood but not in those questionnaire scores underlying Sociability.

Moreover, although PCA factors in the same factor analysis solution (e.g. Positive Social Experience, Social Confidence and Social Connectedness) have a zero correlation with each other, examination of the underlying questionnaire scores shows a different profile. For example, UCLA Loneliness score (comprised in Positive Social Experience) is highly negatively correlated with the Lubben Friendship Networks score (comprised in Social Connectedness); Pearson's r=-.569, p<.0001, Spearman's r_s=-.440, p<.0001. This pattern of strong correlations between the underlying questionnaire scores comprised in the Psychological Mood and Sociability factors is repeated extensively. Within good and poor sleepers separately, the strong correlations between Psychological Mood and Sociability scores are still seen (see Supplementary Table 6.1).

It is an important new finding that whereas good and poor sleepers differ in Psychological Mood, this difference does not extend into Sociability *behavioural* differences between good and poor sleepers. So, for example, while poor sleepers may be lonelier than good sleepers, they do not have differently sized Friendship Networks from good sleepers. Nevertheless, for both good and poor sleepers alike, being lonelier means having smaller Friendship Networks.

6.10.7 ***Main New Findings****: The SF36 Psychological Health Factor derived from the SF36 Short Form Health Assessment is Associated with Good PSQ Sleep and helps to Predict Better VEM Long Term Forgetting*

Four main new related findings are described in sections 6.9.7 to 6.9.10 above.

In addition to the PCA factor analysis carried out on multiple questionnaire scores that resolved into five separate PCA factors (see Table 2.9), exploratory factor analysis was also undertaken on the SF36 Short Form Health Assessment ('the SF36') which comprises 8 separate health measures (see Methods above). PCA factor analysis revealed a strong two factor solution comprising psychological (SF36 Psychological) and physical (SF36 Physical) factors (see Table 6.6).

Correlations between SF36 Psychological and SF36 Physical and age are shown in Table 6.7. Older age is strongly associated with better SF36 Psychological score but (as might be expected) worse SF36 Physical score (in both cases, $p<.0001$). These opposing correlations are also reflected in large differences between younger and older subjects in both SF36 Psychological and SF36 Physical factor scores (see Figure 6.6 a and c). Table 6.7 also shows that better SF36 Psychological score is strongly associated with lower VEM Long Term Forgetting (Pearson's $r=-.254$, $p=.003$, Spearman's $r_s=-.289$, $p=.001$), but also, albeit more moderately, with worse VEM Short Term Recall. SF36 Physical is not associated with either VEM Short Term Recall or VEM Long Term Forgetting, but better SF36 Physical score is strongly associated with better Working Memory.

Although there is a dissociation between older and younger groups in SF36 Psychological and SF36 Physical, there is no such contrast between good and poor sleepers. Good sleepers enjoy better SF36 Psychological health *and* better SF36 Physical functioning than poor sleepers (see Figure 6.9b and d). The association between PSQ good sleep and better SF36 Psychological factor score (Pearson's $r=-.375$, $p<.0001$; Spearman's $rs=-.387$, $p<.0001$) is separately corroborated by the association between better SF36 Psychological factor score and higher Sleep Diary sleep quality rating (Pearson's $r=.245$, $p=.012$; Spearman's $r_s=.317$, $p=.001$). SF36 Psychological therefore appears to be strongly related to self-reported sleep quality in both the PSQ and sleep diaries.

The relationship of age, sleep quality and SF36 Psychological and Physical to VEM Long Term Forgetting is contrasted in Figure 6.7. The correlation between VEM Long Term Forgetting and SF36 Psychological in Figure 6.7 mirrors that seen between VEM Long Term Forgetting and Positive and Negative Social Experience (see Figure 6.2). This raised the question which composite factor measure (if any) best predicted VEM Long Term Forgetting in conjunction with PSQ sleep quality.

Figure 6.8 shows that, alongside PSQ sleep quality, both SF36 Psychological health and, separately, Negative Social Experience make significant contributions to predicting VEM Long Term Forgetting (Positive Social Experience and Diener SPANE positive affect are separately marginal co-predictors). Applying the Stepwise method of linear regression revealed that only SF36 Psychological was retained as a co-predictor when all of the composite factor measures were entered as potential predictors of VEM Long Term Forgetting.

This finding that SF36 Psychological health helps to predict VEM Long Term Forgetting alongside good PSQ sleep quality is new and important. Good SF36 Psychological health is important to VEM Long Term Forgetting and may also play a role, like good sleep, in long term memory consolidation. However, it is also instructive that some psychological health domains (such as social networks and sociability) appear to have little influence over sleep quality and are unrelated to VEM Long Term Forgetting.

Some examples may illustrate this. Table 6.5 shows that two of the strongest differences between good and poor sleepers are in Zung Anxiety (Cohen's d effect size=0.80) and in the UCLA Loneliness Scale (Cohen's d effect size=0.62). These differences are also reflected in strong correlations between Zung Anxiety score and PSQI score (Pearson's r=.442, p<.0001; Spearman's r_s=.453, p<.0001) and between the UCLA Loneliness scale score and PSQI score (Pearson's r=.317, p=.0001; Spearman's r_s=.361, p<.0001). However, there is no correlation between Zung Anxiety score and VEM Long Term Forgetting (Pearson's r=.073, p=.39; Spearman's r_s=.080, p=.34) or between the UCLA Loneliness scale score and VEM Long Term Forgetting (Pearson's r=.094, p=.27; Spearman's r_s=.096, p=.26). Alongside PSQ sleep quality, neither measure makes a significant contribution to predicting VEM Long Term Forgetting (Zung Anxiety: β=-.051, p=.56; UCLA Loneliness: β=.001, p=.99). The combination of being correlated with good sleep *and* helping to predict VEM Long Term Forgetting is unusual and appears to be confined to the composite psychological health measures revealed by PCA factor analysis. In summary, exploratory factor analysis methodology has played an important role in

identifying VEM Long Term Forgetting, as well as the composite psychological health factors that are important contributors to healthy functioning in this particular memory domain.

6.10.8. Limitations

There are two main limitations with this study. First, as previously mentioned, this is not a longitudinal study, so it is not possible to determine whether, for example, psychological health or social networks of these subjects may have changed over time. Second, and again as discussed already, this sample includes a large number of socially active older subjects. This might accentuate (e.g.) differences between psychological mood of younger and older subjects. However, it is less clear that this should limit other findings, for example, such as the differences between good and poor sleepers in loneliness and psychological mood, which have in any event been previously reported elsewhere (e.g., Rezaei, 2018).

6.11. Summary of Chapter 6

The hypotheses in this Chapter 6 were, broadly, that while older subjects may have better psychological health, they may have smaller social networks and that this may contribute to lower cognitive performance; additionally, it was hypothesised that, based on quite recent findings (Rezaei, 2018), poor sleepers may show some evidence of worse psychological health. No evidence was found that older subjects have smaller social networks, or indeed higher loneliness, and larger social networks do not appear to be associated with higher levels of performance in any of the tested memory domains.

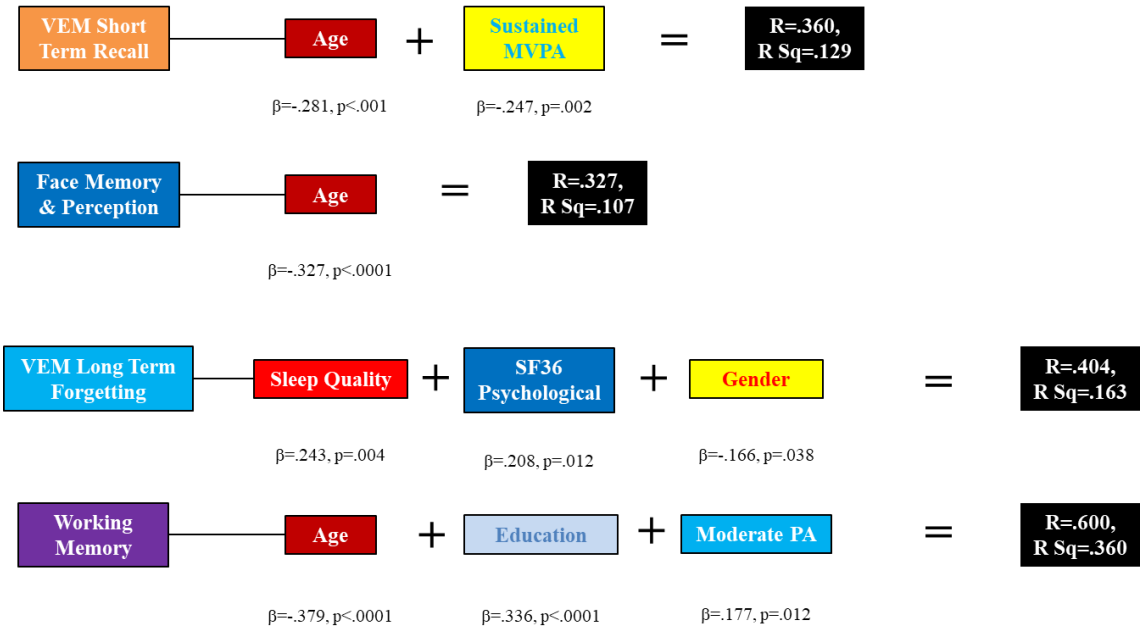
However, based on the analysis from testing these hypotheses, two new and important findings emerged. The first is that, in line with earlier findings, good and poor sleepers do differ in matters of psychological health, but in attempting to ascertain which psychological health measures best encapsulate the differences between good and poor sleepers, factor analysis has enabled clear differentiation between measures of 'Psychological Mood' (where good and poor sleepers differ) and measures of 'Sociability' and social behaviour (where they do not). This is more remarkable because of the ordinarily strong relationship between these different measures of 'Psychological Mood' and 'Sociability'.

The second important new finding was determining that good psychological health is a major additional factor in better VEM Long Term Forgetting. Again, factor analysis guided this answer. Disregarding factor analysis, the underlying psychological measures which reveal differences between good and poor sleepers appear to be largely unrelated to better VEM Long

Term Forgetting. However, factor analysis produced composite factor measures of psychological health which do help to explain substantial variance in VEM Long Term Forgetting. One of these, SF36 Psychological health is not only strongly associated with better sleep quality, but is also the strongest co-predictor of VEM Long Term Forgetting.

The updated regression models are shown in Figure 6.9.

Figure 6.9: Updated Regression Models for Chapter 2, 3, 4, 5 &6 Variables



Note: Although different regression models for VEM Long Term Forgetting are shown in Figure 6.8, only the best model is shown for this memory domain in these overall Updated Regression Models

The relationship between sleep quality, psychological mood, age and memory is complex and multi-faceted. In the next and final chapter, the findings of this and earlier chapters will be brought together in order to determine whether specific recommendations can be developed for the healthy preservation of memory function in ageing.

Table 7.1 Summary of Replicated Findings, Main New Findings, Secondary New Findings & Unexpected Findings

