Evaluation of blue light exposure, illuminance level and the associations with sleep/wake patterns in two populations living with sensory impairment.

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Abstract

Exposure to sufficient light during the daytime is fundamental for the regulation of the sleep/wake cycle, with the blue part of the spectrum most influential. This thesis explores exposure to environmental blue light and level of illuminance in two populations that experience circadian disruption i.e. older people and young people with autism spectrum disorder (ASD). The aim was to examine associations between blue light exposure, illuminance level and sleep/wake and physical activity patterns. Firstly, an exploratory study was conducted in adolescents with ASD living in a residential school setting aged 13-17 years (n=8). Secondly, a cross-sectional study carried out in two seasons (summer and winter) with a comparative study between seasons of varying light exposure and sleep/wake and physical activity outcomes was conducted in older people aged 72-99 years (n=20). In both studies quantitative measures were used to examine personal light exposure and sleep/wake patterns by use of novel equipment known as an actiwatch.

This research demonstrated that objective measures of sleep/wake and light monitoring could be successfully administered in two populations with complex sensory issues. Preliminary findings from the exploratory study in adolescents with ASD indicated that exposure to blue light prior to bedtime was associated with a delay in sleep onset. The methodology developed for participant recruitment and engagement in a study using body sensors proved to be successful. Results for the study in older people suggested that between seasons daytime physical activity, blue light exposure and illuminance levels were significantly higher in summer. Correlated component regression (CCR) was used to investigate predictors of sleep parameters, suggesting morning blue light exposure (a predictor of total night-time sleep), daytime activity level (a predictor of sleep efficiency) and visual function (a predictor of minutes awake during the night) may contribute to sleep quality.

The findings from these studies suggested that light exposure and health outcomes, such as physical activity and visual function could be responsible for sleep quality. This has important implications for design and health interventions promoting health and wellbeing, i.e. morning light exposure and time outdoors are important for circadian entrainment and building design and routine should reflect a diurnal light pattern light.

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Contents

List of Tables

List of Figures

Glossary of Terms

Category	Term	Definition
Light	Illuminance	A measure of how much the incident light illuminates the surface, wavelength-weighted by the luminosity function to correlate with human brightness perception.
	Luminous efficiency	The average spectral sensitivity of the human visual perception of brightness.
	Spectral irradiance	The power density at a particular wavelength.
Vision	Scotopic	The visual function of the eye under low light conditions through rod cells.
	Photopic	The visual function of the eye under bright light conditions and perception of colour vision, mediated by cones cells.
	ipRGC	Intrinsically photosensitive Retinal Ganglion Cells (ipRGC), also called photosensitive Retinal Ganglion Cells (ipRGC) are a type of cell in the retina of the mammalian eye regulating the circadian system.
	Contrast sensitivity	The ability to distinguish between finer and finer increments of light versus dark (contrast).
	Visual acuity	A measure of central vision, the ability to distinguish details and shapes of objects.
Sleep	Actiwatch	A wrist-mounted device typically used to record sleep/wake an activity patterns. The output is referred to actigraphy or actigraph
	Total sleep time	The total time within each rest interval scored as sleep.
	Sleep efficiency	The percentage of time in bed actually sleeping.
	Sleep onset latency	The number of minutes taken to fall asleep.
	Wake after sleep onset	The number of minutes awake during the sleep cycle.

List of abbreviations

Abbreviation	Definition
ANOVA	Analysis of variance
ASD	Autism spectrum disorder
BLE	Blue light exposure
CCR	Correlated component regression
CS	Contrast sensitivity
CCT	Colour correlated temperature
IEQ	Indoor environment quality
ipRGC	Photosensitive retinal ganglion cells
MANOVA	Multivariate analysis of variance
MMSE	Mini mental state examination
MOR	Multivariate odds ratio
NC	Normal cognitive function
PIC	Potentially impaired cognition
PSQI	Pittsburgh sleep quality index
SCN	Suprachiasmatic nucleus
SE	Sleep efficiency
SOL	Sleep onset latency
SRT	Simple reaction time
TST	Total sleep time
U	Denotes the Mann-Whitney U statistic
VA	Visual acuity
WASO	Wake after sleep onset
WEMWBS	Warwick Edinburgh mental wellbeing scale
Z	Denotes the Wilcoxon signed-rank test statistic
*	Denotes a statistical significance in a table
Bold type	Denotes a statistical significance in a table
<	Less than
>	Greater than
Lux	Is the SI unit of illuminance
$\mu W/cm^2$	The unit measure of light intensity i.e. spectral irradiance
nm	Nanometers – a measure of length for each wavelength of light

Chapter 1 : An introduction to light and daily human functioning

1.1 Introduction

Humans have evolved with exposure to a diurnal cycle of bright light from daylight to darkness, keeping our circadian rhythms in synchronicity. The evolution of architecture, differences in social conduct and access to technology can shield us from daylight, or create over exposure to light at the incorrect time of day causing irregularity to the light-dark cycle. As a result we can experience disruptions to our biological rhythms and specifically the sleep/wake pattern, which may result in poor physical and mental health (Navara and Nelson, 2007).

The primary function of light is to create an environment that provides sufficient illuminance to perform visual tasks, create ambience, and allow easier living and to navigate environments. Until recently, people have been unaware that light facilitates many other biological functions in the body (Berson, Dunn and Takao, 2002). Now there is a growing awareness of the power light has and the potential effects on daily human functioning. People may already sense the possible effects of light, such as our experiences of seasonal change, e.g. the warmth of the sun on skin in summer time, or the first long days of spring. In countries of northern latitudes it is well recognised that summer days are long and filled with light, whilst the winter sees the opposite with short days and dark nights. Many people experiences changes in their mood or energy levels between seasons, particularly low mood and less energy during the winter months (Alfred *et al.*, 2009; Flaskerud, 2012; Khaled and Keef, 2013). They may also be aware of home light therapy applications through dawn simulation lamps or Seasonal Affective Disorder (SAD) lamps that may help to alleviate symptoms (Pail *et al.*, 2011). What people may not be aware of are the effects of light from other sources, such as television screens, laptops, computers, smartphones or tablets. Exposure to these types of light at the wrong time of day has the potential to shift the habitual sleep cycle or circadian rhythms by suppressing hormones that help induce sleep (Figueiro, Lesniak and Rea, 2011; Wood *et al.*, 2013). This has led researchers to explore the effects of

light beyond the need for visual functioning and to explore the physiological and by extension the psychological impacts of light on humans.

Interest in lighting research spans many disciplines. For example, neuroscience explores brain function, chronobiology, researching circadian rhythms and psychology exploring associations with mental health and wellbeing. The discovery that the eye is the gateway to the area of the brain controlling the endogenous biological clock increased interest in this subject and broadened the field of lighting research. A substantial number of studies have demonstrated that under laboratory controlled conditions blue light can alter circadian rhythms, the secretion of hormones and the sleep/wake cycle (Lockley, Brainard and Czeisler, 2003; Warman *et al.*, 2003; Cajochen *et al.*, 2004; Bullough *et al.*, 2008; Smith, Revell and Eastman, 2009; Papamichael, Skene and Revell, 2012; Appleman, Figueiro and Rea, 2013; Rüger *et al.*, 2013). Researchers in the lighting field recognise that lighting quality and the blue spectral irradiance of light is an important component in health and wellbeing of humans. However, there are a limited number of studies conducted in a natural setting exploring blue light exposure.

In older people a deterioration in the area of the brain where the circadian system functions can cause reduced levels of cognitive ability, lower daytime physical activity levels and disrupted sleep patterns (Hofman and Swabb, 2006). The result is often reduced daytime physical activity, increased night-time awakenings, frequent daytime napping and early wake up times (Mirmiran *et al.*, 1992; Hofman and Swabb, 2006; de Bruijn *et al.*, 2013). Research has also indicated that the eye facilitates light transmission to the area of the brain, which regulates circadian rhythms (i.e. the body clock). Natural changes in the eye occur with ageing (such as a yellowing of the lens and narrowing pupil) and impede light transmission. The diminished levels of light received can contribute to a disruption in the timing of the body clock and the sleep/wake cycle. In adolescents, changes in the hormone patterns and circadian rhythmicity, during puberty cause a decrease in total sleep time, a tendency to delay sleep and increase daytime sleepiness (Carskadon, 1990). In adolescents with ASD this can be more pronounced due to inherent symptoms of the condition, such as cognitive developmental delays and irregularities in hormone secretions (Ritvo *et al.*, 1993). Out-

with the body, environmental zeitgebers influences the sleep/wake cycles and aid daily entrainment of circadian rhythms. These are cues (natural and artificial) in the environment, such as a diurnal pattern of light exposure, ambient air temperature, regulated food intake or access to time of day (Aschoff *et al.*, 1975).

Fieldwork studies exploring light exposure and, specifically, blue light exposure, in both of these populations are limited, yet there is growing interest in the effects on human health and wellbeing. It appears relevant and timely to explore the associations between blue light exposure, illuminance levels and the sleep/wake patterns in older people living in a care home setting and creating a novel area of research piloting a protocol exploring in adolescents with ASD.

This thesis explores, in a natural setting, blue light exposure and levels of illuminance in two specific populations that present symptoms of potential circadian disruption. Specifically, this research investigates older adults living in care homes and adolescents with autism spectrum disorder (ASD) living in a residential school. These populations share many similarities, although at opposite ends of the life span. Older adults and adolescents (typically developing and those with ASD) begin to experience changes in circadian rhythmicity and the habitual sleep/wake cycle.

This chapter sets out the fundamentals for light and daily human functioning. Firstly, a definition of the visible spectrum of light and how blue light sits within this. The non-visual pathway, passage of light through the eye and the link to circadian rhythms is described. The relationship between light, circadian regulation and cognitive function is outlined. This is followed by a report of the importance of timing, duration and seasonality of light exposure. Finally, the chapter sets out the rationales for study cohorts, with details of the relationship between blue light and illuminance in older adults and in adolescents with ASD. The chapter ends by setting out the thesis framework.

1.2 Light and the visible spectrum

Visible light is part of the electromagnetic spectrum (Figure 1.1.). The human eye can detect this spectrum from around 400nm, Ultraviolet light (UV) to 700nm, Infrared light (IR). The eye does not have a uniform response across the visible spectrum; sensitivity to wavelengths of light varies. Shorter wavelengths (from 400nm) appear much brighter than longer wavelengths (to 700nm). Luminance efficiency function for the standard Scotopic[1] observer has a maximum sensitivity at 555nm, green light (CIE 1983), giving the impression of highest brightness. The blue light bandwidth extends from 450-500nm. The internal body clock (or circadian system) by contrast has a peak sensitivity to blue light at 460-480nm. Exposure to light of this wavelength and at the correct time of day is important for circadian synchronisation. The blue light wavelengths are the most documented in their ability to alter circadian rhythms, the sleep cycle, mood and feelings of alertness (Warman *et al.*, 2003; Brainard *et al.*, 2008; Anderson *et al.*, 2009; Vetter *et al.*, 2011). Blue light is transmitted through the eye and enters the area of the brain where the body clock functions. The ability of the eye to transmit blue light changes over time. The natural ageing process causes the lens to yellow and pupil to narrow (Kessel *et al.*, 2010; Turner, Van Someren and Mainster, 2010). It is known that orange filters will block blue light (Sasseville *et al.*, 2006; Burkhart and Phelps, 2009; Sasseville *et al.*, 2015), therefore, in older adults it is likely that they will require bluer and brighter light, compared to younger adults and children, to synchronise the circadian system.

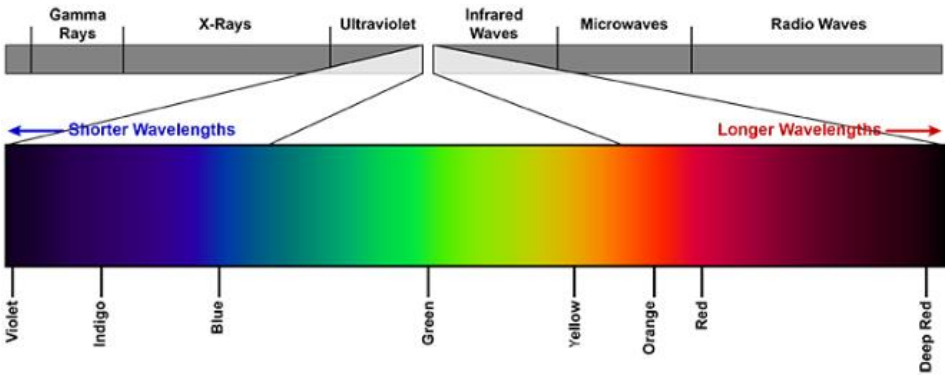


Figure 1.1 Electromagnetic Spectrum (www.york.ca, accessed 3/10/2015)

[1] Scotopic Vision- the visual functioning of the eye under low light conditions, such as those in the evening hours

1.3 The non-image forming eye

It is well established that the primary function of the eyes is to enable vision. The eyes contain a complex set of image-forming photoreceptors, which communicate visual information to the brain. Rods and cones are light sensitive cells, located at the back of the retina that detect the light entering the eye and transmit the photic information via the optic tract to the visual cortex (Boyce, 2003). Scotopic vision, (the eyes adaption under dim light conditions) is supported by rods and photopic vision (colour vision and fine detail perception under bright light) is facilitated by cones only. The eye is comprised of 3 types of cone receptors, each with a different spectral sensitivity. These include short (S-cones, blue spectrum), medium (M-cones, green spectrum) and long (L-cones, red spectrum).

Research has now established that the eye plays a non-image forming role (Berson, Dunn and Takao, 2002; Berson, 2003). It was discovered that the eye contains a third class of photoreceptors in the retina, known as photosensitive retinal ganglion cells (ipRGC) (Berson, Dunn and Takao, 2002; Hattar *et al.*, 2002). This pathway projects into the area of the brain that regulates circadian rhythms, such as the sleep/wake cycle, as well as feelings of alertness and mood (Hattar *et al.*, 2002; Gooley *et al.*, 2003; Hattar *et al.*, 2006; Vandewalle, Maquet and Dijk, 2009; Kretschmer, Griefahn and Schmidt, 2011; Lucas *et al.*, 2012). The primary route of information to the brain is through the retinohypothalamic tract to the Superchiasmatic Nucleus (SCN), located in the hypothalamus – this is where the internal body clock regulates circadian rhythms (Figure 1.2) (Berson, Dunn and Takao, 2002; Hattar *et al.*, 2002; Berson, 2003; Gooley *et al.*, 2011; Lucas *et al.*, 2012). The photopigment melanopsin is thought to be contained in the ipRGC and primarily responsible for the non-image forming responses of light (Provencio *et al.*, 2000; Hattar *et al.*, 2002; Güler *et al.*, 2008; Lucas *et al.*, 2014). However, it is also believed that the rods and cones may contribute to the non-image forming effects of light, particularly at low intensity light levels and similarly the ipRGC to vision (Dacey *et al.*, 2005; Güler *et al.*, 2008; Gooley *et al.*, 2010; Lucas *et al.*, 2012; Lucas *et al.*, 2014).

In addition to differences in the projection into the brain between ipRGC and classic rods and cones, the ipRGC also has a different spectral sensitivity to light. Light wavelengths around 460nm-480nm (i.e. in the blue part of the visible spectrum) and higher light levels have the most effect upon melanopsin (Berson, Dunn and Takao, 2002; Hattar *et al.*, 2002; Berson, 2003; Dacey *et al.*, 2005; Güler *et al.*, 2008). In addition to requiring higher light levels the ipRGC cells also have a response latency to light exposure, i.e. the non-image forming effects of light are not immediate.

Discovering the eye is performing a non-visual role and understanding that it is the pathway in which light travels to the brain, causing activation in different areas (other than for vision), has dramatically increased the awareness about the role of light exposure for daily functioning (Hattar *et al.*, 2002). Laboratory studies have shown that intensity, duration, spectral distribution and time of day can have differing physiological effects on the body (Lockley, Brainard and Czeisler, 2003; Cajochen *et al.*, 2004; Chellappa *et al.*, 2011; Rüger *et al.*, 2013). Primary aims in lab studies have included investigations into the consequence of light upon the human circadian system, the regulation of hormone secretions (such as melatonin and cortisol) and changes in tympanic temperature (i.e. core body temperatures) (Cajochen *et al.*, 2000; Lockley, Brainard and Czeisler, 2003; Cajochen, 2007; Chellappa *et al.*, 2011). Research has shown that light is a significant modulator for circadian rhythms and may cause temporal changes (phase-shifts) in the rhythmicity of the 24-hour cycle (Dijk *et al.*, 2012). Temporal changes are not instantaneous and often present after days or sometime weeks (Foster, 2012). Similarly, light can also cause acute effects – these are more immediate and relate to a subjective experience, such as alertness or mood (Revell *et al.*, 2006; Cajochen, 2007; Chellappa *et al.*, 2011; Sahin *et al.*, 2014; Smolders and de Kort, 2014).

1.4 Circadian rhythms and the effects of light

Circadian rhythms refer to physical, behavioural, mental and hormonal changes that occur in the body over a 24-hour period. It may be more commonly referred to as the

'body clock' or the 'master clock'. The regulation of circadian rhythms supports timing of behaviour and physiology as well as peripheral timings in the body, e.g. organ functioning (Foster and Kleitzman, 2005). The human body clock has an internal oscillation of approximately 24-hours, however, this needs to be entrained daily to the natural rhythmicity of the environment (Foster and Kreitzman, 2014). The SCN is the critical component in sleep regulation; within it a collection of neurons are expressed depending upon time of day - referred to as 'clock gene expression' (Hofman and Swabb, 2002). In order for the SCN to sustain oscillation around the 24-hour clock direct light stimulations activates a network of clock genes and thus creating circadian rhythms (Hamada, Antle and Silver, 2004). Clinical studies documenting disruption to circadian patterns report involvement in the SCN region of the brain (Schwartz, Boris and Hedly-Whyte, 1986; Cohen and Albers, 1991). Studies in ageing populations and those experiencing cognitive decline attribute deterioration of neural behaviour in the SCN to changes in circadian rhythms (Moore, 1991; Swabb and Hofamn, 1995; Swabb *et al.*, 1996; Hofman, 2000). Similarly, studies exploring people with other cognitive impairments and developmental delays (such as those experienced on the autism spectrum) have also suggested anomalies might occur in the SCN and expression of clock genes regulating circadian rhythms (Wimporay, Nicholas and Nash, 2002).

Changes in circadian rhythms also respond to the light and dark cycle in the environment. Synchronicity or dysfunction of circadian rhythms can present in various physiological and psychological processes. These include (but are not limited to) sleep patterns, hormonal secretion and changes in body temperature (Czeisler, Allan and Strogatz, 1986; Refinetti and Menaker, 1992; Cajochen *et al.*, 2000; Huang *et al.*, 2011). Anticipating changes in the environment (as opposed to passively responding) are also prompted by circadian rhythms and help adjust behaviours depending upon the time of day, e.g. sensing temperature changes or the differences in light at dawn and twilight (Foster and Kleitzman, 2005; Foster, 2010). Not only do circadian rhythms sense temporal changes, but reports suggest seasonal changes in circadian rhythms are sensed too (Hofman, 2004). Described earlier (section 1.3), the optic tract projects into the SCN communicating light sensitive information about time of day. Therefore, entrainment of circadian rhythms occurs by accessing a 24-hour light/dark cycle. If

circadian rhythms are not synchronised each day by accessing sufficient levels of light then the cycle can begin to free-run (Foster, 2010). Oscillations may extend beyond a 24-hour pattern and cause difficulties in bodily functioning. De-synchronization in the master clock can have subsequent effects in other areas of the body.

In addition, to circadian rhythms, the SCN controls the regularisation of hormonal secretions from the pineal gland. Melatonin, the key hormone, which aids sleep, is secreted from the pineal gland (Figure 1.2) (Cassone *et al.*, 1993; Borjigin, Samantha Zhang and Calinescu, 2012). Irregularities in the melatonin profile can affect circadian rhythmicity and in turn the sleep/wake cycle (Skene and Swaab, 2003). The body anticipates sleep by secreting melatonin, reducing the core body temperature and thus elevating feelings of tiredness (Foster, 2010).

Investigations have shown that light inhibits melatonin secretion, thus promoting feelings of wake during daylight hours (Dawson and Encel, 1993). Whilst darkened conditions stimulate melatonin secretion, promoting feelings of sleepiness at night (Brzezinski, 1997). Therefore, if we are exposed to bright light in the morning hours upon wakening then melatonin is suppressed during the daytime and feelings of alertness are promoted (Partonen, 1994). Similarly, exposure to light during the habitual sleep period (or in the hours preceding bedtime) can delay sleep onset (Wallace-Guy *et al.*, 2002; Burgess and Molina, 2014). It is clear that light has the power to advance (Warman *et al.*, 2003; Bullough *et al.*, 2008; Smith, Revell and Eastman, 2009; Crowley and Eastman, 2014) or delay the circadian clock (Figueiro and Rea, 2010b; Paul *et al.*, 2015).

Research indicates the circadian clock is more sensitive to the blue part of the spectrum (Cajochen *et al.*, 2000; Brainard *et al.*, 2008) and that even relatively low levels of illuminance at night can cause a phase-shift, i.e. delaying sleep onset and wake time (Fonken *et al.*, 2013). These insights are particularly relevant to people living with a de-synchronised internal clock, such as older people living in a care home setting that may not access daylight regularly, people on rotated shift work, travel crossing times zones and/or people with multiple sensory issues such as those living with autism spectrum

disorder. Misaligned circadian rhythms may be made worse by impaired cognitive function, inability to access a 24-hour light cycle and can cause long term effects, such as changes in daily activity patterns, e.g. sleeping during the daytime and spending large periods awake at night (Figueiro *et al.*, 2012; Kondratova and Kondratov, 2012).

In older people, studies have indicated that personal light exposure may be low and have attributed this as a cause of circadian misalignment and irregularities in the sleep/wake profile (Shochat *et al.*, 2000; De Lepeleire *et al.*, 2007; Sinoo, van Hoof and Kort, 2011). Light therapy and increasing time outdoors has been reported to ameliorate symptoms of poor circadian entrainment and stabilise the sleep/wake cycle (van Hoof, Schoutens and Aarts, 2009; McCurry *et al.*, 2011). Similarly, studies in younger populations, specifically, those with development disorders such as autism spectrum, disorder have also reported circadian misalignment. Evidence exists to suggest this may occur due to an irregularity in melatonin secretion (with light being the strongest synchronisers of this) and/or as a result of daily lifestyle choices (Richdale and Wiggs, 2005; Ruggeri, 2014).

In essence, the internal clock is entrained by what are known as zeitgebers (Arendt and Broadway, 1987). These are any external or environmental cues that entrain or synchronises biological rhythms to the Earth's 24-hour and 12-month cycle. Environmental factors include a diurnal pattern of light, sensing differences in light irradiances at dawn or twilight; access to clocks, regulated food intake, daily routine, social interactions and changes in the landscape vegetation (i.e. leaves and vegetation changing colour in autumn and winter). Access to this information is vital in maintaining a regular lifestyle and sleep/wake pattern.

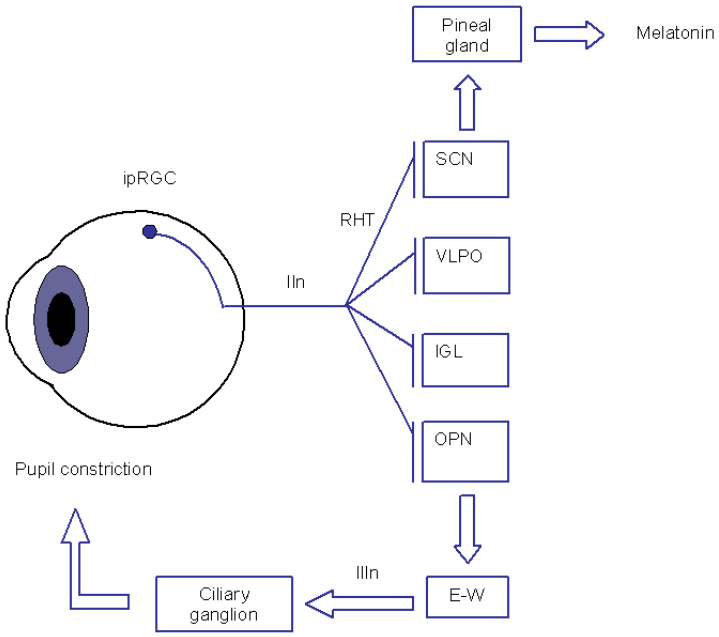


Figure 1.2 Schematic of the Non-Visual Eye, Schmoll *et al.* (2010)

1.5 Circadian regulation of sleep and links for cognitive function

The sleep/wake cycle is regulated by two mechanisms; the circadian timing process (C) and the homeostasis sleep/wake process (S) (Borbély, 1982). The homeostatic process S refers to the body's internal biochemical system accumulating the drive to sleep, effectively reminding the body that it requires sleep after a certain period of wake (Dijk, Duffy and Czeisler, 2000a). This is balanced against the circadian rhythms generated by environmental zeigebers and sensing the 24-hour daily cycle. Chronotypes refer to when the circadian clock entrains to the 24-hour cycle. Naturally some people are late 'owl' types, whilst others are early 'lark' types (Schmidt *et al.*, 2007). Researchers are still to establish the cause of chronotypes, but suggest that they can be defined by natural behaviours, such as activity levels, social/lifestyle choice etc. In general, children are early type, which becomes progressively later during the development years (Ohayon *et al.*, 2004; Fromm *et al.*, 2011). By the early-20's the 'lateness' peaks and the reversal happens with advancing age (Ohayon *et al.*, 2004). As a result sleep/wake patterns differ across the life span and within subgroups such as those with cognitive impairments or developmental delays (Hofman, 2000; Ohayon *et al.*, 2004). Circadian rhythms,

influence numerous cognitive processes including attention and memory (Carrier and Monk, 2000; Schmidt *et al.*, 2007; Vandewalle, Maquet and Dijk, 2009). Lights effect on circadian rhythms, such as synchronisation and/or phase-shifting sleep/wake schedules can, therefore, alter cognitive performance (Santhi *et al.*, 2005).

A meta-analysis and systematic review reported infants are not born with regulated circadian rhythms and these are established in the early weeks of life and nocturnal sleep becomes habitual (Galland et al., 2012). Galland *et al*. (2012) reviewed 34 eligible observational sleep studies. From this it was deduced that mean sleep duration in children ages 4-5 years was 11.5 hours, by age 10 year this was 9.1 hours and at age 12 years this was 8.9 hours. In contrast, in late adolescents (age 18 years) total sleep time is only 7.6 hours (Anders, Carskadon and Dement, 1978; Carskadon, 1990). These recordings reflect sleep time during the week, with factors such as attending school and adapting to the parental routine possibly influencing total sleep time. Reports indicate there may be variability in bedtime between weekdays and weekend. Between the ages of 10-14 years there is approximately a 30 minute delay in bedtime and by age 18 years this can be approximately 2 hours later at weekends compared to weekdays (Carskadon, 1990). Similarly, rise time can be delayed by up to 3 hours at weekends (Anders, Carskadon and Dement, 1978; Carskadon, 1990). One of the underlying reasons for these changes in sleep/wake cycle is a delay in circadian phase during adolescent development (Carskadon *et al.*, 1998). What remains to be confirmed is whether the adolescent circadian response to light is more or less sensitive, and hence a differencing melatonin secretion and circadian rhythmicity (Carskadon, 2002). Others have hypothesised that the school routine may be a factor in sleep changes with naturally later bedtimes but enforced early start times for school causing sleep deprivation in children (Carskadon *et al.*, 1998; Hansen *et al.*, 2005). Additional cognitive and development delays, such as those experienced by people with autism can see further change in the sleep profile (Cortesi *et al.*, 2010; Cohen *et al.*, 2014). Reports suggest the prevalence of sleep disruption is much greater in children and adolescents with autism (Krakowiak *et al.*, 2008; Chou *et al.*, 2012; Cohen *et al.*, 2014) and have linked this to biological processes (Andersen *et al.*, 2008; Cortesi *et al.*, 2010), communication and social functioning (Wever, 1988; Richdale and Prior, 1995), daily routine (Johnson, 1996) or brain pathology and cognitive functioning (Bauman and Kemper, 1994).

In adults, ageing is associated with several changes in sleep patterns, for example temporal changes (a phase-advance), resulting in an earlier time to bed and earlier time

to wake. Typically, with ageing the sleep duration reduces and the level of sleep disruption can increase (Huang *et al.*, 2002). Whilst sleep disruptions can occur at any stage of life, the prevalence of disruption has been associated with older age and with differences in cognitive ability (Czeisler and Dumont, 1992; Dijk, Duffy and Czeisler, 2000a; Dowling *et al.*, 2008). Huang *et al.* (2002) measured objective sleep outcomes across a range of healthy young (21-34 year) to older adults (80-91 years). Multivariate analysis of variance (MANOVA) suggested a main effect of age on sleep/wake rhythmicity [$F(21,246)=5.71$, $p<.01$]. Findings also suggested the total amount of sleep reduced from 7 hours 5 minutes between the ages of 21-34 years to 6 hours 25 minutes by age range 80-91 years. Reports using the multivariate odds ratio (MOR) indicate longer sleep latency was associated with higher risk of cognitive impairment (MOR=1.23; 95% CI, 1.13–1.33) as was increased duration of night-time awakenings (MOR=1.15; 95% CI, 1.06–1.23) (Blackwell *et al.*, 2006). However, studies to the contrary indicted no differences in sleep quality measures owing to cognitive ability (Corchrane, Robertson and Coogan, 2012). The inconsistency in current literature leaves scope to continuing to explore associations, specifically measured in a natural setting.

1.6 Light exposure, duration and intensity

In lighting research the most effective time and duration of exposure to blue and/or bright light remains unknown for regulating the sleep/wake cycle in those with a disrupted pattern. Much of this depends upon the desired outcome. For example morning bright light exposure will advance the circadian clock and evening light exposure will delay the timing of sleep (Czeisler, Kronauer and Allan, 1989; Minors, Waterhouse and Wirz-Justice, 1991; Khalsa *et al.*, 2003; Rüger *et al.*, 2013). Moreover, age, cognitive functioning and level of daytime activity may play a role in tailoring a light exposure patterns - to date no firm recommendations have been made.

In a range of experimental studies, in older people, findings have been inconclusive in relation to time, duration and illuminance levels (Okumoto *et al.*, 1998; Koyama,

Matsubara and Nakano, 1999; Yamadera *et al.*, 2000). Studies exploring morning light exposure (08:00-11:00, a 3 hour duration) to higher lux levels (6000-8000 lux) have reported increased sleep efficiency, reduced total sleep time and reduced sleep onset latency (Fetveit, Bjorvatn and Skjerve, 2003) as well as reducing the frequency of daytime napping (Fetveit and Bjorvatn, 2006). Other studies have indicated similar effects might be achieved with lower lux levels (4000 lux) and/or a shorter duration of light exposure (09:30-11:00, 1 hour and 30 minute duration) (Okumoto *et al.*, 1998; Koyama, Matsubara and Nakano, 1999; Yamadera *et al.*, 2000). In randomised control trials reports suggest similar associations with whole day bright light exposure (09:00-18:00, i.e. 9 hour duration) (Riemersma-van der Lek, Swaab and Twisk, 2008). What these studies do propose is that daytime bright light exposure is important to sleep quality and circadian regulation.