Replicated Findings	Main New Findings
• Younger subjects perform better than older subjects on VEM Short Term Recall, Face Memory & Perception and Working Memory (e.g. Larrabee, 1988; Van Der Elst, 2005; 2006) • Age is correlated with some aspects of longer term recall (although it is not correlated with VEM Long Term Forgetting) (e.g. Mary, 2013) • Results support a factor 'f' for face processing (Verhallen, 2017) • Scores on the Pittsburgh Sleep Questionnaire (PSQ) are consistent with those seen elsewhere (e.g. Nebes, 2009) • Distribution of larks (39%) and owls (61%) in the sample is consistent with those suggested elsewhere (e.g. Walker, 2017) • Owls have later chronotypes and later MSW and MSF than larks (Tankova, 1994) • Younger subjects have later Morningness than older subjects (but only at weekends) (e.g. Fischer, 2017) • Younger subjects have higher Social Jet Lag and higher Sleep Debt than older subjects (e.g. Roenneberg, 2019) • Physical activity levels are sustained into older age (66 plus) (e.g. Hall, 2017) • Subjects with lower distress have larger social networks (e.g. Cohen & Wills, 1985) • Older subjects have better psychological health (mood) than younger subjects (e.g. Oerlemans, 2011) • Poor sleepers have higher distress (Rezaei, 2018)	• **Better/lower VEM Long Term Forgetting is predicted by good sleep quality. This is underpinned by strong relationships between lower/better scores in the Pittsburgh Sleep Quality Index (PSQI) and better test scores in free and cued recall after 2 weeks** • **Although good and poor sleepers do differ, owls and larks do not differ in VEM Long Term Forgetting** • **Good and poor sleepers do not differ in either Social Jet Lag or Sleep Debt. These behaviours are unrelated to PSQ sleep quality and neither contributes to better or worse VEM Long Term Forgetting** • **When owls and larks are categorised according to their behaviour on weekdays and weekends, both Circadian types are seen to adjust Morningness and Eveningness behaviour at weekends and do not differ from each other in either Social Jet Lag or Sleep Debt** • **Good and poor sleepers differ on psychological mood (e.g. distress and loneliness) but do *not* differ in aspects of related social behaviour, such as sociability and size of social networks** • **The SF36 Short Form Health Survey divides clearly into two factors representing psychological and physical health** • **Older persons and good sleepers have better SF36 Psychological health, whereas younger persons and good sleepers have better SF36 Physical health** • **Better/lower VEM Long Term Forgetting is associated with higher Positive Social Experience and lower Negative Social Experience** • **Better/lower VEM Long Term Forgetting is predicted by good sleep quality and better SF36 Psychological health** • **Better Working Memory is associated with higher moderate levels of physical activity in older subjects and with higher levels of more vigorous physical activity in younger subjects**
Secondary New Findings	**Unexpected Findings**
• Lark-like behaviour may emerge at around age 35, driven by earlier weekday Morningness • There is a trend towards gradual conformity between weekday and weekend Eveningness and Morningness behaviour across detailed age groups (i.e. differences between weekday and weekend behaviour progressively reduce) • The difference between bed duration on working days and work-free days narrows progressively with older age • Sleep Debt extends into older age, whereas Social Jet Lag declines faster and more progressively • Lower Sleep Debt may contribute to better VEM Short Term Recall; lower Social Jet Lag may contribute to better Working Memory • Subjects are reasonably able to self-assess physical activity levels at the extremes (of active or inactive) but struggle with accurate self-assessment at more modest levels • Higher levels of physical activity are associated with higher Social Confidence	• In younger subjects, lower levels of physical activity are associated with better VEM Short Term Recall • No relationship was found between better Social Connectedness (larger Social Networks) and better performance in any memory domain (this is a failure to replicate earlier findings, e.g. Cornwell & Waite, 2009; Giles, 2012, rather than an unexpected finding per se).

In the previous chapters 2-6, the findings in the present study have generally been differentiated between findings that replicate those in previous studies, *main* new findings and *secondary* new findings. These are summarised in Table 7.1 above. This final chapter will focus on the main new findings. Replicated findings and secondary findings, discussed in the previous chapters, will not be considered in any further detail.

7.1. Main New Findings

7.1.1. Better (lower) VEM Long Term Forgetting is Predicted by Good Sleep Quality

Chapter 2 showed how differences exist between the two main age groups in the three memory domains of VEM Short Term Recall, Face Memory & Perception and Working Memory; performance in these memory domains, derived from factor analysis and which comprise standard neuropsychological measures, is negatively correlated with older age. Exploratory analysis in more detailed age groups suggested that performance in these composite factors declines appreciably with more advanced age (i.e., in the 66+ age group). The substantial decline between the 50-65 and 66+ age groups, in particular, in these three memory domains contrasts strongly with the relatively similar performance between these same two older groups (i.e. the 50-65 and 66+ age groups) in VEM Long Term Forgetting.

It was hypothesised in Chapter 3 that older age may be associated with poorer sleep quality and that together older age and poorer sleep may co-predict lower performance in some memory domains. This hypothesis was based on earlier studies which had found poorer cognitive performance in older adults to be associated with poor sleep quality (e.g. Nebes, 2009; Mary, 2013) and poorer Pittsburgh Sleep Questionnaire (PSQ) sleep quality in older adults (e.g. Nebes, 2009). The results in the present study are not inconsistent with some of these previous findings. For example, older age is associated with worse performance in the underlying scores for free and cued recall in Buschke's Verbal Selective Reminding Test ('the Buschke VSRT'; Buschke, 1973) both at phase 1 testing and again two weeks later at two weeks; see Figure 3.3a. However, older age is not associated in the present study with a worse Pittsburgh Sleep Quality Index (PSQI, Buysse, 1989) score (Pearson's r=.092, p=.28), and in linear regression models, for absolute scores on free and cued recall at two weeks, PSQ sleep quality made a larger contribution to performance than older age (Free recall at 14 days: PSQ sleep quality, β=-.278, p=.001, Age, β=-.172, p=.036. Cued recall at 14 days: PSQ sleep quality, β=-.297, p=.0002, Age, β=-.277, p=.001).

Two methodological steps were critical to the next stage of the analysis. First, the absolute scores at phase 1 and phase 2 testing for both free and cued recall were combined into 'long-term forgetting scores', which took proper account of the differential memory demands at phase 2 for subjects who remembered more or fewer words at phase 1 (Loftus, 1985). Second, Exploratory Principal Component Analysis (PCA factor analysis) was used to reduce the number of cognitive test scores into separate, independent (i.e. not correlated) memory domains.

Exploratory Principal Component Analysis (PCA factor analysis) revealed that the two relative measures of forgetting (for free and cued recall) were a separate factor with a correlation of 0 to the standard immediate, cued and delayed recall tests comprised in VEM Short Term Recall (see Table 2.6). Moreover, the PCA factor analysis result was not dependent on the methodology for calculating long-term forgetting. The same result was obtained if different measures of calculating long-term forgetting were used (see Chapter 2).

Based on these twin methodologies (the calculation of forgetting and PCA factor analysis), it was demonstrated that older age is not correlated with VEM Long Term Forgetting (Pearson's r=.088, p=.29, Spearman's r_s=.038, p=.65). It might be argued that including Buschke's cued recall as a measure of forgetting skews the results because it is not (in comparison with Buschke's standard 30 mins free delayed recall) one of the main reported measures of Buschke's VSRT (see Chapter 2). However, excluding cued recall from the VEM Long Term Forgetting PCA factor would simply weaken the age relationship with long-term forgetting, as older age has a stronger relationship to cued recall at two weeks than free recall at two weeks.

Further analysis then revealed the unique relationship between PSQ good sleep and VEM Long Term Forgetting. The importance of this new finding is made clearest by contrasting the different contributions of age and good sleep in the two PCA factors, VEM Short Term Recall (comprising standard measures from Buschke's VSRT) and VEM Long Term Forgetting (comprising the new extended delay measures added to Buschke's VSRT). This is encapsulated in the striking double dissociation between younger and older subjects and good and poor sleepers shown in Figure 3.4.

The main new sleep finding of the present study is therefore a strong *double dissociation* whereby good sleepers (as characterised by the PSQ) have lower VEM Long Term Forgetting than poor sleepers, although there is no difference between younger and older subjects. In contrast, while younger subjects outperform older subjects on VEM Short Term Recall, there

is no difference between good and poor sleepers. This is a major, new finding which points to the benefit of good sleep in the process of *long-term* memory consolidation, and in addition, to the benefit of good sleep to that process in older and younger subjects alike. It also shows that while the standard neuropsychological tests of delayed recall (comprised in VEM Short Term Recall) may be strong measures of memory performance in their own right, they are not necessarily such good tests of *longer-term* memory.

7.1.2. Good and Poor Sleepers Differ in VEM Long Term Forgetting but Owls and Larks do not

Circadian behaviour has been described as "the new science" of sleep (Foster, 2022) and is more concerned with sleep timing, sleep regulation and bed behaviour (habits) than sleep quality, although these areas are clearly linked (Walker, 2017). Some aspects of sleep and bed behaviour that may signpost dysregulation or dysfunction, such as Sleep Debt and Social Jet Lag, have been the subject of recent research (e.g., Fox, 2018; Roenneberg, 2019) and the influence of these matters on both sleep quality and cognitive performance in healthy ageing remains largely unresolved.

Unlike PSQ 'good' and 'poor' sleepers, the Circadian types known as 'owls' and 'larks' are not technical terms with clearly agreed boundaries. Categorisation depends on heterogenous methodologies and can range from a single question (such as 'do you prefer evenings or mornings?', Piffer, 2014) to more detailed chronotype-based preferences (see, e.g., Adan, 2012). The new methodology devised in the present study to categorise owls and larks has two important components. First, rather than rely on a questionnaire self-assessment approach to determine normal bed and sleep times, actigraphy has been used, corroborated by sleep diaries to discern actual 'going to bed' and 'getting up' times, as well as actual times for 'sleep onset' and 'sleep offset' over a two week period. Second, the present study has taken a more holistic, nuanced approach to bed and sleep behaviour, taking into account working day as well as work-free day behaviour.

Traditionally, chronotype and owl/lark preferences are determined by reference to 'normal' bed and sleep behaviour when unconstrained by the exigencies of work (Roenneberg, 2007b; 2019); this means that measurement is often confined to bed and sleep behaviour on work-free days (or at weekends). However, whether bed and sleep behaviour on work-free nights alone is in fact a 'more natural' indicator of Circadian preference is debatable; in many respects, work-free night behaviour might be quite unnatural. The present study did not adopt such a

limited approach and instead, actigraphy was used to measure sleep and bed behaviour across the entire week. In line with this different approach, a bespoke methodology was used to determine Eveningness and Morningness preferences on working days and work-free days. A combined scoring system for Eveningness and Morningness on working days and work-free days allowed for the identification of extremes of owl and lark behaviour (i.e., subjects who had consistent extremes of 'going to bed' and 'getting up' times on work days and work-free days) but also provided for a more nuanced assessment of behaviour that was inconsistent. The system also permitted a simple, binary categorisation of intermediate types (i.e., persons who show mixed owl and lark tendencies).

The present study showed that owls and larks did not differ in their PSQI score (p=.97); see Table 4.1, and they did not differ in their sleep quality diary assessment either (p=.69). As far as is known, this is a new finding that has not been previously reported. Intuitively, it is a reasonable result; it might be unusual if one type of Circadian behaviour enjoyed clear superiority in sleep quality. However, consequentially, owls and larks also do not differ in VEM Long Term Forgetting (p=.74), where good sleep quality is a differentiator (see Chapter 3). For the avoidance of doubt, owls and larks also do not differ in any other measured memory domain either: VEM Short Term Recall (p=.63), Face Memory & Perception (p=.70) and Working Memory (p=.58).

To summarise this important new finding therefore, a categorisation of owls and larks based on an objective and holistic assessment of Circadian behaviours reveals no innate advantage in memory performance to either Circadian type, and specifically no evidence of any advantage that is as clear cut as age in most domains, or good sleep in VEM Long Term Forgetting.

7.1.3. Good and Poor sleepers do not differ in Social Jet Lag or Sleep Debt and these matters are Unrelated to Sleep Quality and Better VEM Long Term Forgetting

While categorisation as an owl or lark might indicate *normal* Circadian preference or behaviour, the measures of Sleep Debt and Social Jet Lag might be described as unusual or perhaps dysrhythmic Circadian behaviours (the label 'abnormal' might be a little strong and is apt to confuse in the context of memory performance analysis). Sleep Debt might be described as a mild form of work or study based sleep deprivation, not however to be equated with chronic forms of sleep deprivation such as insomnia. As a measure of insufficient sleep duration, it might be expected that too little sleep (high Sleep Debt) would be manifested in lower arousal and perhaps lower memory domain performance, particularly when this is tested during the

working week (very few subjects in the present study were tested at weekends). Social Jet Lag is a form of self-imposed clock change which occurs for everyone twice a year with clocks moving forward and back by an hour in the spring and autumn respectively. It has been estimated that 44% of people incur at least one hour of Social Jet Lag (Roenneberg, 2019), which as a stark measure of its dysfunctional effect, is equivalent to nearly half the population experiencing a spring or autumn clock change every single week.

Bearing in mind the nature of these dysrhythmic behaviours, it is surprising to find that, whilst younger age is strongly associated with higher amounts of Sleep Debt and Social Jet Lag, good and poor sleepers do not differ in either Sleep Debt ($p=.18$) or Social Jet Lag ($p=.67$) and PSQI score is unrelated to either Sleep Debt ($p=.68$) or Social Jet Lag (.79). In other words, as dysfunctional as these forms of sleep and bed behaviour may be, they appear to be unrelated to sleep quality. Put simply, it seems possible to amass quite large amounts of Sleep Debt and Social Jet Lag and be a 'good sleeper'. Importantly for the main finding in the present study, it follows that neither Sleep Debt nor Social Jet Lag is correlated with, or helps to predict, VEM Long Term Forgetting. A tentative conclusion may be therefore that whilst higher Sleep Debt and Social Jet Lag are strongly associated with younger age, there is no evidence that either measure has an effect on sleep-based processes, such as long-term memory consolidation.

7.1.4. Owls and Larks do not differ in Social Jet Lag (or Sleep Debt)

The present study is also the first (so far as is known) to examine levels of Social Jet Lag in owls and larks. Unsurprisingly, results here showed that owls have on average a 75 minute later chronotype than larks ($p<.0001$, Cohen's $d=1.38$). Later chronotype is also strongly correlated with higher Social Jet Lag (Pearson's $r=.439$, $p<.0001$). It is easy to see therefore how it might be assumed that owls would have higher Social Jet Lag than larks (see, e.g. Nowack & Van Der Meer, 2018).