Conversely, research has investigated the effects of evening and/or night-time light exposure. Findings here indicate the phase response of the circadian system to bright light may be dependent upon the duration of exposure (Dewan *et al.*, 2011; Chang *et al.*, 2012). Dewan *et al.* (2011) and Chang *et al.* (2012) reported longer duration of exposure at lower intensities may have more effect on delaying or phase-shifting sleep. New insights have suggested, to the contrary, that short durations of bright light might have a similar phase-shifting effect (St Hilaire *et al.*, 2012). Furthermore, there is evidence to support repeated intermittent exposure to bright light (either in the morning or evening) causes a phase-shift response (Rimmer *et al.*, 2000; Duffy, Rimmer and Czeisler, 2001; Gronfier *et al.*, 2004; St Hilaire *et al.*, 2012). Whilst these studies have relevance in demonstrating the importance of bright light, they are experimental in design, and fail to capture conditions and impacts upon sleep in a natural setting.

Seasonality of natural light exposure is also influential upon sleep regulation, sleep quality and factors such as variances in mood. In particular, there has been a substantial body of research into the effects of seasons on mood since Rosenthal and colleagues defined seasonal affective disorder in 1984 (Rosenthal *et al.*, 1984). This disorder is characterised by frequent bouts of low mood and depressive feelings during the winter period. These symptoms usually dissipate during the summer period when daylight is

plentiful. Fewer studies have looked at the effects of seasonality of light, natural patterns of exposure and the associations with sleep/wake cycle. Eastman (1990) suggested that light exposure varies at time of day . Light levels rapidly rises in the morning and decline in the afternoon and latter part of the day, with this variance being greatest at northern latitudes (Eastman, 1990; Graw *et al.*, 1999; Rufiange, Lachapelle and Dumont, 2003; Goulet *et al.*, 2007; Park, Kripke and Cole, 2007). Moderate evidence exists about the natural patterns of light exposure in humans' during summer and winter, with no indication of optimal exposure in either season for sleep regulation having yet been reported. Studies have suggested that sleep patterns may differ by season, for example temporality of sleep, duration and frequency of awakenings (Kohsaka *et al.*, 1992). Researchers have hypothesised reasons for changes in sleep regulation are caused by variation in available hours of daylight (Kohsaka *et al.*, 1992; Park, Kripke and Cole, 2007) and new insights that the spectral composition of light, to which people are exposed to over the 24-hour day, may also play a role (Thorne *et al.*, 2009). A cross-sectional study of young adults (n=34, aged 18-29 years), exploring natural light exposure patterns and spectral contribution of blue light, by Thorne *et al*. (2009) suggested light exposure was significantly higher in summer compared to winter (p=0.0002) as was the contribution of blue light (p=0.0006). The authors assessed subjective sleep quality and object daytime physical activity level. They reported no significant differences across the suite of sleep quality measures (i.e. sleep onset and off set or sleep duration) or in levels of physical activity. By contrast, Tsuzuki *et al*. (2015) explored seasonal light patterns in males aged 60 year and over (n=8). Results suggested daytime illuminance (p<0.05) and durations in bright light above 2500 lux (p<0.05) were significantly higher and longer in summer. The authors also reported objective sleep efficiency (p<0.05), wake up time (p<0.05) and daytime physical activity level (p<0.05) were significantly different between seasons, i.e. sleep efficiency was higher, wake time earlier and physical activity higher in summer compared to other seasons. These studies bring new insights into the variability and availability of blue light exposure in the natural environment as well as the possible associations of older aged on sleep physiology.

In younger people, studies have investigated the impact upon circadian timing by reducing morning blue light exposure and increasing night-time blue light exposure. A reduction in vital morning short wavelength light was suggested to delay the onset of melatonin secretion by approximately 30 minutes ($p=0.006$) in young adolescents age 13-14 years old (Figueiro and Rea, 2010a). This demonstrated that a phase delay in the timing of sleep may be cause by insufficient blue light exposure in the morning hours. Research has also explored the impacts of over exposure to light, with a high blue spectral content, particularly in the evening hours preceding bedtime. Studies by Wood *et al.* (2013) and Figueiro *et al.* (2011c) have demonstrated that light from electronic sources, such as self-luminous tablets or computer monitors, has the potential to delay sleep onset. Combined, these studies indicate that the light emitted from common household items such as tablets, smartphones and computers, is potent in short wavelength blue light, strong enough to supress the secretion of the sleep hormone melatonin. This is of concern due to adolescents growing up in a world where much of daily communication is carried out online or via a computer. Excessive usage, specifically in the evening, may risk further disruption to the sleep/wake cycle.

A delay in circadian timing is already experienced during the pubescent developmental years (Carskadon *et al.*, 1998). Therefore, inadequate morning blue light or over exposure in the evening hours preceding bedtime may contribute to a further delay in the timing of sleep. Regulating light exposure to ensure that sleep is not excessively delayed is important in adolescents as they attend school with a fixed early start time. A result of this could be sleep deprivation. A lighting routine is of increasing interest in young people that may be more susceptible to circadian disruption or present irregularities in the patterns of biomarkers. In particular, reports suggest that young people with autism may be more likely to experience circadian disruption (Richdale and Schreck, 2009; Tsai *et al.*, 2012). Evidence suggests this could be linked to irregular melatonin secretion or behavioural and lifestyle factors (Taylor, Schreck and Mulick, 2012). Explorations of light exposure in line with these factors in very scant, but highlights an important area requiring further exploration.

In summary, more research is needed to examine these associations, i.e. do older people experience lower light exposure depending upon season and how might this be associated with a disruptive sleep pattern? Specifically, there are limited studies exploring the two-populations chosen for this thesis (i.e. older people and young people with autism). This thesis bridges a gap by continuing explorations of natural light patterns by obtaining an objective measure of blue light exposure, illuminance patterns and investigating the associations with the sleep/wake cycle.

1.7 Rationale for study populations

For reasons outlined above, namely, 1) changes in circadian rhythmicity with ageing, 2) links between circadian rhythms, sleep and cognitive ability, 3) strong evidence of the non-image forming eye and ageing eye, 4) circadian sensitivity to blue light exposure and 5) a growing need for fieldwork exploring seasonality of light, two populations emerged from the literature and are explored in depth in this thesis.

Firstly, the adolescent body clock is already experiencing notable changes from the patterns observed in childhood. A shift in bedtime and wake time is common in typically developing adolescents (Carskadon *et al.*, 1998). In those not typically developing more disruptions to the circadian cycle may be observed (Cortesi *et al.*, 2010). For example, in people with autism spectrum disorder (ASD) many more sleep disruptions are observed (Johnson and Malow, 2008; Cohen *et al.*, 2014). Research has suggested that adolescents with ASD could be at a greater risk of developing sleep disruptions (Cortesi *et al.*, 2010; Cohen *et al.*, 2014). Some have indicated that this could be due to an irregularity in the secretion of the hormone melatonin (Tordjman *et al.*, 2012), whilst others hypotheses lack of routine (Richdale and Prior, 1995; Johnson, 1996) or cognitive function (Bauman and Kemper, 1994). The evidence remains inconclusive and points towards the need for further investigations.

Secondly, studies with older people have suggested the ageing eye requires much higher levels of illuminance to elicit the same circadian response (Turner, Van Someren and

Mainster, 2010). Due to a narrowing pupil and yellowing lens, less light, and more specifically, blue light wavelengths, are impeded through the eye to the ipRGC (Kessel *et al.*, 2010). As a result older adults can begin to experience disruptions in the circadian clock and explicitly the sleep wake cycle. Studies suggest that low-level lighting in residential care homes may be a contributing factor to poor sleep quality (De Lepeleire *et al.*, 2007; Sinoo, van Hoof and Kort, 2011). More naturalistic studies are required to investigate this further.

The following two sections address the rationale for these study populations in more detail. First, details of the young adolescent population and presented then followed by the older adults in a residential care setting.

1.7.1 Rationale for adolescents with Autism Spectrum Disorder (ASD)

Autism Spectrum Disorder (ASD) usually presents in early childhood as young as age 2 (Moore and Goodson, 2003). The condition is characterised by difficulties in communicating and relating to others and over or under sensitivities to sound, touch, taste, smells, light or colour. In the UK there are a reported 695,000 people living with autism spectrum disorder, which is an estimated 1.1% prevalence rate applied to the 2011 UK census data. Over the last 5 years the number of school children diagnosed with ASD has increased by over 50% (2011 UK census data), equating to an increase from 39,465 to 61,570. This does not mean the condition has become more widespread, but simply that it is more easily detected (Gotham *et al.*, 2007). Awareness encourages more detailed investigations and accompanies informed attitudes towards therapies to ameliorate difficult characteristics e.g. specialist schooling and behavioural, cognitive and communication therapies.

In typically developing children, adolescents' and adults' circadian rhythms are normalised through a regular lifestyle routine and exposure to light at the correct time of day. The natural exposure to a system of zeitgebers in the environment, cues such as daylight, air temperature, regular food intake, activity in movement and social

interactions all aid circadian entrainment. Reduced exposure to zeitgebers and a lack of access to information that relates to the time of day can result in a de-synchronisation in the 24-hour daily cycle, digression of the sleep/wake pattern with the oscillation of circadian timing extending to approximately a 25-hour period (Aschoff and Wever, 1980; Endo *et al.*, 1999). This indicates that the internal body clock is sensitive to diurnal and environmental factors and these fundamental to maintaining the natural rhythmicity of the day. In avoiding environmental influences that regulate sleep/wake patterns, either by choice or as a result of an inhibiting health condition, humans may be susceptible to disruptions in circadian rhythms. Results may be an irregular sleep/wake cycle, which may exacerbate pre-existing health issues.

Missed environmental cues can be a characteristic of those with ASD, often finding mainstream social and environmental situations difficult to negotiate (Ochs *et al.*, 2001). The result can be to withdraw, spending prolonged periods indoors, experience social isolation and miss important environmental zeitgebers (White, 2009; Corbett, Middleton and Arendt, 2012). As a consequence the sleep/wake pattern can suffer chronic disruption and is often a complaint in individuals with ASD and their families (Takasu, Toichi and Nakamura, 2011). A de-synchronization in circadian rhythms can impact negatively on many other biological and physiological, causing further learning and behavioural problems (Reddy and O'Neill, 2010).

Research has identified that up to 70% of children with ASD display delay and/or developmental abnormalities in their circadian sleep/wake cycle (Segawa, 2006). A higher incidence of circadian sleep disorders has been found in children with ASD compared to typically developing peers (Giannotti *et al.*, 2008; Krakowiak *et al.*, 2008). Problems can reach chronic levels resulting in additional behavioural or learning impairment, which may affect a family's ability to function (Hill, Hogan and Karmiloff-Smith, 2007; Meltzer and Mindell, 2007). In support of how light may impact on sleep in young people with ASD it has been reported that sleep problems worsened during the winter months resulting in more fragmented sleep at night (Richdale, 1992; Giannotti *et al.*, 2006). In northern latitudes (such as Scotland) there is an acute awareness that daylight and sunlight hours vary greatly between seasons and that changes in light

exposure patterns can affect sleep patterns (Paul *et al.*, 2015). Therefore, it may not be unreasonable to think that children and adolescents in northern countries have an increased likelihood of further circadian disruption due to their geographical location.

The circadian system is linked to the release and regulation of the hormone melatonin (Czeisler, Duffy and Shanahan, 1999). Abnormalities in the melatonin secretion profile can be an underlying cause of irregularities in sleep-wake rhythms (Cajochen, Kräuchi and Wirz-Justice, 2003). A pilot study (n=20) by Ritvo *et al*. (1993) used Analysis of Variance (ANOVA) to investigate between groups differences. Results suggested melatonin was higher during the day than at night in those with ASD compared to typically developing peers (measuring the concentration of the hormone in urinary sampling) [F=3.9, Df=3.41, p=0.0016]. Characteristically, melatonin is higher at night than during the day in typically developing children (Ritvo *et al.*, 1993). Further studies by Nir et al. (1995), Kulman *et al*. (1999) and Tordjman et al. (2005) found that melatonin concentration was higher at the opposite time of day for ASD participants than in typically developing participants. As a consequence children with ASD often sleep during the day and are awake at night making participation in a regular lifestyle difficult. Attempts at regulating the melatonin and circadian rhythms have included clinical trials in which participants take a prescribed dose of melatonin. A randomised control trial by Gringras *et al*. (2012) found that administering melatonin 45 minutes before a child's habitual bedtime increased subjective sleep time at night by 22.4 minutes (p=0.04) and reduced objective sleep onset latency (measured using an actiwatch) (p<0.001). Other studies exploring the use of melatonin, as a way of modulating sleep, have found that it may help towards increased total sleep time (Camfield *et al.*, 1996) and reduce sleep onset latency (Dodge and Wilson, 2001), but it remains uncertain if melatonin will reduce night time awakenings (Camfield *et al.*, 1996; Dodge and Wilson, 2001). It may be that there are more complex differences in the neural behaviours (Bauman and Kemper, 1994) or simple sleep hygiene and daily routine (Wever, 1988; Richdale and Prior, 1995; Wiggs and Stores, 2004; Richdale and Wiggs, 2005).

Research has suggested a possible trait of ASD is the preference to sleep with a light on during the night (Hoshino *et al.*, 1984; Wiggs and Stores, 2004). Such individuals could risk further disruption to sleep cycles as nocturnal light has been shown to suppress melatonin production (Dijk, Cajochen and Borbély, 1991; Cajochen, Dijk and Borbély, 1992; Zeitzer *et al.*, 2000). Without further investigation the extent to which a night-light may be disrupting sleep and indeed causing additional behavioural and developmental issues remains unknown. Studies in mice have indicated that exposure to dim light at night during the early stages of development increase anxiety-like responses (Borniger *et al.*, 2014). The authors state that it is yet to be confirmed in humans and if this relationship is caused only by persistent circadian disruption or parental interactions. People living with ASD have a series of sensory issues, and anxiety is something that they are more susceptible to develop (Mannion, Leader and Healy, 2013). Furthermore, anxiety levels have been linked to poor sleep quality in young people with autism (Richdale and Wiggs, 2005; Delahaye *et al.*, 2014).

In summary, these findings suggest there is a need to understand the links between light exposure, sleep and autism and raise the following questions: could infants, children and teenagers, with ASD, be more susceptible to inherent behavioural difficulties that may be associated with exposure to light at the incorrect time of day and poor sleep quality?

This study attempted to bridge the research gap by piloting a protocol exploring ASD, light exposure and sleep patterns. Specifically, the research focused on blue light exposure due to documented evidence of the associations with circadian rhythmicity (Brainard *et al.*, 2008), yet it is underexplored in this population.

1.7.2 Rationale for ageing population

The circadian system shows changes as part of naturally ageing. The amplitude of the circadian rhythms reduce, found in functions such as the regulation of arousal, tympanic

temperature and hormone secretion (Van Someren, 2000). Change occurs not only in the amplitude of the rhythm but also in the ability to synchronise and resynchronise, sensitivity to environmental zeitgebers and consequentially rhythms may become misaligned (Dijk, Duffy and Czeisler, 2000b; Weinert, 2000). Deterioration occurs in the SCN, which is characterised by a decrease in neural activity (Swaab, Fliers and Partiman, 1985; Swaab *et al.*, 1992). It has been suggested that in older people, and more specifically in those with impaired cognitive function, the SCN receives diminished levels of stimulation, e.g. reduced exposure to bright light through lower levels of activity, reduced time outdoors and prolonged periods of sleep during the daytime (Van Someren, 2000). Circadian rhythm disruptions in older adults with a decline in cognitive ability has also been related to alterations in the secretion of the sleep hormone melatonin (Kabuto *et al.*, 1982; Swaab, Fliers and Partiman, 1985; Nair *et al.*, 1986; Sack *et al.*, 1986; Sharma *et al.*, 1989; Skene *et al.*, 1990; Uchida *et al.*, 1996; Mishima and Hishikawa, 1997; Skene and Swaab, 2003). These alterations in the circadian system are thought to be a contributing factor to other age related conditions such as sleep disruption and depression (Buysse *et al.*, 1991; Campbell, Dawson and Anderson, 1993; Cutler *et al.*, 1997). Typically, as cognitive ability declines so too does sleep physiology, whereby people spend large periods of the day asleep and increased hours awake during the night (Wulff *et al.*, 2010; Keage *et al.*, 2012; Amer *et al.*, 2013; Maggio *et al.*, 2013). In a cross-sectional study of older people living in a care home (n=100), Amer *et al.* (2013) reported cognitive ability was negatively correlated with perceived poor sleep quality (r_s=-0.212, p=0.035). Similarly, people may experience frequent nocturnal awakenings, difficulties falling asleep and early awakenings during the morning hours (Cutler *et al.*, 1997; Uchimura *et al.*, 1997; Espinosa-Fernandes, Cano-Lozano and Miro-Morales, 1998; Maggi *et al.*, 1998). Maggi *et al.* (1998) reported in a cross-sectional analysis (n=2398, noninstitutionalized individuals) that two thirds of older people self-report frequent night-time awakenings. For people living in care home facilities these symptoms may be exacerbated by the nursing routine, e.g. checking on residents during the night-time, ambient noise from medical equipment or monitoring alarms (Schnelle *et al.*, 1999).

In addition to changes in circadian rhythms, sleep patterns and cognitive functioning, there are also changes in the eye that take place. The characteristics of the ageing eye are a narrowing pupil and yellowing lens (Hughes and Neer, 1981; Teresi *et al.*, 1994). These ageing characteristics impede light transmission through the eye to vital non-image-forming ipRGC (Kessel *et al.*, 2010; Turner, Van Someren and Mainster, 2010). It is known that yellow/orange-tinted lenses will block blue light wavelengths; this yellow/orange-tinting happens naturally with increasing age (Sasseville *et al.*, 2006; Burkhart and Phelps, 2009). Blocking these vital blue light wavelengths may hinder circadian entrainment and contribute to a fragmented sleep pattern. Therefore, reduced lighting stimulus to the SCN would indicate that lighting requirements are likely to differ across the life span. Turner *et al*. (2010) identified that at age 75 years a person requires three times the amount of light that a 45 year-old needs to elicit the same circadian response. Furthermore, Kessel et al (2010) suggest at age 18 years 70% blue light is transmitted thought the eye with this decreasing to around 10% by age 62 years (Figure 1.4). In general, older people in care homes are exposed to lower levels of light during the daytime, e.g. median of 52 lux (Shochat *et al.*, 2000). This may be caused by a reduction in time spent outdoors; with reduced mobility or frailties limiting exposure to vital hours of daylight or indeed suggest that indoor lighting requirements are poor.

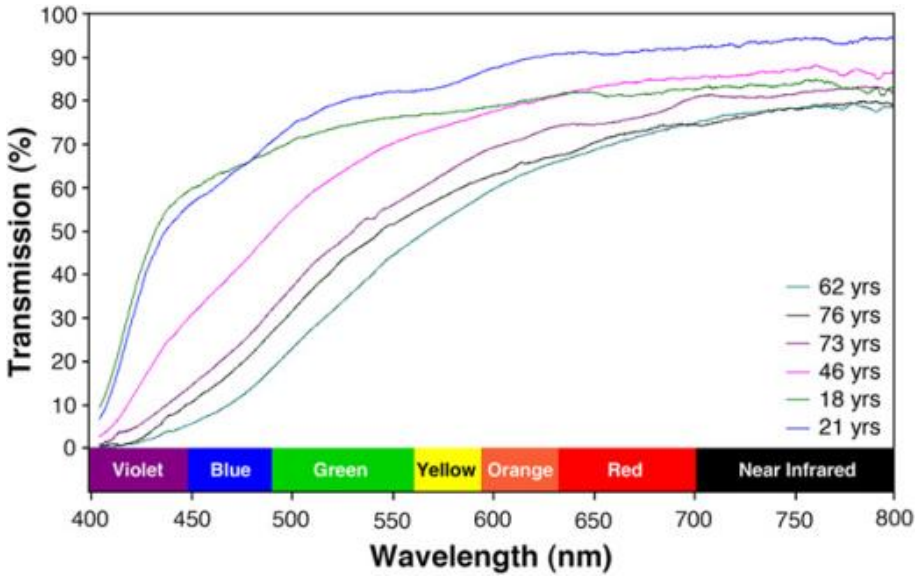


Figure 1.3 Age-related changes in the transmission properties of the human lens and their relevance to circadian entrainment, Kessel *et al.* (2010)

Cognitive function and visual health both limit stimulus of the SCN and therefore cause misalignment of circadian rhythmicity (Mirmiran *et al.*, 1992). Research suggests a

possible link between the level of cognitive function and health of the visual system (Kondo, Niino and Shido, 1994; Chang *et al.*, 2014; Mandas *et al.*, 2014; Nylén *et al.*, 2014). People with a decline in cognitive function may suffer from cataracts[2] three-times more often than healthy older adults and are less likely to go outside (Van Someren, 2000). Furthermore, where cognitive decline has manifested there are increased incidence of cataract and macular degeneration and increased deterioration of the retinal ganglion cells (Campbell *et al.*, 1988; Sanchez, Ge and Zee, 1993; Ancoli-Israel *et al.*, 1994; Blanks *et al.*, 1996; Paquet *et al.*, 2007; Rastmanesh, 2011). Studies suggest that reductions in light transmission and cognitive functioning attenuate the regulation of circadian rhythms and sleep patterns. A recent study by Schmoll *et al.* (2011) reported in older people aged 59-87 years old (n=15), post cataract surgery cognitive reaction time (as a measure of cognitive function) become quicker and more consistent ($p=0.016$). The author postulated that this was not due to learning of the test, but that blue light transmission through the lens was improved, advocating that improved light transmission through the eye has beneficial effects upon cognitive function. Lighting studies, particularly with older people living in care homes, have yet to explore the association of these variables (i.e. cognitive reaction time, visual function, light exposure and sleep patterns).

It is known that a reliable 24-hour light/dark cycle is an effective stimulus for entraining the circadian system and in turn promoting better sleep, health and increased wellbeing (Moore, 1999). There is also evidence to suggest that many care home facilities are inadequately lit, not only for photopic day vision, but also for entrainment of an ageing circadian system (De Lepeleire *et al.*, 2007). In studies carried out in care homes in countries of northern latitude, such as the Netherlands or Belgium (De Lepeleire *et al.*, 2007, Van Hoof *et al.*, 2009) it has been suggested that the amount of light delivered may be notably below the European Standard for light and lighting of indoor workplaces (EN 12464-1:2002) and rarely sufficient to meet the visual needs of the residents and most certainly below their circadian requirements (De Lepeleire *et al.*, 2007). Research has stated that care homes may be equipped with satisfactory lighting

[2] Cataracts are a clouding of the lens in the eye leading to a decrease in visual performance and reduced light transmission.

installations, but are ineffectively utilized (De Lepeleire *et al.*, 2007; Sinoo, van Hoof and Kort, 2011). There are limited studies exploring the natural light exposure patterns and indeed the natural seasonal patterns of older people. Additional evidence is needed to examine the deficits in light exposure in older people living in a residential care setting.

Research has, however, indicated that sufficient lighting has the ability to stabilise the rest activity patterns of older people in care home facilities. Studies suggest that high-intensity light delivering a lux level of 1000 lux or greater can consolidate sleep, delay peak activity and reduce restless behaviour (Van Someren *et al.*, 1997; Shochat *et al.*, 2000; Sloane *et al.*, 2007). Many people living in care facilities receive fewer than 10 minutes of exposure exceeding 1000 lux and median lux levels as low as 54 lux (Shochat *et al.*, 2000; Ancoli-Israel *et al.*, 2002). In lighting interventions studies, researchers have yet to establish the exact time of delivery of bright light for older people. In a stepwise regression analysis, Van Someren *et al*. (1997) suggested (n=22) a stabilized rest-activity pattern after whole day light therapy exposure to over 1000 lux ($p<0.002$). Linear regression modelling by Sloane *et al*. (2007) suggested (n=66) that night-time sleep was consolidated in the experimental group exposed to morning bright light and whole day bright light (increase in 16 minutes, $p=0.008$). Results with daytime sleepiness were, however, inconsistent. Correlational analysis in a cross-sectional study by Shochat *et al*. (2000) found that people (n=66) with more minutes spent in light over 1000 lux had fewer night-time awakenings ($r_s=-0.21$, $p=0.089$). It is not only the level of illuminance that may be important to sleep regulation, but also the spectral distribution, and colour correlated temperature. Van Hoof *et al*. (2009) examined the effects of ambient bright light on behaviour and circadian rhythmicity (n=22). Ceiling mounted luminaires, categorized as blue 6500 K or yellow 2700 K were used as the test conditions[3]. Outcomes were based on staff recordings of tympanic temperature[4]. An independent *t*-test indicated that those under the 6500 K luminaires showed a significant reduction in restless behaviour and an increase in the range of their tympanic

[3] "K" is a measure of colour collated temperature in Kelvin. The higher the K output the more blue/white the colour appearance.

[4] Typically the daily fluctuation core body temperature is lower in the early morning and higher later in the day and lowest during the second half of the sleep cycle.

temperature (more typical of non-demented peers) (0.6 K, $p<0.005$). These works support the need to improve indoor lighting for older people, but it is equally important to acknowledge that the best source of light exposure is to ensure adequate time spent outdoors. McCurry *et al*. (2011) implemented a randomised, controlled trial (either a 30-minute walk, light therapy – i.e. 1-hour exposure to 2500 lux delivered via light box or a combination of both walking and light conditions) in community group (n=132). Results suggested a significant improvement of comparable effect size in total wake time across all three groups (i.e. walking, $p<0.05$, light, $p<0.04$ and combination, $p<0.01$). It was also suggested that a moderate effect size improvement in sleep percentage (measured by an actiwatch) in active treatment participants. Research into similar associations with blue light exposure is scant. This thesis attempts to address the knowledge gap by exploring these using methodologies similar to those already established in measuring illuminance levels and sleep/wake patterns.

Investigating the associations between cognitive abilities, visual function and sleep is timely owing to the growing rise of people living with cognitive decline. In the UK statistics suggests that 1 in 14 people aged 65 year and above are living with a dementia related disease and cognitive impairment (http://www.alzheimers.org.uk, accessed 2nd October 2015). This is not just a national concern, but has global implications. The World Alzheimer's report (Prince *et al.*, 2015) suggests that 46.8 million people worldwide are living with dementia or dementia related diseases in 2015, with this set to double over the next 20 years. Although the impacts of light are not fully understood adequate light exposure has demonstrated great promise as an effective, low cost and easily implemented non-pharmaceutical alternative in promoting sleep regulation in older people. A limitation of previous studies was that they were conducted during spring and summer months when natural daylight is at its maximum. Specifically, research is required during the autumn/winter period when natural daylight occurs for a short period of time and is of a lower lux level and artificial light heavily depended upon. This thesis will explore the seasonal variations in light exposure in a care home setting, by making two waves of data collection (summer and winter).

1.8 The research problem and thesis rationale

The majority of research relating to light exposure and the associations with sleep/wake patterns have been conducted in predominantly healthy populations and often under laboratory conditions. However, many people that would benefit from good lighting conditions are those with limited abilities to attend a laboratory study and/or spend long periods of their day at home or in a residential setting. In northern latitudes the winter period brings limited possibilities to experience bright light for prolonged durations across the day. Therefore, good interior lighting is even more pertinent. There is clear potential for the health and wellbeing benefits to be gained from considered indoor lighting scheme and lifestyle routines that incorporate sufficient time outdoors during the daytime. If a carefully orchestrated light pattern can help entrain circadian rhythms the implications of this are far-reaching.

Evidence from existing research has identified that 1) the UK is experiencing a growing older population and 2) an increase in diagnosis of young people living with ASD. In the *Dementia UK, the Second Edition* (2014), report by the London School of Economics (LSE), the economic impact of caring for an older population, with declining cognitive ability, now costs £26 billion annually. In a parallel report, by the LSE (*Autism is the most costly medical condition in the UK*, 2014), they estimate the yearly cost of autism to the UK economy is £32 billion, however, incorporating los of earnings, and the care and support of children and adults with autism. These reports state that research investment is required to establish effective interventions and best use of available resources. Therefore, exploring associations between existing lighting conditions and sleep quality may help in suggesting evidence-based, cost effective and easy to implement solutions, which promote health and wellbeing.

A dysfunctional circadian rhythm and irregular sleep/wake cycle can cause multiple health issues for both older people (Van Someren, 2000; O'Donnell *et al.*, 2009) and young people with autism (Martin *et al.*, 2007). Beyond the detriments experienced by the individual there are broader repercussions for example strain on caregivers, family dysfunction and difficulty integrating in the wider community may occur (Pollock and

Perlick, 1991; Lovell and Wetherell, 2015). A body of research has however, suggested that regularised sleep/wake patterns can improve not only the health and wellbeing of the individual, but also those in a supportive role (Figueiro *et al.*, 2012; Lovell and Wetherell, 2015). Therefore, identifying methods to ameliorate symptoms and promote a regular and healthy lifestyle have benefits for a much wider audience.

Although, research has demonstrated light has the ability to regulate physiological functions, quantification of the amount, threshold duration, spectral distribution and timing of exposure remains inconclusive. Associations between sleep/wake cycles and durations in bright light illuminance thresholds are documented (Shochat *et al.*, 2000; Hubalek *et al.*, 2006; Hubalek, Brink and Schierz, 2010; Scheuermaier, Laffan and Duffy, 2010). However, there is limited empirical evidence exploring the associations in blue spectral irradiance thresholds (Hubalek, Brink and Schierz, 2010) and even fewer, which have measured this in a natural setting. A key aspect of this research was to establish a set of blue light irradiance threshold in line with illuminance thresholds and investigate associations with sleep/wake patterns.

In review of the current literature, it was evident there was a strong argument to carry forward a larger study in older people. Reasons included, 1) a growing ageing population, 2) the need for more studies conducted in natural settings and the possible variations in seasonal light exposure and 3) a requirement to build further evidence of the effects of the ageing eye and the associations with sleep/wake patterns. The implications of research with older people were felt to be farther reaching, specifically, due to the ageing population faced globally. The outcomes and impacts emerging from autism studies were felt to reach a more modest portion of the population, yet still important to pilot investigations in those with complex sensory issues. Finally, the outcomes relating to older people will not only benefit this demographic, but will be relevant independent of age.

1.9 Aims and objective of the research

The aim of this research is to investigate blue light exposure and levels of illuminance in two populations that present possible symptoms of circadian disruption and to examine the association with the sleep/wake pattern.