However, in the present study, using the bespoke methodology of examining Eveningness and Morningness separately on work days and work-free days, it was possible to see that both owls and larks change their sleep and bed behaviours across weekdays and weekends and so do not differ in Social Jet Lag. This is important because it means that larks may be just as dysfunctional as owls in accumulating higher Social Jet Lag; the suggestion that as much as 44% of the population accrues more than an hour of Social Jet Lag (Roenneberg, 2019) may not therefore be confined to or concentrated in owls, but may extend across the whole

population. This means that explanations for (say) cognitive performance differences based on Circadian preference cannot be simply attributed to assumptions about dysrhythmic behaviour.

7.1.5. Good and Poor Sleepers differ in Psychological Mood but not in related Social Behaviours

A recent study (Rezaei, 2018) has shown that subjects with higher DASS 21 distress severity ratings for depression, anxiety and stress have higher/worse PSQI scores. The replication of those findings in the present study is described in Chapter 6. Earlier research had also associated poor sleep quality and higher loneliness (McHugh & Lawlor, 2013), and this is also confirmed in Chapter 6. Accordingly, the relationship between poor sleep and poorer psychological health is not confined to one underlying measure. In the present study, subjects completed a wide range of psychological health questionnaires, including the DASS 21 questionnaire (Lovibond & Lovibond, 1995) and the UCLA Loneliness scale (Russell, 1980), and PCA factor analysis was used to reduce these multiple questionnaire results into psychological health factor scores. Again, PCA factor analysis was instrumental in signposting an important new finding which may have been less clearly seen from the underlying results alone.

As described in Chapter 6, a better PSQI score is strongly correlated with better PCA psychological health factor scores for Positive Social Experience and Negative Social Experience (both $p<.0001$). By comparison, the relationship between better PSQI score is only very moderate with Social Confidence ($p=.037$) and is non-existent with Social Fearfulness ($p=.07$). The PCA factor scores for Positive and Negative Social Experience have been broadly conceptualised as relating to 'Psychological Mood', whereas the Social Confidence and Fearfulness factors have been labelled as relating to 'Sociability'. The underlying questionnaire scores comprised in the PCA psychological health factors are shown in Table 2.9 and there is some overlap between the different PCA factors; for example, the UCLA Loneliness scale appears in both Positive and Negative Social Experience and the Liebowitz social anxiety results are included in both Social Confidence and Social Fearfulness. This approach to factor analysis was principally as a result of a case:variable ratio limits, which in turn was attributable to constraints imposed on subject numbers by the Covid 19 outbreak, which prevented the development of a single factor analysis model using all psychological health variables. The net effect of having 'twin' PCA factor analysis models was that Positive Social Experience and Negative Social Experience are, to an extent, mirror image positive and negative psychological

mood factors, and Social Confidence and Social Fearfulness are mirror image positive and negative sociability factors.

The dissociation of strong correlations between PSQI score and both Positive and Negative Social Experience but not between PSQI and Social Confidence or Social Fearfulness signposted a possible important difference between good and poor sleepers. Detailed exploratory analysis of the underlying questionnaire scores demonstrated that PSQ good and poor sleepers differed strongly in underlying measures of Psychological Mood (in line with recent research such as Rezaei, 2018 and Sella, 2021) but they did *not* differ in underlying measures of Sociability. Moreover, this dissociation between good and poor sleepers in Psychological Mood and Sociability transcends the normal, strong correlations between many of these measures of Psychological Mood and Sociability, such as for example, a strong Pearson's $r=-.578$, $p<.0001$ correlation between UCLA Loneliness (where good and poor sleepers differ) and the Social Situation questionnaire score (where good and poor sleepers do not differ). This is not an isolated example and the dissociation in the relationship between good and poor sleepers in strongly associated areas of Psychological Mood and Sociability is extensive, as shown in Chapter 6.

This is an important new finding and may indicate a significant limitation on the reported relationship between poor psychological health and poor sleep (Driscoll, 2008; Lo & Lee, 2012; Rezaei, 2018; McHugh & Lawlor, 2013; Sella, 2021). One interpretation of the very strong results in the present study may be that although poor Psychological Mood may influence poor sleep (and/or vice versa, the direction of causation being unclear), poor sleep does not spill over into psychosocial problems like social fear, lower sociability or an inability to form stronger and larger social networks. This is a very important limitation on the effect of poor sleep, which may mean, for example, that it does not contribute to detrimental social behaviour that has been shown to be associated with poorer cognitive performance, such as e.g., having smaller social networks and worse cognition (e.g. Cornwell & Waite, 2009; Giles, 2012).

7.1.6. Better VEM Long Term Forgetting is Predicted by Good Sleep and Better Psychological Health

Chapter 6 also explained how the association between good sleep and better Psychological Mood (but not Sociability) was 'matched' by an association between better VEM Long Term Forgetting and better Psychological Mood (but not Sociability). Specifically, better

performance in VEM Long Term Forgetting is correlated with higher Positive Social Experience and lower Negative Social Experience, but better performance is not associated with either Social Confidence or Social Fearfulness. These correlations essentially match those between the PSQI score and the PCA psychological health factors. This relationship was only made clear by PCA factor analysis because correlations between underlying Psychological Mood questionnaire scores and VEM Long Term Forgetting are largely non-existent.

In addition, whereas individual questionnaire scores do not generally contribute, alongside sleep quality, to predicting better VEM Long Term Forgetting, the PCA Psychological Mood factors are more powerful co-predictors. The strongest co-predictor, labelled 'SF36 Psychological', is derived from a further exploratory factor analysis of the SF36 Short Form Health questionnaire ('the SF36', Ware Jr & Shelbourne, 1992) which comprises 8 underlying scores that appear to resolve firmly into two factors, conceptualised in the present study as 'SF36 Psychological' and 'SF36 Physical'. So far as is known, this is the first time that PCA factor analysis has been reported in relation to the SF36.

This is an important new finding because it suggests two important conclusions might be drawn. First, the PSQ is not (merely) some form of proxy assessment of Psychological Mood, because different composite measures of Psychological Mood (e.g., Negative Social Experience and SF36 Psychological) clearly make *additional* contributions to predicting VEM Long Term Forgetting that are independent of, and separate from, PSQ sleep quality. Second, it suggests that long-term memory consolidation may be facilitated by good sleep (in line with previous reports, see e.g., Stickgold & Walker, 2005), *but also* by better Psychological Mood (again, so far as is known, not reported elsewhere to date). This represents an important new finding for long-term memory consolidation.

7.1.7. Different Levels of Physical Activity Benefit Working Memory in Younger and Older Subjects

The new findings in this study for PA and its effects on memory performance are perhaps not as fundamental as for sleep (above). However, some findings are quite unexpected and go beyond the hypothesised benefits of (simply) 'more activity equals better memory performance'. The best example of this is how apparently equivalent benefits to specific memory domains can be achieved by different levels of physical activity in different age groups. In older subjects, for example, higher levels of quite *moderate* PA are associated with better Working Memory, although the same result is achieved in younger subjects by more

sustained moderate and vigorous activity. So far as is known, this distinction between the differential effect of different levels of physical activity on Working Memory benefits in different age groups has not been previously shown. This is important for cognitive health messaging to older persons; namely, it is not necessary for physical activity to be at the same levels as younger persons for equivalent benefits in the same memory domains to be achieved.

7.2. Unexpected Results

7.2.1. An Unusual Result: Higher Physical Activity is associated with Lower VEM Short Term Recall

Perhaps the major unexpected finding in this study is that higher levels of moderate PA is associated with *worse* VEM Short Term Recall. In linear regression, younger age and *less* PA (sustained MVPA) together predict better performance in VEM Short Term Recall. A simple explanation for this unusual result is hard to suggest. For all subjects, higher VEM Short Term Recall is also unusually associated with lower Psychological Mood. Any potential explanation for this is made more difficult by the fact that there is no apparent association between either higher or lower PA and Psychological Mood more generally. Although the results appear to be anomalous, some previous research has occasionally struggled to find memory performance improvements in younger persons with higher levels of PA (see e.g., Prakesh, 2015; Hayes, 2016). Further detailed research is required here.

7.2.2. Social Networks and Memory Performance

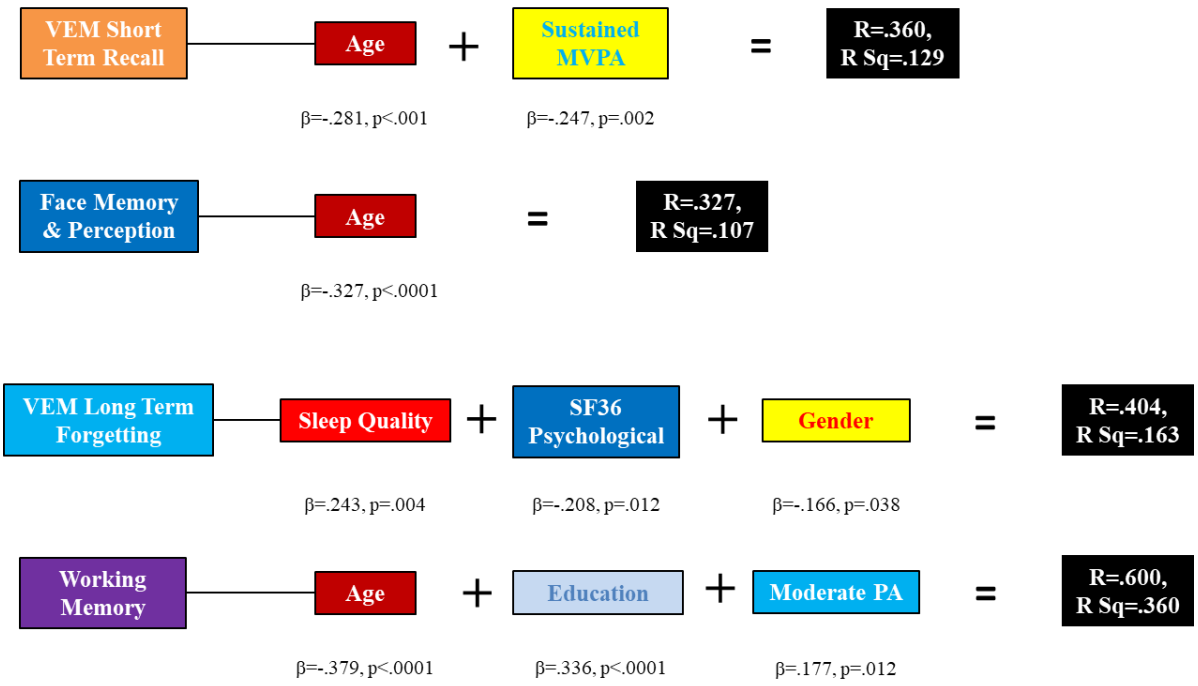
As described above, surprisingly no *direct* association was found between larger social networks and better memory domain performance in the present study. There is therefore no evidence to support the view that greater social stimulation (from, say, having larger Friendship networks) may enhance cognitive stimulation and thereby result in better memory domain performance. There is also no evidence to support any hypothesis that stronger social networks are potentially underpinned by better social cognition. However, it is possible that this absence of evidence may be attributable to the particular demographic profile of the population sample in the present study (see further under Limitations below).

7.3. Putting it all together: Factors Helping to Preserve Healthy Memory Performance in Normal Ageing

7.3.1. Predictors of Memory Domain Performance

Linear regression models for each of the four memory domains were developed, using all of the contributing variables to each of the memory domains identified in Chapters 2 to 6 and the statistical approach used is set out in detail in section 2.1.6 in chapter 2. The final results are shown in Figure 7.1.

Figure 7.1: Stepwise Method: Regression Models for all Contributing Variables



7.3.2. The best predictors of VEM Short Term Recall are Age and Lower Sustained MVPA

In the regression model, the only significant contributory variables to better VEM Short Term Recall are lower age and lower sustained MVPA. One notable aspect however (given the results of previous research) is that female gender makes no contribution to VEM Short Term Recall performance.

7.3.3. There are No Other Contributors than Younger Age to Face Memory & Perception

Younger age is the sole significant predictor of better Face Memory & Perception and in this respect this memory domain is unique amongst the four PCA factors, with no other sleep, physical activity or psychological variable making any additional contribution to better performance.

7.3.4. VEM Long Term Forgetting

Good sleep quality (as determined by the PSQ) is the main predictor of better/lower VEM Long Term Forgetting, although here female gender does make an additional contribution (see Figure 7.1). As described above, better Psychological Mood (as determined by the SF36 Psychological factor score) also makes a significant contribution to the model.