Objectives

In fulfilling the aim the following objectives were achieved:

1. Establish a methodology to explore BLE, illuminance and sleep/wake patterns in two populations with sensory issues.
2. Develop a workable protocol to investigate BLE, illuminance and sleep/wake patterns in young people with autism.
3. Investigate within group differences and associations of light, sleep/wake and health and wellbeing measures in two seasons.
4. Investigate between group differences of light, sleep/wake and health and wellbeing measures. Do light or health measures predict sleep parameters?
5. To make evidence informed conclusions and recommendations.

1.10 The thesis framework

The thesis is structured around the objectives set out above. Firstly, Chapter 2 describes the relationship between light and the built environment. The details of this are weighted towards environments for older people, but stresses these considerations are applicable across the life course and in multiple architectural settings. Chapter 3 describes the methodology and study design to explore sleep/wake patterns and personal light exposures. Chapter 4 describes the exploratory pilot work carried out in young people with autism spectrum disorder. In Chapter 5, the pilot study and protocol devolvement in older people is reported followed by a within group seasonal comparison and explorations of associations across a suite of health, wellbeing and light measures. Chapter 6 reports the between groups differences based on cognitive ability

across the same suite of health, wellbeing and light exposure measures. Additionally, this chapter introduces a new regression modelling technique investigating predictors of sleep quality and cognitive reaction time. Finally, Chapter 7 brings together the key conclusions across the thesis. It sets out the implications and recommendations for the built environment and policy as well as the future research agenda (see Figure 1.4 below).

Evaluation of blue light exposure, illuminance level and the associations with sleep/wake patterns in two populations living with sensory impairment.

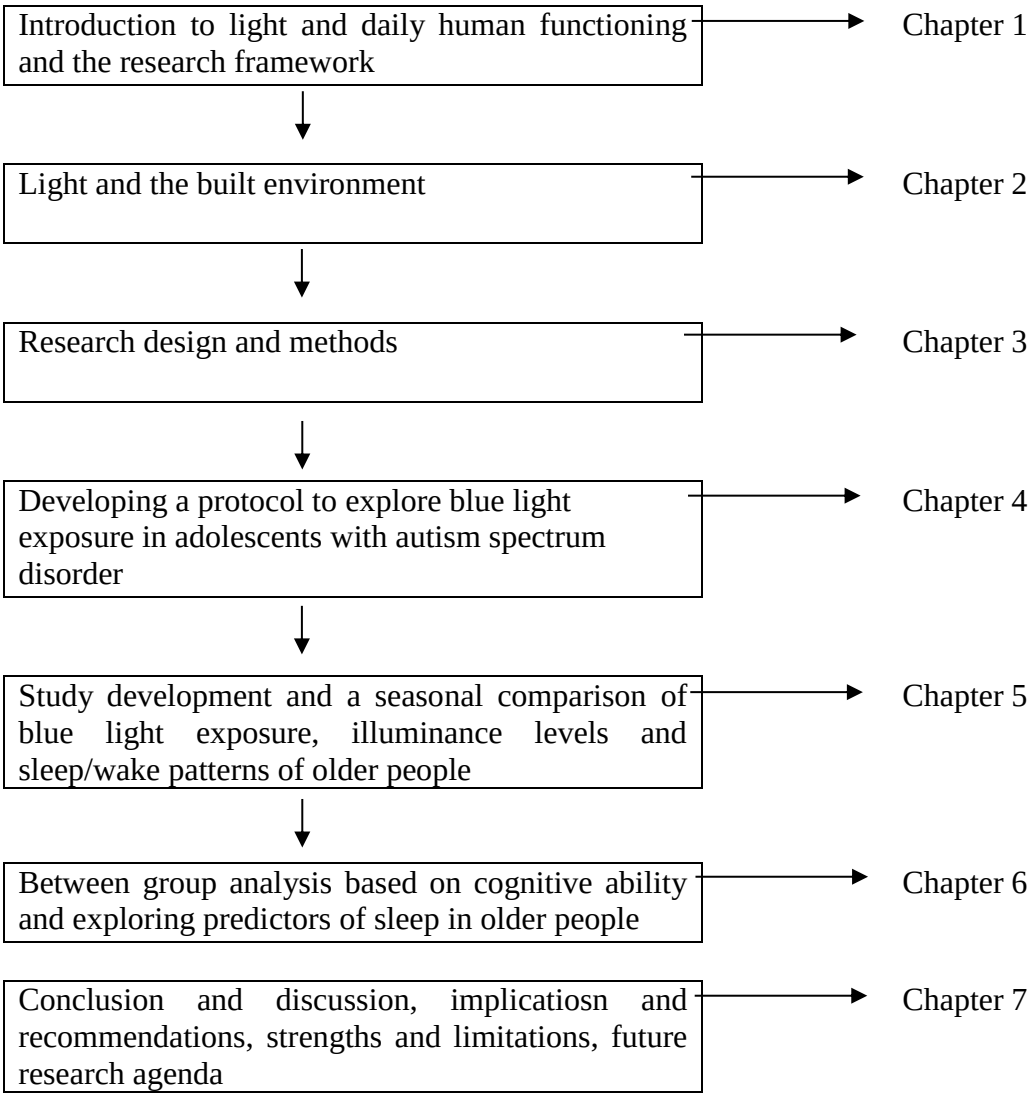


Figure 1.4 Thesis framework

Chapter 2 : Light and the built environment

2.1 Introduction

This chapter introduces light in the built environment and explores current architectural and design strategies. It is evident that lighting research crosses many disciplines from medical practitioners, environmental psychologists to design professionals. The core message from each discipline is that light exposure at the correct time of the day is important to all beings for circadian entrainment. Therefore, this chapter explores the architectural and design considerations important to human health and wellbeing. Discussion is weighted towards environments for older people and the care home setting with relevant and applicable factors to other populations highlighted.

2.2 An architectural response to light

At present, design guidelines and regulations (be they architectural or lighting) are often focused on building performance, health and safety. Whilst these parameters are vital to good architectural design, they undervalue the impact of architecture and lighting design upon humans. There has been a slow move towards addressing human needs within design communities (e.g. dynamic or human centric lighting) but there remains room for improvement. In the UK, there are several governing bodies that offer guidance and regulation towards design (e.g. Chartered Institution of Building Services Engineers (CIBSE), Society of Light and Lighting (SLL, a sub-branch of CIBSE), Institute of Lighting Professionals (ILP), Scottish Building regulations and Technical Handbook). Some of these standards are regulatory, including design guidance that must be followed (i.e. Scottish building regulations), whilst others are informative, with designers choosing to implement the guidance or not (e.g. SLL lighting guides). Having a range of technical organisations and standards makes it difficult to track and implement changes. Each organisation makes changes to guidance and updates information at differing time scales.

Architectural design can be constrained by many factors, such as finance, location and site, clients and contractor or legislation and regulations. At times this can drive decisions that limit the quality of a building and leave little room for consideration of the finer details (i.e. lighting design). This current research, consistent with the existing body of work, (Sinoo, van Hoof and Kort, 2011; Figueiro *et al.*, 2014) indicates that indoor light exposure may be a contributing factor to poor sleep quality - this has important implications for health and wellbeing. In particular, this research suggested that morning (08:00-12:00) blue light exposure may be a predictor for the amount of sleep a person has at night and that light exposure levels in both seasons were low. It would be sensible if architectural layout and building function responded more closely to the diurnal path of the sun facilitating circadian regulation. It should be argued that design should endeavour to accommodate the needs of people especially for those that spend limited time outdoors due to reduced mobility, cognitive difficulties or lack confidence. Consideration should be given to the psychological and physiological wellbeing of building occupants by professionals in the design field. *Would older people, and those that spend limited time outdoors, benefit more from a bedroom orientated towards morning sunrise or a daytime conservatory filled with natural light?*

2.2.1 Orientation

In situations where new architecture is created, and location allows, orientation and room function should respond to the desired circadian direction. This is not an entirely novel approach and has been considered as part of the Society of Light and Lighting (SLL), guide 9: *Lighting for communal residential buildings* (original image Appendix A). Illustrated in Figure 2.1 is a guide to zone planning a care home based on the direction of sunrise and sunset. The image identifies key rooms that are important to older people, 1) bedroom, 2) living (or communal room), 3) dining and 4) conservatories or sunrooms. Designers should show consideration to the daily routine in a care home, e.g. group breakfasting, the function of the lounge area across the daytime and utilising a conservatory space for people that are predominantly indoor bound. Extracting this detail when assembling the design brief would be helpful towards

informing the layout of the building. It also highlights the timely need for co-designing buildings i.e. truly understanding the needs and requirements of the end user.

To best promote wakefulness in the morning it is essential to have access to daylight (Ancoli-Israel *et al.*, 2002; Skjerve *et al.*, 2004; Fromm *et al.*, 2011; Lamba *et al.*, 2014). If bedrooms were orientated east to southeast occupants would be exposed to morning light necessary for promoting wake and alertness as well as helping to provide an environmental cue that it is morning time. It would also be beneficial if morning daylight were accessible year round, in order to maintain a sense of time of day across the year. Older people are often free to set their own daily routine and may spend time in their own room at various points across the daytime. Therefore, access to good daylight throughout the daytime would be a desirable attribute of bedrooms. Whilst essential to promote good lighting in the morning and daytime it should be noted that in order to aid a restful sleep light exposure at night-time should be limited (Figueiro, 2013). Adequate measures should be taken to ensure that bedrooms receive no (or very limited) light pollution during the habitual sleep period. This can be achieved by heavy blackout blinds and curtains. Any artificial light exposure during the night-time period should be specified with outputs in the longer wavelengths in the visible spectrum (i.e. red/orange/yellow) as these have been documented in to minimise circadian disruption (Figueiro *et al.*, 2014).

Similarly, the daytime lounge area would be suited to orientations that can maximise the duration of natural light exposure across the daytime. The living spaces may be rooms that are used continuously across the day. Therefore, it would be beneficial to have morning and evening light in these rooms. Providing the ability to sense changes in light across the daytime will promote feelings of the environment changing (Hubert, Dumont and Paquet, 1998; Dumont and Beaulieu, 2007). For example bright light signalling morning and softer warm light of dusk can create a sense of relaxation prior to bedtime. A south to southwest orientation would enable good light exposure across the daytime. In knowing the time of day, and sensing changes in light irradiance levels, allows the body access to vital zeitgebers i.e. environmental cues, which help entrain the circadian system to a 24-hour cycle.

Dining areas facing towards east would take advantage of morning light at breakfast time. Meal times may often be a long process in care homes, with residents spending extended periods of time in one room eating. Good lighting, specifically in the morning, would facilitate an opportunity for residents to capture essential circadian entraining light exposure. Reduced light in the evening dining session, again, could enforce a sense of the day ending and signalling that bedtime is approaching (i.e. a natural zeitgeber).

A conservatory (with adequate heating and ventilation to regulate indoor temperature) would be a desirable characteristic to the building. This type of space is flooded with natural light and creates a sense of being outdoors without being affected by weather. Facilitating long duration of daylight exposure inside a building would help those who are indoor bound (or choose to be indoors) to receive maximum exposure to a natural light source (Pachana, McWha and Arathoon, 2003). Conservatories have been criticised in the past for overheating in summer and being too cold in winter. However, glass technology has advanced offering much better u-values and thermal properties (a measure of heat transmission through a given material, with a lower value more desirable) and thus controlling heat gains and losses.

Whilst orientation towards the sun at the correct time of day is fundamental the location on a particular level of the building should also be considered. Rooms on the ground floor will receive less light than those higher up in the building, but are more likely to benefit from access to outdoor spaces and gardens. Considerations should be given to accessing safe outdoor areas. Exposure to daylight is the most valuable to circadian entrainment (Duffy and Wright, 2005), but time outdoors brings other therapeutic benefits (Kaplan, 2001; Raanaas *et al.*, 2012). Designers might consider that bedrooms and regularly occupied communal spaces to be located on upper levels to benefit from maximum daylight exposure and with balcony or terraced access to outdoors. Ancillary spaces, without consistent occupancy, have less emphasis to require good daylight. Storage, bathrooms, lifts, circulation, should face northwards and similarly can be placed on lower levels. Spaces, such as stairwells or corridors offer social opportunities, a place where people might gather to talk as they transition from room to room.

The orientation of layout as a response to the diurnal path of sunlight is not exclusive to buildings for older people. These principles should be transferred to other architectural designs. For example, health care and hospital facilities may also see benefits to patient recovery when daylight exposure is considered (Joarder and Price, 2013). Similarly, in a residential development setting should the human requirements and promotion of the same principles (i.e. bedroom orientation to access morning light) would be equally beneficial (Andersen, Gochenour and Lockley, 2013).

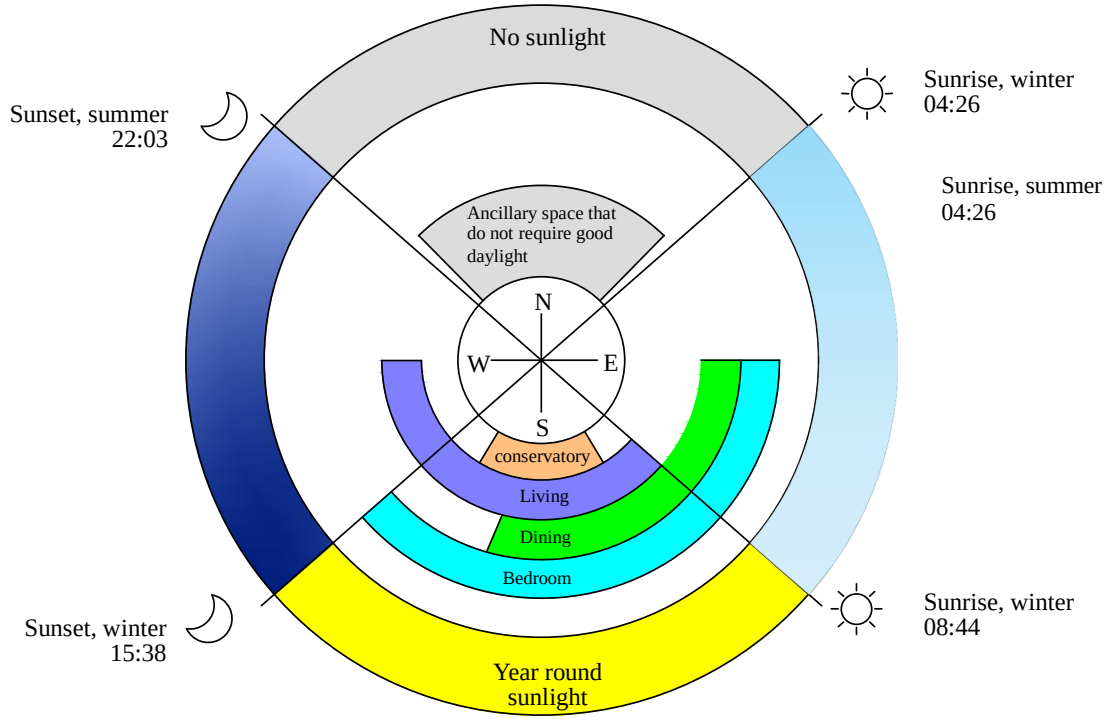


Figure 2.1 Proposed room orientations for circadian entrainment, Latitude 56° north

2.2.2 Scale

In addition to the orientation of rooms consideration must be given to the size of apertures, such as windows, skylights and clearstory glazing. These openings control the amount of daylight entering a space. The current Scottish Building Standards (Section: Environment, Standard 3.16) states - *Every building must be designed and constructed in such a way that natural lighting is provided to ensure that the health of the occupants is not threatened*. These standards give designers little indication as to a minimum aperture size and certainly do not describe the importance of daylight for circadian requirements. Windows are more than an aesthetic tool, the placing of these can greatly affect daylight distribution in rooms, the amount of visible sky and views outside to connect with a daily rhythm.

Reproduced below (Figure 2.2) are a set of diagrams illustrating possible window arrangements and light distribution from the SLL lighting guide 10: *Daylighting – a guide for designers*. Design 1 shows the pool of light created by a large single opening, as a small distribution of light into the room. Designs 3, 5 and 6 show spaces with multiple apertures, this creates a greater distribution of natural daylight within the space. This type of design would enable light to enter the room from different directions with a possible benefit being light at different times of the day. The least desirable window design would be low level windows, as there will be the least amount of visible sky and little distribution of light towards the back of the room (a deeper the plan building and a smaller window means that the less light will reach the back of a room). In design 4 there is an interpretation of clearstory glazing. These are high-level windows that can bring light deeper into a room and provide a wider view of the sky, but may offer the poorest distribution in terms of light filling a room. Such designs might be helpful in corridors or space that require good lighting for orientation, but not continually occupied or in need of view. Aperture size is an important part of the lighting design in a building. The aim should be to maximise natural light through a considered window design, it is also a free source of illumination. Designers should consider window openings in multiple walls, thus enabling changes in daylight to be sensed across the day. Other architectural features that could be employed are elements such as light

shelves. These are horizontal ‘shelves’ located at the window which serve to push daylight deeper into a room by reflecting daylight on the ceiling and across the room (Figure 2.3). In a world where climate change is occurring, it is pertinent to consider the heat and solar gains. These should be monitored to ensure a stable indoor temperature and human comfort. Discussed in brief in the previous section (2.2.1) glass technology has advanced to help balance heat transmission through building surfaces.

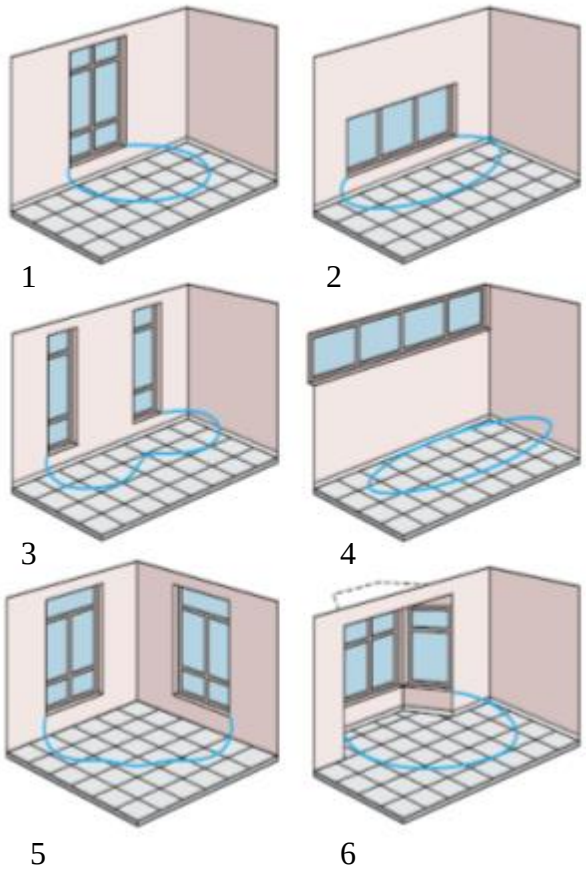


Figure 2.2 Schematic of window size and daylight distribution. SLL-lighting guide 10 – Daylight in buildings, (2014, pp. 20)

Figure 2.3 Example of light shelf used to distribute daylight

2.2.3 Destination and view

In addition to the strategic layout planning or zoning of a building there is also an argument that the interior design is of equal importance, e.g. the positioning of furniture or layout of a room. It is recognised that there is a relationship between light, sleep, health and wellbeing. Perhaps there is an argument that light should be celebrated more in buildings and become destination or focus? Interior design ought to consider layouts that maximises exposure from daylight and facilitate opportunities to spend time in bright light, particularly during the morning hours, whilst creating a calming light atmosphere in the evening.

The concept of the window and view as a destination could be a method to promote better light exposure, particularly for people that may spend limited amounts of time outside. The simple strategy of placing seating by the window or indeed integrating seating as a part of the window design, to create a destination, might encourage people to sit by the window and subsequently receive good daylight exposure. A recent design

study from Architecture and Design Scotland[5] looked at personal space as part of the design for mental health facilities[6]. Evidence-based research suggests that spaces such as bedrooms should promote a place of healing and have a sense of home not institution (Torrington and Tregenza, 2007). One particular outcome was around the design of windows and how these could become *"a cosy environment, with a view, rather than simply a hole in the wall".* This advocates that bedrooms and communal areas in care homes, and the wider architectural application, need to be considered for the health and wellbeing benefits of building occupants.

Sitting by a window offers advantages beyond circadian entrainment - a view. Views from windows and daylight have been shown in other studies to promote healing and wellbeing (Ulrich, 1984). Creating light and views as a positive distraction could help alleviate stresses, which have been linked to other health problems associated with sleep quality (Maggio *et al.*, 2013). Based on the environmental psychology theories that positive distraction can help alleviate symptoms of stress (Kaplan, 2001; McCuskey-Shepley, 2006), windows and views are hugely beneficial to people that may be less able to go outside. An early study by the environmental psychologist Kaplan, examining different views from windows in residential apartments, found that a view of the sky and notion of the weather contributed to a person's sense of effective functioning[7]. The author suggested that views of nature were a strong factor in wellbeing and residents' satisfaction. In healthy adult populations research has suggested that views and green spaces can contribute to a person's wellbeing (Gilchrist, Brown and Montarzino, 2015). Although, not investigated as part of this thesis, it suggests the interplay between light exposure, nature and sleep quality. Moreover, views within and out with the building my serve as a method of way-finding. Research by Faith *et al*. (2015) reported in a design analysis that visual connections enable way-finding and orientation though care homes. In the same study the authors postulate that good care home design facilitates access to outdoors. This is in line with research by Marshall (2001) and Brawley (1997; 2006), who recognise the importance of accessible outdoor environments for older

[5] Architecture and Design Scotland is department within the Scottish Government that champions excellence in architecture, place-making and planning.
[6] Mental health developments in this document include older people in a care home setting.
[7] Effective function was a factor created for the statistical analysis in the Kaplan et al. 2001– *The view from home*. This factor included items such as *energetic, satisfaction, focused, positive etc.*

people. Hadjri *et al*. (2012) reported in an audit of existing care homes (n=53), against the Stirling University Dementia Service Development Centre (DSDC) design audit tool[8] (Marshall, 2001), one of the main deficits was a lack of the provision of safe and enclosed outside space. This post-occupancy appraisal of nursing and care homes highlights the growing need to create evidence based design guidance that will benefit not only those living with a cognitive decline but also carers of older people and visitors to the care home.

2.3 Lighting design strategies

For decades a lighting designer's primary concern was to create a lit environment adequate for vision i.e. designing a solution that allows sufficient light to carry out the necessary visual tasks. Since the discovery of the non-image forming cells and the understanding that the eye is the gateway to the circadian clock lighting designers now have a responsibility to ensure that the design provides not only sufficient light for vision but also for circadian entrainment.

Light exposure and the quality of light play a pivotal role for older people (or those who spend long periods indoors). Maximising daylight in buildings should always be the first step in lighting and architectural design as this is the most circadian-effective source. However, it cannot always be assumed that there will be sufficient daylight inside buildings. Daylight levels drop as the distance from the window increases. As a result there can sometimes be a large contrast in brightness across a room or a creation of shadows that might be misinterpreted. Here, electrical lighting can be utilised to supplement a lack of daylight ensuring that there are even light levels across the space. An even light distribution helps with life tasks (outside circadian entrainment), such as allowing for better orientation through spaces and reducing fall risks (Bakker, Iofel and Lachs, 2004; De Lepeleire *et al.*, 2007; Figueiro *et al.*, 2011b; Eshkoor *et al.*, 2013; Stone *et al.*, 2014; Hu *et al.*, 2015).

[8] DSDC dementia audit tool are a series of resources for carrying out self-assessment of environments used by people with dementia. The framework covers: making decisions about design; addresses the physical and social environments and identify areas fro improvement.

When it is not possible to only utilise daylight for circadian entrainment an electrical lighting scheme based on human physiology should be considered. Researchers suggest a 24-hour lighting scheme, reflecting the diurnal path of the sun, would be one of the most effective ways in regulating circadian rhythms (Figueiro, 2013). The design should promote high circadian stimulation in the morning hours (i.e. brighter and bluer light) and low circadian stimulation in the late afternoon and evening, with no stimulation preferred during the night-time. The healthiest and most effective method is to encourage time outdoors in the morning hours and ensure electrical light sources used during the afternoon and evening have output weighted towards longer wavelengths (i.e. yellow/orange tones), (McCurry *et al.*, 2011). The most desirable electric lighting scheme would be a dynamic light setting, which changes automatically with time of day (Izsó, 2009; Izsó, Laufer and Suplicz, 2009). A temporary solution would be use of artificial light boxes that emit over 1000 lux (vertical) of blue-white light in the morning hours after wake. These can be placed on tables close to residents and may help to stabilise a sleep/wake pattern (Dowling *et al.*, 2008; Burns *et al.*, 2009; van Hoof, Schoutens and Aarts, 2009).

In the lighting community there remains ambiguity over the precise colour correlate temperature[9] (CCT) of lamps and illuminance levels required for older people. This is because multiple solutions will be variable in colour temperature, retinal illuminance and duration of exposure. Studies by Van Someren *et al*. (1997), Rheaume *et al*. (1998), Riemersma-van der Lek *et al.* (2008) van Hoof *et al*. (2009) all conducted experiments in which older people (with dementia) living in care homes were exposed to ambient bright light. They showed a positive effect such as a lessened sleep disruption. van Hoof *et al*. (2009) then continued by exploring the colour temperature of lamps (investigating 2 lighting conditions 17,000 K (cool) versus 2700 K (warm). The authors reported no improvement in tympanic temperature[10] under the cooler light temperature (17,000 K). They suggested that illuminance levels are likely to be equally important in establishing

[9] Colour-correlated temperature (CCT) - is a measure of light sources colour appearance. This is measured in Kelvin (K). A light sources that burn an at low K temperatures has a warmer yellowish appearance e.g. 2500 K and cool white-blue burn at higher temperatures e.g. 6500K.

[10] Tympanic temperature is also an indicator of circadian rhythms and is a measure of core body temperature. Typically this this measure is at its minimum during habitual sleeping hours 04:00-06:00.

a sensible lighting design to help older people with circadian misalignment. It remains unclear, what CCT, illuminance level and duration of exposure would be optimal. There is a consensus that bright light is essential upon wakening and light exposure should be limited at night-time. Generally, it is sensible to assume that morning light sources would be helpful in the higher Kelvin range i.e. 5000 K, whilst in the late afternoon and evening warmer CCT would be desirable, e.g. 2500 K and below. However, it is yet to be determined as to the optimum CCT exposure for circadian efficiency.

An exciting advancement in indoor lighting was launched in 2014. This is the closet step towards sunlight indoors advertised to date. An artificial skylight (CoeLux) was created by Trapani and colleagues at the Insubria University, Italy. This invention uses optical based technology to mimic the sunlight spectrum indoors. Light is scattered from an LED light source in a similar way in which light from the sun scatters across the Earth's atmosphere. This generates a sense of distance between sky and sun. The end result is a blue sky through the window effect. This is a radical solution, which appears as a realistic interpretation, of daylight and sunlight, in a space where it may not be possible to access a natural light source. The limitations of the artificial skylight are two-fold, 1) cost - current retailing in a financial bracket that most would find excessive and 2) though effective in imitating the sun in spectral distribution, it does not create movement, i.e. it is static without mimicking a change in light across the day. The latter point (2) here should be carefully considered before application and administering light, as it is important to sense change across the day to entrain the circadian clock (see section 1.5 discussion on zeitgebers).

The creators also understand the potential regional applications of this system and have created a geographical cast of light beams. These include 60° to create a tropical light (Figure 6.10), 45° for Mediterranean latitudes (Figure 6.11) and 30° for higher Nordic countries (Figure 6.12). Technology such as this is a significant progression in the lighting and architectural design field. CoeLux is intended for spaces where there is no, or very limited amounts of natural light. This "window" could be used in spaces to promote a sense of wellness, particularly in places such as care homes, through the psychological benefits provided by sunlight. As the lighting and design community

become more aware of the health and wellbeing benefits of light exposure these types of technology will likely become more accessible. The caveat to this is that it has not been reported for any circadian benefits or measured against circadian markers. However, this opens a new field of research to be explored.

A cautionary notice should be issued: light can be both friend and foe for older people and to building occupants in general. Poorly controlled strong sunlight possesses the potential to over-heat the room or cause too much glare to sensitive eyes. Designers should be mindful of this when aiming to achieve good daylight exposure. Strategies to control this might include external solar shading, defused window coverings, coated glazing, e.g. Pilkington's Insulight™**,** which will reduce heat gain and maximise daylight penetration (also see CIBSE, SLL – lighting guide 10).

Figure 2.4 60º Tropical light angle

Figure 2.5 45° Mediterranean light angle

Figure 2.6 30° Nordic light angel

2.4 Summary

This chapter presented the relationship between light and the built environment. It is now pertinent to give thorough consideration to the architectural form, orientation of layout, the need to utilise daylight within the building and facilitate time outdoors. There is also a strong suggestion that supplementary indoor lighting should be focused towards mimicking the spectral distribution and duration of daylight (at the given latitude). Some of the concepts discussed in this chapter are guidelines, which are readily available, yet they can be neglected or the existence of this information fails to reach the correct audience.

In summary this chapter underlined the value of orientation of room and function of space towards the desired circadian light pattern and described the potential advantage of light and view as a destination to facilitate light exposure. The key criteria to consider are:

1) Orientate bedrooms east to southeast to maximise morning light exposure and introduce the environmental cue that the day has begun, whilst ensuring that rooms are dark at night to aid a restful sleep.

2) Imagine windows are more than openings in the wall. These are opportunities to create a destination and positive distraction this could facilitate better light exposure for building occupants.
3) Consider aperture size and the use of multiple openings in walls facing different orientations. This will allow views that will indicate the time of day and daylight exposure at different times of the day.
4) Indoor lighting schemes should take on a human-centred approach. Light levels should be higher in the morning hours and lower in the evening hours prior to sleep.

Chapter 3 : Research design and methodology

3.1 Introduction

In this chapter the quantitative methods used to meausre objective sleep/wake, activity patterns and personal light exposures in two populations, 1) older people living in a residential care home and 2) young people with autism, are described (objective 1). The qualitative methods used to establish the viability of an exploratory study in young people with autism and engage and recruit particioants are also described. The cross-sectional study design used to profile light exposure, sleep/wake and activity vaiables is reported.

3.2 Design

Cross-sectional study approach

A cross-sectional design was used to characterise the sample population(s). This design estimates the prevalence of the main outcomes of interest i.e. the environmental blue light and illuminance levels. A ‘snapshot’ of light exposures builds a picture of current lighting provisions and enables an investigation of associations with the sleep/wake pattern. The design provides a naturalistic view of sleep patterns and light exposure levels both in older people and young people with autism by profiling day and night without manipulating the environment or behaviour. Other advantages of this design include,

1) Allows for many variables to be measured in a single assessment e.g. objective sleep/wake and personal light exposure patterns.
2) Provides evidence that the protocol works for a baseline assessment and offers new knowledge to build upon for controlled trials.
3) Assists in drawing conclusions relevant to design professionals and care policy makers.