7.3.5. Working Memory

In Stepwise regression, the only variables contributing significantly to better performance are lower age, higher education and more moderate level physical activity (see Figure 7.1). However, when the same predictor variables are used for the Stroop test alone, the position changes slightly. In this case, the only remaining variables contributing significantly to better performance are lower age, higher education and lower daily sedentary time (this is not shown in Figure 7.1).

7.3.6. Predicting Performance in Memory Domains: Summary

Examining Figure 7.1, the standout model in the present study is the one for VEM Long Term Forgetting, with better performance predicted by good sleep, better Psychological Mood and female gender. Although this composite result is a new finding, it is consistent with, and underpinned by, earlier research on sleep memory consolidation benefits (e.g. Stickgold & Walker, 2005), PSQ good sleep benefits to some types of cognitive functioning (Nebes, 2009), female gender advantage in verbal memory (e.g. Manoli, 2018) and the recently-reported link between PSQ good sleep and lower distress (Rezaei, 2018).

The result shown in Figure 7.1 for Working Memory is that, alongside younger age and higher education, more moderate physical activity helps to improve performance. The finding that less sedentary time contributes to better Stroop performance suggests that the underlying message for better Working Memory and its underlying components may be that, essentially, *any* form of activity/movement is better for this domain than a more sedentary lifestyle. Others have

found that higher Social Jet Lag impinges on performance in the Stroop test (McGowan, 2020) and, although a moderate predictive relationship was also found in this study, the Stepwise regression analysis showed that Social Jet Lag is not a contributory factor alongside age, education and physical activity. However, this remains an area that merits further research.

The more unusual, and perhaps unexpected result, is for VEM Short Term Recall. If sustained MVPA is accepted as, to some extent, a proxy for intended, purposeful exercise, it is surprising that lower 'exercise' alongside younger age contributes to better VEM Short Term Recall. This finding might be more easily dismissed as a simple anomaly were it not for the fact that lower Psychological Mood was also seen to be associated with better VEM Short Term Recall (see Chapter 6). This result merits further research.

Younger age alone predicts better Face Memory & Perception. Factor analysis confirmed the high correlations in the three underlying tests in the Face Memory & Perception PCA factor and the results in the present study generally therefore support the proposition of a 'f' factor for face processing (Verhallen, 2017). No evidence has been found in the present study that 'f' factor performance is susceptible to strong influence by physical activity, sleep or psychological health and is associated only with a strong and reliable age-related decline.

7.3.7. Limitations

Each chapter of this study has outlined the limitations which are particular to the subject being considered. Chapter 2 also described some general limitations. In closing, it should perhaps be re-stated that the present study aimed to look at the inter-relationship of a number of different factors in helping to preserve healthy cognitive functioning across a range of different memory domains. Such an aim is not best achieved by a piecemeal approach, where a specifically limited and focussed study can be gradually extended into different areas. The more open-ended design of this project has required instead 'post hoc' controls, particularly in the form of dimension reduction (e.g. Principal Component Analysis) to place some constraints on the wide-ranging nature of the data collected.

Despite adopting such balancing statistical techniques, the number of potentially confounding variables in a study such as this makes it necessary to approach all results with a degree of caution. For the most part, the present study has attempted to differentiate modest or moderate results from more strongly significant results, but very occasionally, moderate results have been shown, where they help the analysis. The general approach taken was first to establish

strong baseline hypotheses, consistent with earlier research (e.g. age-related changes in memory performance, physical activity and Circadian behaviour) and use 'confirmatory' findings in these areas as the basis for further, more detailed analysis. Again, as no controls have been applied for confounding variables, only the most significant results have generally been reported or afforded any prominence in discussion.

7.4. Conclusions

7.4.1. PCA Factor Analysis has played an Important Role in Revealing Results that may otherwise have been Subsumed in an Abundance of Data

One theme of this concluding Chapter is the important role played by PCA factor analysis in reducing the voluminous data collected in the present study into more manageable elements that facilitated analysis of key elements in the results. First, PCA factor analysis resolved the underlying test scores into four wholly independent memory domain factors and, in particular, helped to distinguish the new, relative measure of long-term forgetting from the standard, absolute measures of verbal episodic memory traditionally used and reported. Second, factor analysis highlighted the different contributions of age and sleep to different memory domains, and explicitly revealed the double dissociation in the effects of age and sleep in performance on VEM Short Term Recall and VEM Long Term Forgetting. Third, reducing the numerous psychological health questionnaire scores into two constructs broadly approximating to Psychological Mood and Sociability, effectively enabled a distinction to be drawn in the relationship of these constructs to sleep quality. Fourth, this distinction was given added emphasis by using PCA factor analysis to reduce the SF36 Short Form Health questionnaire to show how good Psychological Mood may make a separate, independent contribution to better long-term memory consolidation.

As well as PCA factor analysis, the new findings in the present study have been substantially helped by actigraphy. Actigraphy does have limitations as an accurate tool for measuring sleep, and some of these limitations have been seen in the present study. However, as an objective measurement tool in the 'new science' of Circadian behaviour (Foster, 2022), it has been invaluable, providing detailed and comprehensive objective data for assessing different Circadian measures over a two week period, and allowing for strong differentiation between Circadian preference (owls and larks) as well as close analysis of more dysfunctional Circadian behaviours such as Social Jet Lag and Sleep Debt.

7.4.2. A Summary of the Factors Preserving Healthy Memory Performance in Normal Ageing is a Mix of Straightforward and More Complex Results

Putting everything together in a summary of factors helping to preserve healthy memory performance in normal ageing, there are, seemingly, some straightforward conclusions and some more complex findings. As an example of straightforward cognitive health results, it seems clear that good sleep quality helps to preserve long-term memory consolidation, a benefit achievable even in older age. Separately, higher levels of physical activity and less sedentary time is beneficial for working memory, although this may alter subtly between the level of required physical activity for younger people (more vigorous PA) and for older people (more moderate activity). Other findings are less straightforward. A good example is the contribution to good sleep (and long-term memory consolidation) made by Psychological Mood. However, the present study has importantly identified this attribute as a separate contributory factor to better long-term memory.

7.5. Overall Impact of Findings and Implications for Future Research

7.5.1. Overall Impact of Findings

The overall impact for society from the findings in the present study may be summarised as follows:

- The study demonstrates the importance of good sleep quality to better long term memory, even in older age
- The study substantially extends earlier findings that there is a strong relationship between subjective sleep quality and psychological mood, and,
- Critically, the study shows the separate important contribution of psychological mood *alongside* sleep quality to long term memory

Based on a single learning episode, the present study has shown that good subjectively-assessed sleep quality, based on the PSQ, is the main differentiator between good and poor long-term forgetting in verbal episodic memory. Earlier research has shown that, in older subjects, PSQ sleep quality and psychological mood may be related (e.g., Driscoll, 2008; Lo & Lee, 2012; Rezaei, 2018; Sella, 2021). The present study confirms and substantially extends those findings and, in so doing, suggests that steps taken either to improve psychological mood in older persons (e.g., through higher levels of social engagement) or better sleep quality (e.g., through better sleep hygiene) may help to secure improvements in long-term memory consolidation. The potential impact for targeted interventions to secure real improvements in long term memory highlighted by the present study may improve individual lives and reduce healthcare

costs in an ageing society with significant pressure on public health resources. Moreover, the present study also demonstrates the advantages for younger persons, as much as for older persons, in taking personal responsibility for improving lifestyle behaviours, such as sleep and physical activity, that can have real tangible benefits for their cognitive functioning now, as well as lasting benefits in the future.

7.5.2. Implications for Future Research

The present study highlights some important areas for the direction of future research. First, the findings in this study relate specifically to long term forgetting in verbal episodic memory after two weeks. Further research might be undertaken to determine whether equivalent consolidation benefits in verbal episodic memory are secured after shorter or longer periods (e.g., say, after one week or after four weeks). In addition, it may be possible to modify other memory tests to determine whether similar consolidation benefits extend to other memory domains such as, for example, spatial memory.

Second, although the present study did not find any association between sleep quality and certain dysfunctional Circadian behaviours such as Sleep Debt or Social Jet Lag, this could simply be a Type II error, reflecting either a lack of power in the study or an unrepresentative population sample, or quite possibly both. Sleep and circadian behaviour research is increasingly demonstrating that *when* we sleep is as important as *how well* we sleep (Russell, 2022), and the relationship (if any) between PSQ sleep quality and such Circadian behavioural measures as Sleep Debt and Social Jet Lag might be usefully re-examined elsewhere. If it is assumed that irregular Circadian behaviours are potentially harmful to cognition, the 'good news' from the present study is that such behaviours tend to be eradicated or substantially reduced with older age. Future studies might attempt to measure the 'cognitive benefit' of this age-related process and, perhaps as a corollary, the extent to which it may also be a 'cognitive cost' in earlier stages of life that could be better managed behaviourally.

Third, further research might examine what is specifically underpinning the separate and independent contribution of poor psychological mood to lower long term memory consolidation. The possible explanations suggested by the present study can only be speculative. It has, for example, been previously shown that sleep deprivation (i.e., one aspect of poor sleep quality) may preferentially enhance consolidation of negative verbal memories over positive or neutral verbal memories (Walker & Stickgold, 2006); i.e., sleep deprivation may lead to 'negative salience' (Foster, 2022). However, the findings in the present study are

somewhat different; the present study does not show that poor sleep quality facilitates or leads to negative salience, but rather suggests that a negative view of the world (as seen in higher Negative Social Experience or worse SF36 Psychological scores) may *supplement* poor sleep quality as a predictor of lower levels of 'neutral' verbal memory consolidation (see Figure 6.8). It is unclear whether, if at all, having a more positive outlook may help to enhance long term memory. A quite different, alternative explanation may perhaps be that low psychological mood is a stressor co-contributing to lower memory consolidation, although in a recent study (Raven, 2020) stress hormones did not mediate memory consolidation impairment in sleep-deprived mice. Further research here would substantially help to formulate better sleep and psychological health interventions.

Finally, and building on the last point, longitudinal experimental research could be undertaken to determine whether specific targeted sleep actions might be taken to shift the PSQI ratings of subjects across the poor/good category boundary and to determine the extent to which such actions may ameliorate long term memory consolidation, perhaps across different memory domains. This experimental approach could be extended to include complementary psychological mood interventions. Creating a working model for proactive interventions in both sleep health and hygiene and psychological mood may transform the practical approach to preserving healthy cognition in normal ageing.

References

At many points in the thesis, there is fairly extensive citation of key literature. Accordingly, to reduce interruption of flow, papers with three or more authors are referred to by the first-named author only and the words "et al" have not been added. Where there are only two authors, both have been named.

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Cognitive and Social Perception Testing **Appendix 1**

ADDITIONAL INFORMATION SHEET

Project title: Healthy Cognitive Ageing: Factors Preserving Cognitive Health in Older Persons

Researcher: Mark Avery; Lead Supervisor: Dr Colin Lever; Co-Supervisor: Dr James Dachtler

Contact details: *mark.d.avery@durham.ac.uk; colin.lever@durham.ac.uk*

This is additional information for you on the specific phases of the project covering cognitive and social perception testing. The project aims and other general information is included in the Omnibus Information Sheet. *You should read this additional information as well before you sign the consent form entitled 'Cognitive and Social Perception Testing'.*

What will I do if I take part?

You will be asked to complete four 'cognitive tests' and five social perception tests. These will be scheduled to take place at a time and place that is convenient for you. It is likely that more than one session will be required to complete all of the tests, but that is a matter for you. If you were to take all nine tests in one go, the session would last approximately two and a half hours.

The cognitive tests will examine your memory, language and visuospatial skills. The Rey Auditory Verbal Learning Test (or RAVLT), will test verbal memory and learning. The Four Mountains Task (or 4MT), is a test of spatial memory. The Free and Cued Selective Reminding Test (or FCSRT) which will examine your ability to recall words from a list when you are given reminders. All of these tests will together take about an hour.

The social perception tasks involve you making judgments about certain faces that will be shown to you on a series of cards or on a computer screen. Your responses will be recorded. All of these tests together will also take about an hour.

The cognitive tests and social perception tests are likely to be mixed.

Do I have to take part?

Your participation is voluntary and you do not have to agree to take part. Specifically, you are under no obligation to complete any of the cognitive or social perception tests. You may also decline (without reason) to answer any questions in any particular test that you do not wish to answer, although this might make your data unusable as a whole.

Thank you for reading this information and for your consideration in taking part in this experiment.