3.3 Quantitative methods

A set of quantitative methods were used to investigate associations between light exposure, sleep/wake and activity variables. Actiwatches were used to collect data relating to sleep/wake and activity level and personal light exposure levels. The instrument selected is a body mounted (wrist) sensor. It has been used before in a research context and is a familiar measure in lighting, sleep and/or health research with known validity and reliability (Fetveit, 2002; Ancoli-Israel *et al.*, 2003; Danelle *et al.*, 2012; Camargos, Louzada and Nobrega, 2013).

3.3.1 Objective sleep/wake and activity measures

(1) Actigraphy – Detecting sleep/wake and levels of physical activity

The study of sleep is most accurately done by a polysomnography test. This test is typically carried out at night under laboratory conditions monitoring brain waves, oxygen levels in the blood, heart rate and breathing. Similarly, muscular activity i.e. eye and leg movements are logged. This is a meticulous analysis used by medical practitioners to provide a diagnosis of sleep disorders. Whilst this method tells a detailed story of sleep quality it was not a practical solution for this research, as results would not reflect the participant's actions in their current environment. In this research the interest was in sleep performance in a natural setting. The best approach to do this was by using a method known as actigraphy. The equipment used was the Philips Respironic Actiwatch Spectrum Plus. This is a wrist-mounted sensor (actiwatch), worn like a watch that records sleep/wake and activity movements. The actiwatch contains an accelerometer (or piezo-electric transducer) that produces a voltage in response to changes in motion. Data is digitised and downloaded to the compatible computer programme, which utilises an algorithm to distinguish sleep from wake. The detection algorithm was established through a mathematical analysis of synchronising the actiwatch with polysomnographic data (Kushida *et al.*, 2001). It is constructed to distinguish sleep, rest, wake and activity depending upon the amplitude and duration of movement. The actiwatch calculates the activity count based on the sampling epoch (in

this study every 15 seconds was chosen). It then uses the activity value along a 15 second time line to determine if that activity count is higher or lower than the pre-set sleep/wake threshold. Sleep is defined as the total activity count less than or equal to the wake threshold value and wake is defined as total activity count greater than the wake threshold value. This gives the baseline sleep/wake and activity information.

Sleep statistics considered important for understanding patterns and changes in the sample cohort included 1) *Total sleep time* - the total time within each participants' rest interval the actiwatch scored as sleep, 2) *Onset Latency* – the number of minutes that passed between the start of the rest interval and the first epoch scored as sleep i.e. how long it took the participant to fall asleep, 3) *Sleep Efficiency* – the percentage of time in bed actually spent sleeping and 4) *Wake after sleep onset*– number minutes between the sleep cycle starting and the sleep cycle ending that are scored as periods of wake. These statistics are derivatives of the main algorithm and are dependent upon movement or periods of wake leading up to and during the main sleep cycle. They have been widely used in other studies and are considered reliable indicators of sleep quality (Van Someren, 2007; Mulin *et al.*, 2011; Friedman, 2012). The algorithm also detects off-wrist duration and excludes the invalid data when establishing the final statistics.

(2) Actigraphy - Detecting personal light exposure

Contained within the actiwatch are light sensitive photodiodes. These cells record illuminance levels in units of lux and coloured light over 100nm band widths, red (600nm700nm), green (500nm-600nm) and blue (400nm-500nm) spectral irradiances in units of $\mu W/cm^2$ (milliwatts per centimetre squared). The cell display is mounted on the face of the actiwatch. The actiwatch does not use an algorithm to determine light values, as the units are absolute measures of light. However, the time frames created from the algorithm to understand wake-daytime or sleep at night are used as intervals for analysis for light exposure. Illustrated in Figure 3.1 is an example of the actiwatch output data. In brief, the time of day is displayed across the top of the graph, with each day represented on an individual row. The dark black line represents physical activity level and sleep state and the yellow line represent the fluctuations in ambient light exposure levels.

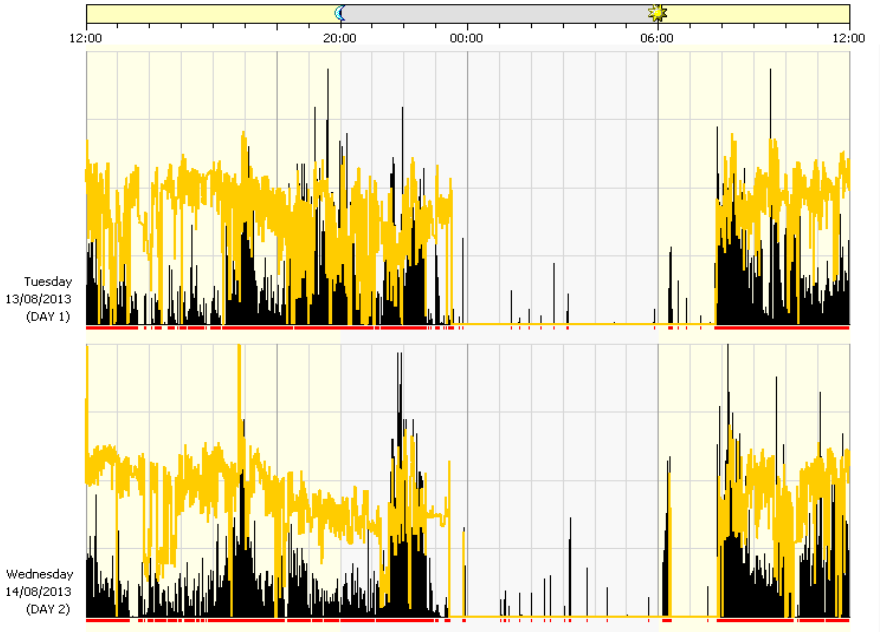


Figure 3.1 Example of actiwatch output

Studies that examine the relationship between light exposure and sleep frequently measure this at a per-person level, i.e. each participant wears a dedicated piece of equipment recording their specific light pattern. The location of the sensor on the participant is of importance. Readings that more accurately represent light incident upon the eye are best recorded in the same plane of the eye (vertical illuminance) (Boyce, 2003; Bierman, Klein and Rea, 2005; Boyce, 2012). Therefore, in this study the light sensing actiwatch was worn at the lapel, with the strap removed and secured with a pin to clothing. Other advantages of this actiwatch include real watch face, so the device does not look unfamiliar to wearers and off-wrist vibration reminder to prompt participant to return it to the wrist if forgotten. The vibration function was deactivated for the lapel-mounted sensor to eliminate confusion.

In order to profile the light exposure pattern the measurements taken during the study period were: 1) mean illuminance level (lux), 2) mean blue spectral irradiance level (referred to as blue light exposure or BLE). For the purpose of this research only blue

spectral irradiance was of interest as research has shown that circadian rhythms are more sensitive to light in this part of the visible spectrum (Brainard *et al.*, 2008). Durations in specific illuminance and irradiance thresholds were explored to profile how long a person might spend in bright, blue light or dark conditions; these are detailed in section 3.5, Table 3.1 summaries the objective sleep/wake and activity measures and the direction of scores recorded in this research.

Table 3.1 Summary of health measures and direction of scores

		Direction of score
Sleep	Sleep onset latency (minutes)	Lower = Fall asleep quicker
	Sleep efficiency (%)	Higher = More consolidated sleep pattern
	WASO (minutes awake after sleep onset)	Lower = fewer minutes awake
	Total sleep time (minutes)	Higher = more minutes of sleep
	Bedtime	Actual bed time
	Wake time	Actual wake time
Activity	Daytime physical activity count	Higher = more activity counts

3.3.2 Health and wellbeing outcome measures

In addition to the actigraphy methods the following quantitative methods assessing health and wellbeing were collected in older adults:

(1) Subjective sleep quality

The Pittsburgh Sleep Quality Index (PSQI), (Buysse *et al.*, 1989) assessed the potential sleep status over the last month (Appendix B). This is a self-rated measure of 19 items generating a 7 component score (i.e. duration of sleep, sleep disturbance, sleep efficiency, daytime dysfunction due to lack of sleep, medication, etc.). The sum of these scores yields 1 global score, i.e. total sleep quality. It allows for an appraisal of personal attributions to poor sleep quality, including reasons for sleep disturbance (e.g. difficulty falling asleep within 30 minutes, night-time awakenings, using the bathroom, temperature, nightmares, breathing and pain) and any abnormalities in sleep that impact

on daily functioning (e.g. loss of interest in activities, difficulties staying awake during the daytime and prescribed sleeping medication). The more recurrent these problems the higher the PSQI score. A score ≤5 is defined as good sleeper and >5 as poor sleeper. The success of using this tool within an older demographic is supported by Amer *et al*. (2013), Valenza *et al*. (2013) and Nebes *et al*. (2009). These studies had sufficiently large samples sizes (minimum n=100) living in a care home. In addition these studies administered the PSQI to participants with a range of cognitive ability. The association between perceived sleep quality and cognitive ability was examined. No limitations in comprehending the scale were reported.

(2) Cognitive function

The Mini Mental State Exam (MMSE), (Folstein, Folstein and McHugh, 1975) was used as an initial screening for potential cognitive impairment (Appendix C) widely for this purpose in older people (Yamadera *et al.*, 2000; Selwood, 2005; Fetveit and Bjorvatn, 2006; Missotten *et al.*, 2007; Amer *et al.*, 2013). The MMSE is an 11-question measure comprising a number of different items. For example, participants were asked to repeat words and recall them at a later point in the assessment, counting down in increments of 7 from 100, spelling backwards and redrawing an image presented to them. The maximum possible score is 30. The cut-off points are defined as score 23-30=Normal, 19-22=Borderline, <19=impaired. A score of <23 is considered as indicative of cognitive impairment (Folstein, Folstein and McHugh, 1975), though it is noted this is not a diagnostic tool and further clinical follow-up would always be required. Based on the MMSE result, 2 groups were defined. Participants scored: 1) greater than 23 and was categorised as normal cognitive function or; 2) less than 19 and was categorised as potential cognitive impairment. Studies have suggested there may be an association between cognitive functioning, sleep and light (Ancoli-Israel *et al.*, 2002; Ancoli-Israel *et al.*, 2003). This study, therefore, examined the associations between blue light exposure, illuminance levels, measures of sleep and cognitive ability.

(3) Cognitive reaction time

To further understand a person's level of cognitive ability the Deary-Liewald Cognitive Reaction Time test (Deary, Liewald and Nissan, 2011) was used. The particular test

chosen for this study was the simple reaction time test (SRT). This was a computer-based activity carried out at the study location through a laptop computer. The appearance of the test consisted of a blue screen with a white box in the centre, within which a black X would appear. Participants were instructed to press any key to start the test. The aim was to press any key again when they saw the X appear to make it disappear; this was repeated for 20 counts. This stimulus appears at varying intervals and reaction time is calculated by how quickly they respond. The final time is given in milliseconds. This specific test and more generally the method of reaction time testing have been used to assess cognition (Deary, Johnson and Starr, 2010; Murray *et al.*, 2011). Reaction time has similarly been tested in clinical trials involving cataract removal (Schmoll *et al.*, 2011). Schmoll *et al*. (2011) postulate that the presence of a cataract can impede the transmission of blue light to the light sensitive cells in the eye, which help synchronise the body clock, and by replacement of the clouded lens saw a statistically improved response to reaction time. This evidence suggested that it was appropriate to use this method of assessing cognitive ability, as a visual assessment was part of the protocol for this study.

(4) Mental wellbeing

The mental wellbeing of older people is of interest in studies relating to their experience within the care home setting (McKee, Harrison and Lee, 1999; Boumans, Berkhout and Landeweerd, 2005; Sjögren *et al.*, 2013). For this study mental wellbeing was assessed with the Warwick Edinburgh Mental Wellbeing Scale (WEMWBS), (Tennant *et al.*, 2007). This is a 14-item scale that covers both hedonic (pleasure) and eudaimonic (meaning and self-realization) aspects of mental health (Appendix D). The scale has a positive focus on feelings such as optimism, cheerfulness and relaxation. It assesses satisfying relationships and positive functioning through energy level, clarity of thought, acceptance and personal development. Typical questions include, 1) *I've been feeling optimistic about the future*, 2) *I've been feeling cheerful*, 3) *I've been feeling loved*, 4) *I've had energy to spare* or 5) *I've been interested in new things.* Participants then rate these statements on a five point Likert scale with *1=none of the time* up to *5=all of the time* to create a single global score. This scale was created in the United Kingdom and since 2008 has been included as a core module of the annual Scottish

Health Survey (available from http://www.gov.scot/Topics/Statistics/Browse/Health/Scottish-health-survey, 2nd June 2015). There is already a large body of evidence to suggest that mental wellbeing can change depending upon the season, this is more commonly known as seasonal affected disorder (SAD). People can often feel periods of low mood or a depressive state during the winter months (Rosenthal *et al.*, 1984; Alfred *et al.*, 2009; Flaskerud, 2012). A recent review by Roecklein et al (2013) suggested that there may be a link between the melanopsin light pathway and changes in seasonal moods and that this area of research is under explored. As the current research investigated seasonal changes in light exposure it was an advantage to explore mental wellbeing in older adults.

(5) Visual function

Participant completed a set of visual function tests selected by ophthalmologists. The first assessment was the Bailey and Lovie LogMAR visual acuity test (Bailey and Lovie, 1976). This is a test of the sharpness of central vision and the ability to see fine details. The letters on the test board are of the same contrast, i.e. black letters on a white test board (Figure 3.2). This time the letters decrease in size from large at the top to very small at the bottom. Again the chart is read in a conventional manor from left to right, top to bottom. There are 5 letters on each line of the test, each line represents a change of 0.1 log units, e.g. first row=1.00 log units, second row=0.90 log units, third row=0.08 log units and so on until the last row=-.30 log units. Therefore, a lower score in this test indicates better the visual acuity.

The second measure was the Pelli-Robson test to measure contrast sensitivity (Pelli, Robson and Wilkins, 1988). Contrast sensitivity is the visual ability to see objects that may not be outlined clearly or that do not stand out from their background. The ability to distinguish contrast declines with age and may be affected by other ocular conditions such as the presence of cataract, age related macular degeneration (AMD) and/or diabetic retinopathy. The test required participants to read aloud (in a conventional manor, i.e. left to right and top to bottom) a series of letters form the test board positioned at a distance of 3 metres (Figure 3.3). The letters are set out 6 per line, with each set of 6 separated into groups of 3 on each side of the chart. The test board is white

in colour and the letters are printed in various shades testing the ability to distinguish contrast. The letters start at the left hand side as black, and gradually change across and down the board through dark grey, pale grey and end in a grey/white pale enough that it is often mistaken for white. Participants are encouraged to read as much as they can see. If a person can read at least 1 of the 3 letters present in that group a log contrast sensitivity (logCS) score is given for each set of 3 letters. A score of 0.05 logCS would indicate poor contrast sensitivity (i.e. top line first set of 3), while a score of 2.30 logCS would indicate good contrast sensitivity (i.e. bottom line last set of 3 letters). Therefore, a higher score indicates better contrast sensitivity.

Visual function assessments were conducted onsite as several participants had reduced mobility and/or other frailties. They were not asked to travel to a clinic for this part of the study. Charts were placed at a distance of 3 metres from the participants and undertaken in a consistent lighting condition as was practically possible in each study setting. The incorporation of a participant's visual function may help towards further understanding how light may be limited in its transmission through the melanopsin pathway to the body clock.

Figure 3.3 Bailey-Lovie LogMAR visual acuity test chart

Figure 3.2 Pelli-Robson contrast sensitivity test chart

(6) Personal questionnaire

A simple questionnaire was used to document participant's age, subjective general health, preferred daily activities and weekly time spent outdoors (Appendix E). Each question was followed by a multiple-choice response e.g. "*For a person of your age how do you consider your health to be? – 1) very good, 2) good, 3) neither good nor poor, 4) poor, 5) very poor*", "*Where do you like to spend time during the morning period*? *– 1) personal bedroom, 2) lounge or dining room, 3) outside weather permitting" and "How often do you go outside during the day and week? – 1) Once a day, 2) A few times a week, 3) Once a week, 4) I never go outside*". This allowed for basic information to be collected that determined the range in age, gender and potential daily pattern of participants taking part in the study.