Physical Activity, Sleep Measurement and Questionnaires

ADDITIONAL INFORMATION SHEET

Project title: Healthy Cognitive Ageing: Factors Preserving Cognitive Health in Older Persons

Researcher: Mark Avery; Lead Supervisor: Dr Colin Lever; Co-Supervisor: Dr James Dachtler

Contact details: *mark.d.avery@durham.ac.uk; colin.lever@durham.ac.uk*

This is additional information for you on the specific phases of the project covering physical activity, sleep measurement and questionnaires. The project aims and other general information is included in the Omnibus Information Sheet. *You should read this additional information as well before you sign the consent form entitled 'Physical Activity, Sleep Measurement and Questionnaires'.*

What will I do if I take part?

Your levels of physical activity and sleep over a period of 7-14 days will be measured by a small device that you will wear on your wrist, like a watch, during the whole day (i.e. including the night-time). The researcher will arrange to meet you at a convenient location to help you fit the device and to provide you with instructions. Once the 7-14 days has passed, the researcher will arrange to meet with you again to collect the device and to de-brief you. Your physical activity and sleep data will be subsequently downloaded from the device. It is unlikely that you will experience any discomfort wearing the device. However, should you do so, you should cease to wear the device and inform the researcher so that it can be collected.

You will also be asked to complete 15 (fifteen) questionnaires in total but each one is short:

1. Lubben Social Networks Questionnaire (10 minutes)
2. Social Situation Questionnaire (5-10 minutes)
3. Liebowitz Social Anxiety Scale (5-10 minutes)
4. Zung Self-Rating Anxiety Scale (~5 minutes)
5. DASS 21 Distress Questionnaire (5-10 minutes)
6. Diener Satisfaction With Life Scale (1 minute)
7. Diener Scale of Positive and Negative Experience (~5 minutes)
8. Diener Flourishing Scale (~5 minutes)
9. Brief Fear of Negative Evaluation Questionnaire (<5 minutes)
10. SF-36 Short Form Health Survey (5-10 minutes)
11. Pittsburgh Sleep Quality Index (~5 minutes)
12. Education Level Attainment Questionnaire (1 minute)
13. Spatial Abilities & Practices Questionnaire (5-10 minutes)
14. General Practice Physical Activity Questionnaire (~3 minutes)
15. UCLA Loneliness Scale (10 minutes)

The experimenter will provide you with instructions as to how to complete each questionnaire online in an email message with an accompanying link to the relevant questionnaire or

questionnaires. You can complete these in your own time and you do not need to be supervised while you do so. If you prefer to complete hard copies of the questionnaires, that can also be arranged.

Do I have to take part?

Your participation is voluntary and you do not have to agree to take part. You can withdraw, without giving a reason, at any time. Specifically, you are free to cease wearing the physical activity/sleep tracker at any time and are under no obligation to complete a particular period of wear. As far as the questionnaires are concerned, you are under no obligation to complete all of them and you may also decline (without reason) to answer any specific questions in any of them, although this may make your data unusable as a whole.

Please note that you may not be given any feedback about your personal scores or rating in either the physical activity/sleep measurement phase or for any questionnaire which you complete.

Thank you for reading this information and for your consideration in taking part in this experiment

Appendix 2

Privacy Notice

PART 1 – GENERIC PRIVACY NOTICE

Durham University's responsibilities under data protection legislation include the duty to ensure that we provide individuals with information about how we process personal data. We do this in a number of ways, one of which is the publication of privacy notices. Our privacy notices comprise two parts – a generic part and a part tailored to the specific processing activity being undertaken.

Data Controller

The Data Controller is Durham University. If you would like more information about how the University uses your personal data, please see the University's Information Governance webpages or contact:

Information Governance Unit
Telephone: (019133) 46246 or 46103
E-mail: info.access@durham.ac.uk

Data Protection Officer

The Data Protection Officer is responsible for advising the University on compliance with Data Protection legislation and monitoring its performance against it. If you have any concerns regarding the way in which the University is processing your personal data, please contact the Data Protection Officer:

Jennifer Sewel
University Secretary
Telephone: (0191 33) 46144
E-mail: jennifer.sewel@durham.ac.uk

Retention

The University keeps personal data for as long as it is needed for the purpose for which it was originally collected. Most of these time periods are set out in the University Records Retention Schedule.

Your rights in relation to your personal data

Privacy notices and/or consent

You have the right to be provided with information about how and why we process your personal data. Where you have the choice to determine how your personal data will be used, we will ask you for consent. Where you do not have a choice (for example, where we have a legal obligation to process the personal data), we will provide you with a privacy notice. A privacy notice is a verbal or written statement that explains how we use personal data.

Whenever you give your consent for the processing of your personal data, you receive the right to withdraw that consent at any time. Where withdrawal of consent will have an impact on the services we are able to provide, this will be explained to you, so that you can determine whether it is the right decision for you.

Accessing your personal data

You have the right to be told whether we are processing your personal data and, if so, to be given a copy of it. This is known as the right of subject access. You can find out more about this right on the University's Subject Access Requests webpage.

Right to rectification

If you believe that personal data we hold about you is inaccurate, please contact us and we will investigate. You can also request that we complete any incomplete data.

Once we have determined what we are going to do, we will contact you to let you know.

Right to erasure

You can ask us to erase your personal data in any of the following circumstances:

- We no longer need the personal data for the purpose it was originally collected
- You withdraw your consent and there is no other legal basis for the processing
- You object to the processing and there are no overriding legitimate grounds for the processing
- The personal data have been unlawfully processed
- The personal data have to be erased for compliance with a legal obligation
- The personal data have been collected in relation to the offer of information society services (information society services are online services such as banking or social media sites).

Once we have determined whether we will erase the personal data, we will contact you to let you know.

Right to restriction of processing

You can ask us to restrict the processing of your personal data in the following circumstances:

- You believe that the data is inaccurate and you want us to restrict processing until we determine whether it is indeed inaccurate
- The processing is unlawful and you want us to restrict processing rather than erase it

- We no longer need the data for the purpose we originally collected it but you need it in order to establish, exercise or defend a legal claim and
- You have objected to the processing and you want us to restrict processing until we determine whether our legitimate interests in processing the data override your objection.

Once we have determined how we propose to restrict processing of the data, we will contact you to discuss and, where possible, agree this with you.

Making a complaint

If you are unsatisfied with the way in which we process your personal data, we ask that you let us know so that we can try and put things right. If we are not able to resolve issues to your satisfaction, you can refer the matter to the Information Commissioner's Office (ICO). The ICO can be contacted at:

Information Commissioner's Office
Wycliffe House
Water Lane
Wilmslow
Cheshire
SK9 5AF

Telephone: 0303 123 1113

Website: Information Commissioner's Office

PART 2 – TAILORED PRIVACY NOTICE

This section of the Privacy Notice provides you with the privacy information that you need to know before you provide personal data to the University for the particular purpose(s) stated below.

Project Title: Factors Preserving Cognitive Health in Older Persons

Types of personal data collected and method of collection:

We will ask you to sign a Consent Form to confirm your willingness to take part in each area of this study. There will be five areas of this study (physical activity and sleep measurement, genetic/DNA testing, cognitive testing, social skills testing and completion of questionnaires). There will be three Consent Forms covering these 5 areas. An 'omnibus' information sheet will explain to you the overall project aims and testing protocol.

For each aspect of the study, you will be allocated an anonymous ID for data collection and this will appear on each Consent Form that you sign. During the project, we will retain a key code which will allow us to identify any data that belongs to you and which is recorded against your anonymous ID. When you complete a task in any of the five areas described, data will be

generated which will be recorded only by reference to your anonymous ID and will not be recorded against your name or any other identifying personal information.

The data that we will collect from you in the five areas described above will be collected by means of 'scores' for cognitive and social perception tests, data for the amount of your physical activity and sleep measurement over a certain period, 'scores' for answers you will give to questionnaires and data results for testing for approximately 12 genetic variants (maximum 20). Some of the questionnaires (which are well-established questionnaires used in psychological assessment) may give rise to self-assessed personal information, such as your own ratings of your subjective health or well-being. However, your answers on such questionnaires will usually be transformed into a single score on a scale and this data (your score) is not reasonably likely to be identifiable as belonging to you (because a third party would need to know exactly how you would score yourself on the questionnaire). For example, you will be asked to rate yourself on the Liebowitz Social Anxiety Scale and your answers will be converted into a score of between 48 and 192. A score of (say) 107 would not, without more, become data that is personally identifiable as yours. These scores should not be personal data. Accordingly, when the project is complete and the key code to your anonymous ID is destroyed, it will not be possible to identify you from the score of 107 on that questionnaire.

Genetic data is personal data and this includes information about your inherited or acquired characteristics which may result from the analysis of a biological sample, such as a saliva sample. As we will be collecting saliva samples from you for DNA analysis, we will be generating genetic data about you which will be personal data. However, we will only be testing for a very small number (approximately 12) of genetic variants. The results from this DNA analysis will not reveal any identifying characteristics about you and it would not therefore be possible to identify you from this genetic data alone, even within a small group of participants (it is anticipated that the participant sample in this research will be reasonably large; circa 150 persons).

How personal data is stored:

Information (such as a key code and/or a Consent Form showing your anonymous ID) that identifies you will be kept separate from any anonymised data in any data file or record. All personal data we hold in electronic form will be stored on a password protected computer, and any hardcopies will be kept in locked storage. Personal data will not be available to anyone outside the research team. If data is included in any publication it will be entirely anonymous and will not be identifiable as yours.

In addition, any biological samples (including your saliva samples and/or extracted DNA) will be kept securely at all times on University locked premises. Your biological samples will be kept with anonymous ID labels and there will be no personally identifiable information on your samples. Only the research team (the researcher and his supervisors) will have access to your samples during the project. Once genetic testing is complete, your samples will be destroyed. The genetic data resulting from your samples will be treated as ordinary research data and that

will be retained, anonymised and deleted in the same way as any other research data (see further below).

Research data will be rendered fully anonymous no later than the end of the project (31st March 2023) by destruction of any information (such as Consent Forms and/or any key code) that identifies you. At this point it will no longer be possible to identify any data as belonging to you and therefore it will not be possible to withdraw or destroy your data. All anonymised research data and records needed to validate the research findings will be stored for a maximum of 10 years after the end of the project (31st March 2023). Your data will not therefore be stored in any form beyond 31st March 2033.

How personal data is processed:

The signed Consent Form provides evidence of your consent to take part in each area of this study which is an ethical requirement. We keep a record of the anonymous code that has been assigned to you only to enable us, during the currency of the project, to withdraw your research data if you request it and to be able to link your responses to data collected in different areas of the project.

Who personal data is shared with:

No personal data will be shared with anyone, however anonymised (i.e. not identifiable) data may be used in publications, reports, presentations, web pages and other research outputs. After the end of the project, (i.e. after 31st March 2023) fully anonymised data may be archived and shared with others for legitimate research purposes.

How long personal data is held:

We will keep your signed Consent Forms and the record of the anonymous code assigned to you until 31st March 2023, as described above. The data will then be completely anonymised and any records which include information that can identify you will be destroyed. You can request withdrawal of your data at any time up until it has been fully anonymised. After that time, it will not be possible to destroy it because it will (of course) not be possible to identify any data that belongs to you. Your data may be retained in fully anonymised form until 31st March 2033 and, as described above, shared with others.

Any biological samples (including saliva samples and DNA) which have resulted in genetic data will be destroyed at the completion of genetic testing. This is likely to be on or before the end of the project on 31st March 2023.

How to object to the processing your personal data:

If you have any concerns regarding the processing of your personal data, or you wish to withdraw your personal data from the project, contact the researcher, Mark Avery (mark.d.avery@durham.ac.uk) or his lead supervisor, Colin Lever (colin.lever@durham.ac.uk).

Further information:

For further information, please contact Mark Avery or Colin Lever (contact details above).

Consent Form: Cognitive and Social Perception Testing **Appendix 3**

Project title: Factors Preserving Cognitive Health in Older Persons

Researcher: Mark Avery
Department: Psychology Department
Contact details: mark.d.avery@durham.ac.uk
Supervisor name: Dr Colin Lever
Supervisor contact details: colin.lever@durham.ac.uk

This form is to confirm that you understand the purposes of the project, what is involved and that you are happy to take part. Please initial each box to indicate your agreement:

I confirm that I have read and understand the documents entitled "Healthy Cognitive Ageing: Whole Project Information" and "Additional Information: Cognitive and Social Perception Testing"	
I have had sufficient time to consider the information and ask any questions I might have, and I am satisfied with the answers I have been given.	
I have been provided with a Privacy Notice in respect of any data collected from me during this task and I understand who will have access to personal data provided, how the data will be stored and what will happen to the data at the end of the project.	
I agree to take part in the above phases of the project.	
I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason.	
I consent to the processing of my personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the provisions of data protection legislation.	
I understand that anonymised (i.e. not identifiable) versions of my data may be archived and shared with others for legitimate research purposes.	

Participant's Signature_____ Date_____

Anonymous
ID:_____Age:_____

(NAME IN BLOCK LETTERS)_____

Researcher's Signature_____ Date_____

(NAME IN BLOCK LETTERS)_____

This project was given advisory approval by the Ethics Advisory Sub-Committee on 17 December 2018

Consent Form: Physical Activity, Sleep Measurement & Questionnaires

Project title: Factors Preserving Cognitive Health in Older Persons

Researcher: Mark Avery
Department: Psychology Department
Contact details: mark.d.avery@durham.ac.uk
Supervisor name: Dr Colin Lever
Supervisor contact details: colin.lever@durham.ac.uk

This form is to confirm that you understand the purposes of the project, what is involved and that you are happy to take part. Please initial each box to indicate your agreement:

I confirm that I have read and understand the documents entitled "Healthy Cognitive Ageing: Whole Project Information and "Additional Information: Physical Activity, Sleep Monitoring & Questionnaires".	
I have had sufficient time to consider the information and ask any questions I might have, and I am satisfied with the answers I have been given.	
I have been provided with a Privacy Notice in respect of any data collected from me during this task and I understand who will have access to personal data provided, how the data will be stored and what will happen to the data at the end of the project.	
I agree to take part in the above phases of the project.	
I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason. This includes my right to cease wearing any monitor at any time without need for a reason.	
I consent to the processing of my personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the provisions of data protection legislation.	
I understand that anonymised (i.e. not identifiable) versions of my data may be archived and shared with others for legitimate research purposes.	

Participant's Signature_____ Date_____

Anonymous ID:_____Age:_____

(NAME IN BLOCK LETTERS)_____

Researcher's Signature_____ Date_____

(NAME IN BLOCK LETTERS)_____

This project was given advisory approval by the Ethics Advisory Sub-Committee on 17 December 2018

List of Questionnaires **Appendix 4**

1. Lubben Social Networks Questionnaire (~10 minutes)
2. Social Situation Questionnaire (~10 minutes)
3. Liebowitz Social Anxiety Scale (~10 minutes)
4. Zung Self-Rating Anxiety Scale (~5 minutes)
5. DASS 21 Distress Questionnaire (~5 minutes)
6. Diener Satisfaction With Life Scale (1 minute)
7. Diener Scale of Positive and Negative Experience (~5 minutes)
8. Diener Flourishing Scale (~5 minutes)
9. Brief Fear of Negative Evaluation Questionnaire (~4 minutes)
10. SF-36 Short Form Health Survey (~10 minutes)
11. Pittsburgh Sleep Quality Index (~5 minutes)
12. Education Level Attainment Questionnaire (1 minute)
13. Spatial Abilities & Practices Questionnaire (~10 minutes)
14. General Practice Physical Activity Questionnaire (~4 minutes)
15. UCLA Loneliness Scale (10 minutes)

Total Questionnaire Completion Time: ~1 hour 35 minutes

Important Note: these questionnaires may be set out below with their scoring criteria. *Scoring criteria will not be provided to participants*. They are also shown in their standard format (e.g. they may ask for 'name' or other personal details). In practice, all forms are likely to be anonymised such that questionnaires only require participants to provide an anonymous code as a personal identifier

Appendix 5: Social Situation Questionnaire

Anonymous ID:_____

Date:_____

Instructions: Please read each question and circle the most appropriate response

Question Number	Question	**Strongly Disagree**	**Disagree**	**Neither Agree Nor Disagree**	**Agree**	**Strongly Agree**
1a	I would describe myself as very sociable	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
1b	This statement has become less applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
2a	I find it easy to meet new people	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
2b	This statement has become less applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
3a	There are people outside of my family that I can talk to about personal matters	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
3b	This statement has become less applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
4a	On an average week, I will only interact with my spouse and/or children	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
4b	This statement has become more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
5a	I have friends outside of family members that I see on at least a fortnightly basis	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
5b	This statement has become less applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree

6a	I can sometimes feel lonely	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
6b	This statement has become more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
7a	I have less desire to meet new people than I used to	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
7b	This statement has become even more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
8a	If I were to have a party, I can think of more than 5 people aside from family members that would attend	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
8b	This statement has become less applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
9a	I tend to avoid social situations unless they are with my immediate family	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
9b	This statement has become more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
10a	I'd rather stay at home than have day trips out	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
10b	This statement has become more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
11a	I've fallen out of touch with many of my closest friends	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
11b	This statement has become more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
12a	I enjoy socialising outside of my home environment	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
12b	This statement has become less applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
13a	I would avoid going to a new place if there were a lot of people I didn't know there	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
13b	This statement has become more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree

14a	If a situation arises where I need to speak to someone new, e.g. a new neighbour, I prefer my partner/family member to lead the conversation	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
14b	This statement has become more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
15a	I am actively involved in my community	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
15b	This statement has become less applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
16a	I think I would find things less stressful if I had more social contact with people	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
16b	This statement has become more applicable to me in the last 12 months	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
	Please indicate whether you have answered all questions in this questionnaire	**Yes**	**No**			

Appendix 6: Spatial Abilities and Practices Questionnaire

Anonymous ID:_____

Date:_____

Instructions: This questionnaire asks about your spatial abilities and practices in everyday life. There is no time limit so please feel free to take your time. We would advise that, if possible, you fill out this questionnaire together with someone who knows you well. Have you filled out this questionnaire with someone who knows you well?

Yes O No O

Read each statement carefully. Answer to what extent you agree with each of the 15 statements by choosing the answer that most applies to you. Please choose one answer only to each question. After each statement, we also ask if you think that there has been a change in your spatial ability in the last 12 months. Again, please select the one answer that most applies to you.

There are 30 questions in total. Thank you for your participation

	Question					
1a	**I am good at recognising a place (e.g. town square, building) even when I approach it from a new direction**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
1b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
2a	**When leaving or returning home, I generally have a good idea of the direction between my home and destination**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
2b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
3a	**When I walk out of a large shop or shopping centre, I sometimes find I am taking the wrong direction from the one I intended**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
3b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		

4a	**I have difficulty accurately visualising in my mind's eye the local walking routes (e.g. to shops, pubs, parks, restaurants) to and from my home**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
4b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
5a	I find it easy to visualise in my mind's eye the routes to places further afield (e.g. to nearby towns)	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
5b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
6a	When walking a route I usually take is completely blocked off (e.g. for maintenance, treefalls), I find it difficult to work out a new route	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
6b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
7a	I find it easy to remember precisely where the car is parked	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
7b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
8a	**I stick to major walking routes, and avoid minor paths and shortcuts, to avoid getting lost**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
8b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
9a	**When visiting new places, I prefer to be with people I know and follow them, rather than find my way myself as I feel that if I am alone, I may become lost**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
9b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
10a	**It is difficult for me to find my bearings in a new town/city**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
10b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
11a	**As a passenger in a car, I usually have to take the same route many times to remember it**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
11b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		

12a	**Before I go somewhere, I tend to visualise the different points along the journey where I need to make a decision (e.g. where I will need to go straight, left or right)**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
12b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
13a	**I can tell quite quickly that I am approaching a place I have been to before, even if I have only been there once or twice**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
13b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
14a	**On an outing or holiday, having walked around visiting several locations (e.g. coffee shop, museum) I can generally calculate a shortcut route back to my starting point without consulting signs and maps**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
14b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
15a	**I can find my way around places when travelling in the dark**	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
15b	Has your spatial ability in this respect changed over the last 12 months? Has it got better, is it the same as before, or is it worse?	**Better**	**Same**	**Worse**		
	Participant: Please indicate whether you have answered all questions in this questionnaire:	**Yes**	**No**			

Supplementary Tables & Figures

Supplementary Table 2.1: A Brief Description of Kurtosis for Key Variables Using

Variable	W	df	p	Brief Description of Skew
Age	.936	145	.001	Skew towards older age in all subjects
BMI	.969	145	.002	Skew towards lower end of BMI range
Education	.667	139	<.0001	Skew towards higher education level for all subjects
VEM Short Term Recall	.963	145	.001	Factor scores suggest bimodal distribution around plus 1 and minus 1
Face Memory & Perception	.969	145	.003	Factor scores show uneven spread towards more positive scores (between minus 1 and plus 1)
VEM Long Term Forgetting	.948	145	<.0001	Factor scores are skewed towards negative end (lower forgetting)
Working Memory	.947	145	<.0001	Factor scores are skewed towards more positive scores (better working memory)
PSQI Score	.942	140	<.0001	Scores are skewed towards the lower end of the 0-21 scoring range (in a 3-8 range)
Sleep Debt	.966	145	.001	Moderate skew towards higher positive Sleep Debt
Social Jet Lag	.936	145	<.0001	Skew towards lower end of positive Social Jet Lag
Chronotype	.978	145	.020	Scores are concentrated in earlier chronotypes (2:00 AM to 3:30 AM)
LMVPA	.971	145	.004	Seemingly normal distribution between 150-400 mins of LMVPA
Sustained MVPA	.853	145	<.0001	Heavy skew towards lower end (25-100 mins) of sustained MVPA
Positive Social Experience	.891	138	<.0001	Scores skewed towards more positive factor scores (0-2) possibly reflecting larger older group
Negative Social Experience	.942	138	<.0001	Scores skewed towards more negative factor scores (0/-2) possibly reflecting larger older group
Social Confidence	.957	138	<.001	Scores skewed towards more positive factor scores (0-2) possibly reflecting larger older group
Social Fearfulness	.936	138	<.0001	Scores skewed towards more negative factor scores (0/-1) possibly reflecting larger older group
Social Connectedness	.967	138	.002	Scores show a slight skew towards more positive factor scores
Family Networks	.938	140	<.0001	Seemingly normal distribution in score range of 5/6 to 12/13 out of 15—top end skew
Friendship Networks	.962	140	.001	Seemingly normal distribution in score range of 5/6 to 12/13 out of 15—top end skew
SF36 Psychological	.907	139	<.0001	Scores skewed towards more positive factor scores (0-1) possibly reflecting larger older group
SF36 Physical	.833	139	<.0001	Strong skew towards positive factor scores (0+) reflecting more physically active/able group

Supplementary Table 2.1 sets out a number of key variables reported in the present study that are not normally distributed according to the Shapiro-Wilks test for normality. The table also provides a short description of the kurtosis or skew in the normal distribution. In many cases, these are evidently the product of the sample population. For example, age is not normally distributed with a clear skew towards older age in the sample; this is deliberate. In many of the tables and figures in the present study, where Pearson's r correlations are reported, Spearman's r_s correlations are also reported, given the extensive number of non-normally distributed key variables.

Supplementary Table 2.2: PCA Factor Analysis (where VEM Long Term Forgetting comprises free and cued recall components based on A-B)

PCA Factor 1 VEM Short Term Recall		PCA Factor 2 Face Memory and Perception		PCA Factor 3 VEM Long Term Forgetting (A-B)		PCA Factor 4 Working Memory	
VSRT Free Recall Baseline	.877	Cambridge Face Memory	.846	VSRT Cued Recall Forgetting	.915	Stroop Test	-0.817
VSRT Cued Recall Baseline	.739	Glasgow Face Matching	.825			Four Mountains	.739
VSRT Sum Recall	.803	Jenkins & Burton Face Learning	.740	VSRT Free Recall Forgetting	.912		
RAVLT Delay	.775						
RAVLT Immediate	.644						
Eigenvalue	4.714		1.781		1.126		1.065
% of Variance	39.28		14.84		11.26		8.87
Cumulative Variance %	39.28		54.12		65.38		74.26

Supplementary Table 2.2 shows the comparable PCA factor analysis solution shown in Table 2.2, again using Varimax rotation as the preferred extraction method and with the same main test result variables *except for* using components for free and cued recall after two weeks based on an A-B method (time 1 minus time 2) in calculating VEM Long Term Forgetting. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy is 0.639 indicating a less mathematically robust factor solution than that shown in Table 2.2 for the (A-B)/(A+B) method (KMO=0.747). Bartlett's test of sphericity is significant (p<.0001) and therefore the data correlation matrix is significantly different from the identity matrix so that there are sufficient significant correlations to proceed. The determinant is 0.001 (i.e. greater than 0.00001) so that there is no evidence of multicollinearity or singularity. Each factor Eigenvalue has a value of >1 so using Kaiser K1 criteria suggests retaining the four identified factors accounting for 74.26% of the variance.

Supplementary Table 2.3: PCA Factor Analysis (where VEM Long Term Forgetting comprises free and cued recall components based on (A-B)/A)

PCA Factor 1 VEM Short Term Recall		PCA Factor 2 Face Memory and Perception		PCA Factor 3 VEM Long Term Forgetting (A-B/A)		PCA Factor 4 Working Memory	
VSRT Free Recall Baseline	.859	Cambridge Face Memory	.843	VSRT Cued Recall Forgetting	.917	Stroop Test	-0.817
VSRT Cued Recall Baseline	.769	Glasgow Face Matching	.821			Four Mountains	.735
VSRT Sum Recall	.779	Jenkins & Burton Face Learning	.744	VSRT Free Recall Forgetting	.915		
RAVLT Delay	.730						
RAVLT Immediate	.584						
Eigenvalue	4.959		1.695		1.227		1.063
% of Variance	41.32		14.12		10.23		8.86
Cumulative Variance %	41.32		55.45		65.68		74.53

Supplementary Table 2.3 shows the comparable PCA factor analysis solution shown in Table 2.2, again using Varimax rotation as the preferred extraction method and with the same main test result variables *except for* using components for free and cued recall after two weeks based on an (A-B)/A method (time 1 minus time 2 over time 1) in calculating VEM Long Term Forgetting. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy is 0.704 indicating a less mathematically robust factor solution than that shown in Table 2.2 for the (A-B)/(A+B) method (KMO=0.747). Bartlett's test of sphericity is significant (p<.0001) and therefore the data correlation matrix is significantly different from the identity matrix so that there are sufficient significant correlations to proceed. The determinant is 0.001 (i.e. greater than 0.00001) so that there is no evidence of multicollinearity or singularity. Each factor Eigenvalue has a value of >1 so using Kaiser K1 criteria suggests retaining the four identified factors accounting for 74.53% of the variance.

Supplementary Table 2.4: Comparison of Memory Domain Performance in Four Different Age Groups

Compared Groups	VEM Short Term Recall			Face Memory & Perception			VEM Long Term Forgetting			Working Memory		
	t	p	df	t	p	df	t	p	df	t	p	df
Group 1 (18-35) & Group 2 (36-50)	1.391	.17	43.389	1.223	.23	52	1.734	.09	52	1.297	.20	52
Group 2 (36-50) & Group 3 (51-65)	.617	.54	66	.664	.51	66	-1.824	.07	66	1.025	.31	66
Group 3 (51-65) & Group 4 (66+)	1.468	.15	89	2.294	.024	89	-.109	.91	89	3.450	.001	89
Group 1 (18-35) & Group 3 (51-65)	2.404	.02	64	1.742	.09	64	-.370	.71	63.999	2.533	.014	63.258
Group 1 (18-35) & Group 4 (66+)	4.055	.0001	74.999	3.832	.0003	75	-.481	.63	74.656	6.009	<.0001	74.804
Group 2 (36-50) & Group 4 (66+)	1.873	.06	77	2.899	.005	77	-1.975	.052	74.971	4.386	<.0001	73.387

Supplementary Table 2.4. shows differences in memory domain performance between four different age groups: Group 1 (18-35 years); Group 2 (36-50) years; Group 3 (51-65 years) and Group 4 (66+ years). Orange shading denotes significant differences between age groups. It is noticeable that for all domains, except VEM Long Term Forgetting, there are significant differences between the youngest and oldest groups (Groups 1 and 4). There are also significant differences between the youngest and second oldest groups (Groups 1 and 3) in VEM Short Term Recall and Working Memory. There are no significant differences at all between any age groups in VEM Long Term Forgetting. The only difference that approaches significance for VEM Long Term Forgetting is between Groups 2 and 4; in this case, equal variances are not assumed ($F=9.115$, $p=.003$). If equal variances were assumed, the difference is non-significant; $t_{77}=-1.746$, $p=.085$.

Supplementary Table 4.1—Assumed Sleep Duration (ASD), MSW, MSF, Chronotype, Sleep Debt and Social Jet Lag—Example Calculation

Days	Sleep Onset (Time)	Sleep Offset (Time)	ASD (mins)	MSF	ASD (mins) Work-Free Day	Sleep Debt[1]	MSFsc[2]	MSW	SJL[3]
Friday/Saturday	22:54	05:58	424	326	424				
Saturday/Sunday	22:50	06:22	452	336	452				
Sunday/Monday	22:13	05:56	463					304	
Monday/Tuesday	23:24	05:59	395					341	
Tuesday/Wednesday	22:46	06:11	445					328	
Wednesday/Thursday	22:48	06:11	443					329	
Thursday/Friday	22:56	05:51	415					323	
Friday/Saturday	22:27	06:57	510	342	510				
Saturday/Sunday	22:33	06:17	464	325	464				
Sunday/Monday	22:35	05:40	425					307	
Monday/Tuesday	22:58	05:42	404					320	
Tuesday/Wednesday	23:11	05:38	387					324	
Wednesday/Thursday	22:32	06:02	450					317	
Thursday/Friday	22:59	05:56	417					327	
Average Scores			435.29	332.25	462.5	27.21	305.04	322	10.25
Average Times				02:32 AM			02:05 AM	02:22 AM	

Supplementary Table 4.1 shows an example calculation for a single subject of their chronotype (MSFsc), Sleep Debt and Social Jet Lag extracted from their actigraphy data for a two week period. Data shown in the Table does not show scores for any actual person in the study. MSF and MSW scores are derived from the Eveningness scoring table shown in Supplementary Table 4.2; see below. Notes: Note 1: Sleep Debt= ASD Work-Free Days minus ASD (462.5-435.29=27.21). Note 2: MSFsc= MSF minus Sleep Debt (332.25-27.21=305.04). Note 3: SJL= MSF minus MSW (332.25-322=10.25), not adjusted for Sleep Debt; see text for full details.

Supplementary Table 4.2: General Scoring System for categorising subjects as Owls or Larks

Eveningness			Morningness		
Bed-time	Score	Category	**Getting-Up time**	Score	Category
9pm	0	Owl	**3am**	0	Lark
10pm	60	Owl	**4am**	60	Lark
11pm	120	Owl	**5am**	120	Lark
11.30pm	150	Owl	**6am**	180	Lark
12.00am	180	Owl	**6.30am**	210	Lark
1.00am	240	Owl	**7am**	240	Lark
2.00am	300	Owl	**8am**	300	Lark
3.00am	360	Owl	**9am**	360	Lark
4.00am	420	Owl	**10am**	420	Lark

Supplementary Table 4.2 shows the general scoring system used to score a subject's 'going to bed' (Eveningness) and 'getting up' (Morningness) times derived from actigraphy devices for each day of a two week period of sleep assessment. Darker blue shading shows stronger owl or lark behavioural tendencies, as appropriate. Scores have been used to categorise individuals as 'owls' or 'larks' for Work days, Work-free days and overall (i.e. 3 separate scores) for both Eveningness and Morningness (i.e. 6 scores in total), by using a cut off of 11.30 pm or later to constitute 'owl'-type behaviour for Eveningness purposes and a cut off of 6.30 am or earlier to constitute 'lark'-type behaviour for Morningness purposes. The threshold for overall binary categorisation is therefore 360 (11:30 pm=150 plus 6:30 am=210).

Supplementary Table 4.3A: Eveningness and Morningness Scores for four Subjects: an Example

Example Subject	Eveningness Weekday	Morningness Weekday	Eveningness Weekend	Morningness Weekend	Eveningness Overall	Morningness Overall
Subject 1 Score	68.18	115.82	60.75	157.5	66.2	126.93
Subject 1 Time	10:08 PM	4:46 AM	10:01 PM	5:37 AM	10:06 PM	5:06 AM
Subject 2 Score	200.75	248.5	275	276	215.6	254
Subject 2 Time	12:21 AM	7:08 AM	01:35 AM	7:36 AM	12:36 AM	7:14 AM
Subject 3 Score	109.36	280.09	135	262.5	116.2	275.4
Subject 3 Time	10:49 PM	7:40 AM	11:15 PM	7:22 AM	10:56 PM	7:17 AM
Subject 4 Score	83.45	228.64	112.5	277.75	91.2	241.73
Subject 4 Time	10:24 PM	6:49 AM	10:52 PM	7:38 AM	10:31 PM	7:02 AM

Supplementary Table 4.3A shows example scores for four separate subjects and the conversion of those scores into 24 clock times (based on Supplementary Table 4.2). Each subject has a total of 6 scores; for Eveningness weekday (Work day), weekend (Work-free day) and overall and for Morningness weekday, weekend and overall. Excluding subjects who wore devices over a Bank Holiday (treated as a Work-free day) most subjects will have weekday averages for Morningness/Eveningness based on 10 days of data and weekend averages for Morningness/Eveningness based on 4 days of data. As shown in Supplementary Tables 4.3B and 4.3C below, subjects 1 and 2 are consistent lark and owl respectively. Subjects 3 and 4 are more inconsistent in their behaviour but the result of the binary distribution (shown in Supplementary Table 4.3C below) is that they are categorised as owl and lark respectively.

Supplementary Table 4.3B: Eveningness and Morningness Scores for four Subjects: Example Categorisation

Example Subject	Eveningness Weekday	Morningness Weekday	Eveningness Weekend	Morningness Weekend	Eveningness Overall	Morningness Overall
Subject 1 Categorisation	1	1	1	1	1	1
Subject 2 Categorisation	0	0	0	0	0	0
Subject 3 Categorisation	1	0	1	0	1	0
Subject 4 Categorisation	1	0	1	0	1	0

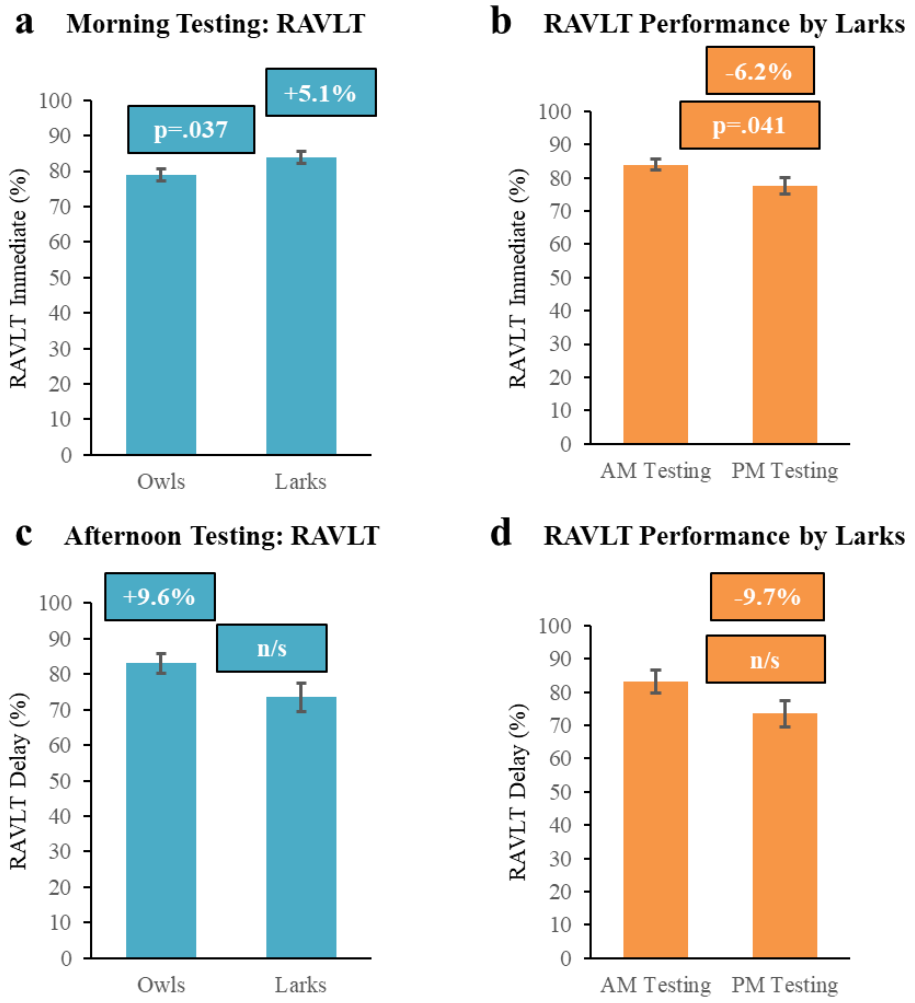
Supplementary Table 4.3B shows an example categorisation of the 4 subjects in Supplementary Table 4.3A (1=Lark, 2=Owl). It can be seen that subject 1 is a 'consistent lark', going to bed on weekdays, at weekends and overall on average before 11.30 PM and getting up on weekdays, at weekends and overall on average before 6:30 AM. By contrast, subject 2 is a 'consistent owl', going to bed on weekdays, at weekends and overall on average after 11:30 PM and getting up on weekdays, at weekends and overall on average after 6:30 AM. The behaviour of subjects 3 and 4 is inconsistent on weekdays, at weekends and overall. Their categorisation will depend upon their combined score

Supplementary Table 4.3C: Example Categorisation based on Eveningness and Morningness Scores

Subject	Combined Score	Combined Rating
1	193.13	1 (Lark)
2	469.6	0 (Owl)
3	391.6	0 (Owl)
4	332.93	1 (Lark)

Supplementary Table 4.3C shows the combined score for each of the four subjects in Supplementary Table 4.3A which is the sum of their overall average Eveningness and overall average Morningness scores. At the binary distribution threshold of 360, subject 3 is categorised as, on balance, an owl and subject 4 is categorised as, on balance, a lark. Subjects 1 and 2 are clearly lark and owl respectively, based on their combined scores. The 'combined score', which is the basis for the 'owl' or 'lark' binary categorisation, is highly correlated with MSFsc (Pearson's r=.771, p<.0001, N=145).

Supplementary Figure 4.4: RAVLT: Differences in Performance by Time of Day of Testing



Supplementary Figure 4.4: RAVLT: Differences in Performance by Time of Day of Testing. a. Comparisons in Morning Testing of Owls and Larks. In morning testing, larks score higher (83.94%) than owls (78.86%) in RAVLT Immediate recall; t_{61}=-2.132, p=.037. b. Comparing performance of larks between morning and afternoon testing. In the afternoon, the performance of larks (77.72%) falls slightly below that of owls in the morning and represents a significant deterioration in performance between morning and afternoon testing; $t_{46.763}$=2.101, p=.04. c. Comparisons in Afternoon Testing of Owls and Larks. In afternoon testing, owls score nearly 10% higher (83.11%) than larks (73.52%) in RAVLT delayed recall although this large difference is not statistically significant; t_{80}=1.985, p=.051. d. Comparing performance of larks between morning and afternoon testing. Owls do not differ between morning and afternoon testing in RAVLT delayed recall, but larks are nearly 10% better in the morning (83.24%) than they are in the afternoon (73.52%) although this large difference is not statistically significant; t_{54}=1.858, p=.069.

Supplementary Table 5.1: Correlations between Different Actigraphy-Measured Physical Activity Levels

	Light PA		Moderate PA		Vigorous PA		MVPA		Sus. MVPA		LMPA		LMVPA	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p
Moderate PA	.360	<.0001												
Vigorous PA	-.114	.17	.405	<.0001										
MVPA	.333	<.0001	.996	<.0001	.487	<.0001								
Sustained MVPA	.044	.60	.808	<.0001	.609	<.0001	.833	<.0001						
LMPA	.658	<.0001	.940	<.0001	.285	.001	.926	<.0001	.669	<.0001				
LMVPA	.631	<.0001	.948	<.0001	.360	<.0001	.942	<.0001	.701	<.0001	.997	<.0001		
Sedentary	-.413	<.0001	-.767	<.0001	-.330	<.0001	-.765	<.0001	-.603	<.0001	-.770	<.0001	-.777	<.0001

Supplementary Table 5.1 shows Pearson's r correlations between different physical activity levels, including sedentary time, as recorded by actigraphy devices. As might be expected, all different levels of physical activity are strongly positively correlated with each other (and negatively with sedentary time), *except* for vigorous activity and sustained MVPA which are *not* correlated with higher levels of light PA. Non-significant correlations are those those shown in red shading.

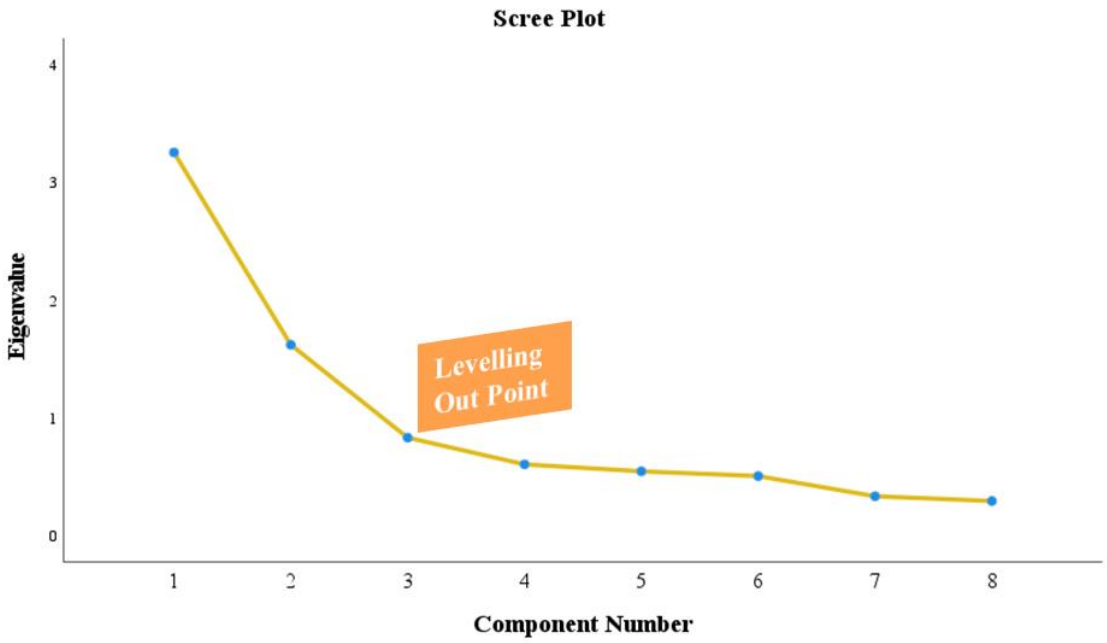
Supplementary Table 6.1: Example Correlations between Items where Good and Poor Sleepers do/do not Differ

'Psychological Mood' Items where Good and Poor Sleepers Differ	'Sociability' Items where Good and Poor Sleepers do not Differ	Correlations between Items (All Subjects)				Correlations between Items (Good Sleepers)				Correlations between Items (Poor Sleepers)			
		r	p	r_s	p	r	p	r_s	p	r	p	r_s	p
UCLA Loneliness	Lubben Friendship Networks	-.569	<.0001	-.440	<.0001	-.615	<.0001	-.452	<.0001	-.578	<.0001	-.499	<.0001
UCLA Loneliness	Social Situation	-.578	<.0001	-.533	<.0001	-.587	<.0001	-.506	<.0001	-.564	<.0001	-.547	<.0001
UCLA Loneliness	Liebowitz Social Fear	.291	.001	.292	<.001	.212	.063	.270	.017	.379	.003	.345	.006
UCLA Loneliness	Brief Fear of Negative Evaluation	.271	.001	.263	.002	.241	.033	.227	.044	.364	.004	.380	.003
UCLA Loneliness	Lubben Family Networks	-.297	<.001	-.280	.001	-.322	.004	-.232	.039	-.254	.048	-.276	.031
DASS 21	Lubben Friendship Networks	-.327	<.0001	-.305	<.001	-.342	.002	-.202	.075	-.341	.007	-.437	<.001
DASS 21	Social Situation	-.379	<.0001	-.465	<.0001	-.359	.001	-.336	.002	-.384	.002	-.577	<.0001
DASS 21	Liebowitz Social Fear	.261	.002	.310	<.001	.242	.033	.266	.019	.283	.027	.366	.004
DASS 21	Brief Fear of Negative Evaluation	.483	<.0001	.410	<.0001	.528	<.0001	.431	<.0001	.507	<.0001	.407	.001
Zung Anxiety	Lubben Friendship Networks	-.260	.002	-.183	.031	-.237	.036	-.146	.20	-.331	.009	-.290	.023
Zung Anxiety	Social Situation	-.331	<.0001	-.272	.001	-.241	.033	-.117	.31	-.401	.001	-.363	.004
Zung Anxiety	Liebowitz Social Fear	.341	<.0001	.260	.002	.275	.015	.178	.12	.442	<.001	.394	.002
Zung Anxiety	Brief Fear of Negative Evaluation	.384	<.0001	.344	<.0001	.366	.001	.357	.001	.516	<.0001	.468	<.001
Diener SPANE Positive Affect	Lubben Friendship Networks	.389	<.0001	.380	<.0001	.491	<.0001	.419	<.001	.314	.014	.339	.007
Diener SPANE Positive Affect	Social Situation	.390	<.0001	.454	<.0001	.464	<.0001	.449	<.0001	.292	.023	.444	<.001
Diener Flourishing	Lubben Friendship Networks	.389	<.0001	.391	<.0001	.372	.001	.313	.005	.441	<.001	.493	<.0001
Diener Flourishing	Social Situation	.426	<.0001	.488	<.0001	.451	<.0001	.411	<.001	.396	.002	.525	<.0001

Supplementary Table 6.1 shows examples of correlations between underlying questionnaire items comprised in 'Psychological Mood' factors, where good and poor sleepers score differently, and 'Sociability' factors where they do not (see Table 6.5 for details of differences between good and poor sleepers). Both Pearson's r and Spearman's r_s correlations are shown for each pair of items. Paired items show correlations for all subjects and, separately, correlations for good sleepers and poor sleepers alone. All correlations for all paired items are significant *except* for those highlighted in red shading.

Supplementary Table and Figure 6.2: Scree Plot, Communalities and Anti-Image Correlations for PCA SF36 Short Term Health Survey Factors

SF36 Measure	Communalities	Anti-Image Correlations
Physical Functioning	.665	.698
Limits (Physical)	.603	.683
Limits (Emotional)	.558	.734
Energy & Fatigue	.662	.789
Emotional Wellbeing	.769	.710
Social Functioning	.580	.836
Pain	.466	.766
General Health	.571	.826



Supplementary Table 6.2 shows communalities and anti-image correlations for the 8 component elements of the SF36 Short Form Health Survey under Principal Component Analysis (PCA) exploratory factor analysis.

Supplementary Figure 6.2 below shows the scree plot for the PCA which suggests a 2 factor solution for the SF36 questionnaire scores.

Supplementary Table 6.3: Comparisons between Subjects in Psychological Health Scores & Associations with VEM Long Term Forgetting

Questionnaire	Better Psychological Health Older or Younger	P value	Effect Size Cohen's d	Better Psychological Health Good Sleeper or Poor Sleeper	P value	Effect Size Cohen's d	Correlation with VEM Long Term Forgetting	
							r	p
Diener Flourishing Scale	Older	.001	0.57	Good Sleeper	.002	0.53	-.031	.71
Diener SPANE (Positive)	Older	.028	0.38	Good Sleeper	.002	0.53	-.205	.015*
Diener SPANE (Negative)	Older	.0002	0.70	Neither	-	-	.064	.45
Diener SPANE (Balance)	Older	.001	0.60	Good Sleeper	.007	0.47	-.148	.08
Diener Satisfaction With Life	Older	.002	0.53	Good Sleeper	.006	0.47	-.097	.25
Zung Anxiety	Neither	-	-	Good Sleeper	<.0001	0.80	.073	.39
DASS 21 Distress	Older	.013	0.63	Good Sleeper	.016	0.50	.054	.52
Brief Fear of Negative Evaluation	Older	<.0001	1.12	Neither	-	-	-.006	.94
UCLA Loneliness Scale	Neither	-	-	Good Sleeper	<.001	0.62	.094	.27
Social Situation	Neither	-	-	Neither	-	-	-.092	.28
Social Situation (Trend)	Older	.011	0.44	Neither	-	-	-.057	.50
Liebowitz Fear Subscale	Older	.025	0.39	Neither	-	-	-.090	.29
Liebowitz Avoidance Subscale	Neither	-	-	Good Sleeper	.008	0.46	.005	.96
Lubben Friendship Networks	Neither	-	-	Neither	-	-	.015	.86
Lubben Family Networks	Neither	-	-	Neither	-	-	-.033	.70
SF36 Short Form Health Survey								
Physical Functioning	Younger	<.0001	0.95	Good Sleeper	.014	0.50	-.152	.07
Physical Limits	Younger	.022	0.40	Neither	-	-	-.179	.034*
Emotional Limits	Older	.014	0.60	Good Sleeper	.02	0.45	-.193	.023*
Energy & Fatigue	Older	.001	0.56	Good Sleeper	.002	0.53	-.263	.002**
Emotional Wellbeing	Older	.001	0.77	Good Sleeper	.007	0.46	.191	.024*
Social Functioning	Older	.023	0.39	Good Sleeper	.001	0.69	-.254	.002**
Pain	Neither	-	-	Good Sleeper	.009	0.45	-.068	.43
General Health	Neither	-	-	Good Sleeper	.002	0.54	-.101	.23

Notes to Table 1: Table 1 compares performance between older and younger subjects and between good and poor sleepers in a range of psychological health questionnaires. The eight elements of the SF36 are shown separately at the bottom of the Table. All comparisons show the results of independent t tests and provide p value differences and Cohen's d effect sizes for all comparisons where differences are significant. Correlations between questionnaire scores and VEM Long Term Forgetting are simple Pearson's r correlations. Correlations marked * are significant at the p<.05 levels and correlations marked ** are significant at the p<.01 level.