3.3.3 Summary of variables and directions

Table 3.2 shows the variables measured in this study and the direction of scores, e.g. if a higher or lower score represents a better outcome. The WEMWBS, MMSE, SRT, PSQI and visual measures only apply to the study conducted in older people.

Table 3.2 Summary of health and wellbeing variables

Health measure		**Direction of score**
Wellbeing	WEMWBS (Warwick Edinburgh Mental Wellbeing)	Higher = better mental wellbeing
Cognition	MMSE (Mini Mental State Examination)	Higher = better cognitive function
	SRT (Simple Reaction Times test)	Lower = better response time to stimulus
Sleep	PSQI (Pittsburgh Sleep Quality Index)	Lower = perceived better sleep quality
	Sleep onset latency (minutes)	Lower = fall asleep quicker
	Sleep efficiency (%)	Higher = more consolidated sleep pattern
	WASO (Number of minutes awake after sleep onset)	Lower = fewer minutes awake
	Sleep time (minutes)	Higher = more minutes of sleep
	Bed time	Actual bed time
	Wake time	Actual wake time
Activity	Daytime physical activity count	Higher = more activity counts
Vision	Contrast sensitivity (CS) right eye	Higher = better contrast sensitivity
	Contrast sensitivity (CS) left eye	Higher = better contrast sensitivity
	Visual acuity (VA) right eye	Lower = better visual acuity
	Visual acuity (VA) left eye	Lower = better visual acuity

Table 3.3 show the expected association directions between health and light measures as well as associations within health measures. The WEMWBS, MMSE, SRT, PSQI and visual measures only apply to the study conducted in older people.

Table 3.3 Direction of associations between health and wellbeing outcomes and light

Health measure	Expected association with light variables
1) MMSE	Higher cognitive function assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.
2) Simple reaction time	Faster reaction time assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.
3) PSQI	Better sleep quality assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.
4) Total sleep time (TST)	Longer TST assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.
5) Sleep onset latency (SOL)	Shorter SOL assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.
6) Sleep efficiency (SE)	Higher SE assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.
7) Wake after sleep onset (WASO)	Fewer WASO assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.
8) Daytime activity level	Higher activity assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.
9) WEMWBS (mental wellbeing)	Higher wellbeing assoc. with higher BLE, illuminance levels and longer duration in brighter, bluer morning light.

3.4 Qualitative methods

Qualitative methods were used to explore the feasibility and develop an exploratory study protocol in young people with ASD. A focus group and one-to-one interviews were carried out to inform the protocol and a graphical representation of the study requirements was developed in order to engage and recruit participants.

3.4.1 Focus group

A focus group was conducted in staff (n=10) at a specialist school that supported young people with autism spectrum disorder and additional needs. The purpose of the focus group was to understand the profile of the typical weekday routine and to begin to inform a methodology, which was later, used to recruit participants.

A discussion framework was developed to explore the following themes: 1) About the child, e.g. *How old is the child? Do they have a pervious history of clinical trials?;* 2) Sleep, e.g. *What time is their typical bed time, How often do they sleep through the night? Does disrupted sleep appear worse during the winter or summer months? How does the lack of sleep impact on them and your family?;* 3) Daily routine, e.g. *Does your child regularly spend time outside during mid-morning to early afternoon? For how long and at what time does your child use a computer/ laptop/iPad /tablet /smart-phone etc.?* (Appendix F). The focus group ran for approximately one hour and all participants were encouraged to voice an opinion. Staff came from a cross-section of the school, e.g. care staff and wardens from the accommodation in the school, social care managers and teachers from various subjects such as science and maths. Each theme was discussed for 20 minutes, with audio and written dictations recording events.

3.4.2 Interviews

Parents were identified and contacted with the help of the staff at the school used for the focus group. The one-to-one interviews with parents (n=5) of children with ASD

established the possible differences in the weekend routine. The researcher aimed to understand what the sleep/wake pattern was like prior to attending the school. In the interviews the same themes used in the focus group were discussed 1) about the child, 2) sleep pattern and 3) daily routine (Appendix F).

3.4.3 Developing a visual aid

A visual storyboard was designed to facilitate recruitment and convey the study protocol to potential participants. The researcher explored visual communication as a means of describing the study protocol. To begin creating a descriptive visual aid the researcher met with a representative from Talking Mats. This is a social enterprise was a recognised reputation for creating comprehensive visual communication aids aimed at helping children through to adults who have difficulties with communication or sensory impairment. The designs they create have enabled people with communication difficulties to express preferences and feelings more clearly, whilst enabling an understanding of potentially difficult situations.

Through simple, clear and intuitive images Talking Mats allows a range of topics to be discussed then provides options with a scale to indicate feelings towards the particular topic. Although in this study the aim was not to connect emotion or preference, it was about effective communication and clarity. A schematic of the principles used by Talking Mats is illustrated in Figure 3.4. The method of visual commination is recognised as a successful tool for those with ASD (Schopler and Mesibov, 1995) and, therefore, considered an appropriate method of communication in this study.

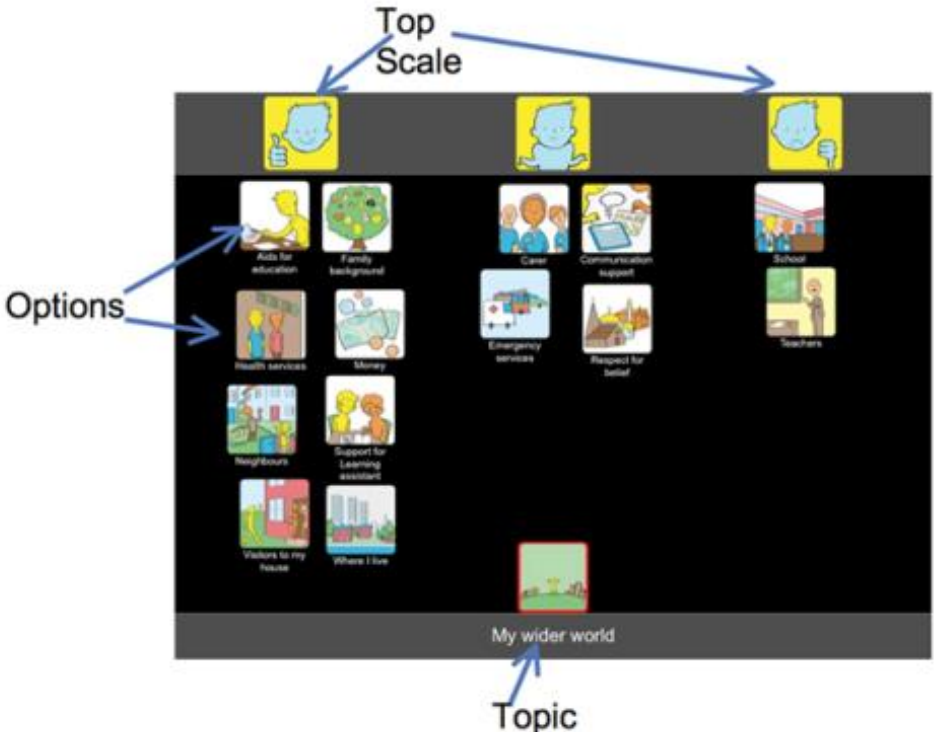
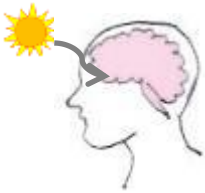


Figure 3.4 Illustration of Talking Mats visual communication tool

Building on discussions held in the focus group, one-to-one interviews and with current visual aid providers the *"sleep and light study"* storyboard was created (Figures 3.5 and Appendix G). The researcher drew on the simplicity of images created by Talking Mats and attempted to take the participants on a six-step journey beginning with a broad introduction to the research through to the proposed protocol. The storyboard was also intended to encourage discussion and provide opportunities to question the protocol. The process of the discussion is outlined below (Figures 3.5 and Appendix G).

Step 1) *The study of sleep and light patterns* – here the researcher explained in simple terms that the study was exploring patterns of sleep and how these might differ between people, days of the week and times of the year. The changes in light exposure were also identified, i.e. it is helpful to have bright light in the morning because it helps towards feelings of alertness and concentration at school and dark conditions at night to help aid sleep.

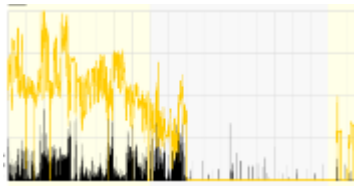


Step 2) *Body clock* – this was the first introduction to the biology of light and the human body. The researcher explained the location of the body clock in the brain and the transmission of light through the eye.

Step 3) *Sources of light* – participants were made aware that light could be emitted from lots of different sources. Participants were asked about the technology they had and how often they used it. Time outdoors and level of activity was also of interest.

Step 4) *Time and effects of light* - The principles behind how light can help to synchronise the body clock or disrupt the rhythms were explained. Examples were given as to how we might disrupt or entrain our body clock, i.e. spending time outside and/or watching TV late at night.

Step 5) *Study protocol* – the proposed protocol was explained to participants i.e. the actiwatch is worn for 5-days, continuously for 24-hours. The equipment was taken along and participants were encouraged to try on the actiwatches.



Step 6) *How we explore the output* – participants were presented with a simplified graphical output from the actiwatch. Two different examples were presented, 1) a regular sleep/wake pattern and 2) a disrupted pattern. These had been annotated with markers of high and low activity, night-time sleep/wake, and bright light during the daytime or light late at night. They were asked if 5 days would be too long to wear the watch. They agreed this was acceptable, but indicated that they would take the watch off if it were bothersome.

Figure 3.5 Study protocol storyboard

3.5 Methods of data analysis

3.5.1 Analysis strategy

Data analysis was carried out using SPSS 21. Distribution of the data was investigated by use of histograms and statistical parameters (i.e. standard deviation – SD). This showed for most variables that there was a left or right skew to the data. All variables were checked for their distribution and to identify any outliers or influential cases. The data was not normally distributed, therefore non-parametric tests were used. A 1.7% random error for the older people study and 1.1% random error for the young people with autism study were found after checking data. A full dataset audit was carried out, cleaned, checked for typographical mistakes, miscoding or wrongly interpreted results. Statistical analysis was conducted on the corrected datasets. All significant results are quoted as two-tailed as guided by Field (2013), one-tailed results will be flagged within the text.

In both study populations (i.e. older people and young people with autism) the participant's time to bed and time to wake were identified by the algorithm used by the actiwatch software. The night-time sleep/wake variables were analysed and defined by the sleep cycle that was detected by the actiwatch. All measure recorded were downloaded to the software and results for sleep/wake, activity and light were aggregated over the study period.

As defined by literature circadian entrainment takes place in the morning hours (Foster, 2012) and circadian disruption may be caused by exposure to too much blue light in the evening (Wood *et al.*, 2013) prior to bedtime. Other studies have shown that light of longer wavelengths at night may be beneficial to the wellbeing of older people living in residential care (Mercier, 2012). Therefore, pre-set time intervals, as well as natural daytime light exposure were based on previous literature (Shochat *et al.*, 2000) and by a visual inspection of datasets relating to both study populations. These include, 1)

morning 08:00-12:00 and 2) natural day[11] (set by the individual). For the evening interval there were two pre-set intervals depending upon the study populations 1) for older people: evening 18:00 to 22:00 and 2) for young people with autism: evening 20:00-00:00. A delay in sleep onset has been reported in those with ASD (Wiggs and Stores, 2004) and as participants did not record a specific bedtime or wake time the interval under investigation was determined by an interpretation of the actiwatch data. Data indicate the mean bedtime was approximately 00:00.

The duration of time spent in particular illuminance thresholds was also investigated in the older population only. These thresholds were derived from works by Bellia *et al*. (2013), Hubalek *et al*. (2010) and Rea *et al*. (2005; 2010; 2011). Based on the initial works of Rea *et al.* (2005; 2010; 2011) and subsequently Bellia *et al.* (2013) - who proposed a mathematical equation to derive a possible circadian stimulus (CS) - the exposure thresholds 1) 50-200 lux, 2) 200-600 lux, 3) 600-1000 lux were established. Using the Rea model, Bellia *et al.*(2013) reported that the duration of time spent in a light threshold between 50-200 lux (at increasing increments of 50 lux) saw a significant increase in CS. However, it was also stated that exposure of duration in illuminance levels of 600 lux or above lead to a smaller increase in CS. Hubalek *et al.* (2010) similarly examined lux and spectral irradiance thresholds. They found that the exposure above 1000 lux to be a significant predictor of sleep quality. Hubalek *et al*. (2010) also stated that there was little information available to explore thresholds of spectral irradiance, therefore, the irradiance thresholds chosen for this study were based on the same grading of illuminance and arranged by a factor of 100 (as carried out by Hubalek *et al*. (2010)). Thus blue spectral thresholds followed: 1) 0.5-20 $\mu W/cm^2$, 2) 20-60 $\mu W/cm^2$, 3) 60-100 $\mu W/cm^2$ and 4) >100 $\mu W/cm^2$. In summary there are three key light variables under exploration, i.e. 1) means over a time-period, 2) durations spent in particular illuminance thresholds and 3) blue spectral irradiance thresholds.

[11] Each participant created an individual day period i.e. went to bed and got up at different times of the day. The natural day period was therefore specific to each participant, so light measures for this would have different start and end times.

3.5.2 Introduction to correlated component regression

Regression modelling is used to estimates the strength of the association between a dependent and a set of independent variables (or predictor variables). This method of analysis investigated which independent variable(s) best predicts the dependent variable, i.e. could light exposure, duration or health and wellbeing covariates predict sleep quality outcomes.

In conventional regression modelling particular criteria are required, such as the number of cases (n) being greater than predictors (*P*) and collinearity is not present (i.e. predictor variables are not highly correlated with each other) (Tabachnick and Fidell, 2001). This data set did not meet the criteria for conventional regression modelling i.e. a small sample size, p is greater than n and moderate to high collinearity is present among independent variables. The Spearman's rho correlations revealed many of the light predictors had a moderate to high correlation with each other (Appendix H). This has been shown to lead to unstable model coefficients, inflated R^2 values (i.e. over estimating the relationship between the predictor variable and the response), model over-fit and poor out of sample prediction (Magidson, 2013).

A recent development in statistical modelling has seen the introduction of correlated component regression **(**CCR). This is a new form of high dimensional regression modelling. In this study the package used was COREXpress statistical innovations using cross-validation (Magidson, 2013). This statistical package is a radical attempt at addressing the problem of collinearity (i.e. predictor variables which have a moderate to high correlation with one another) and is focused on out of sample prediction[12]. CCR is a new form of high dimensional data analysis and allows regression modelling to be carried out on small samples and, specifically, can be used when the number of predictors (*P*) exceeds the number of cases (n). At the heart of the statistical package is a unique regularisation algorithm offering a set of unique tuning parameters and the

[12] Out of sample prediction uses existing data to forecast future relationships

ability to recognise suppressors[13]. The use of the regularisation process prevents over-fit (i.e. describing the noise in the data rather than the underlying relationship) and provides better out-of-sample predictions (i.e. using the existing data to forecast future relationships). The first tuning parameter is *K*, the number of correlated components (each one a linear combination of the predictors) and, secondly, *P* the number of predictors. Through a regularisation process, imposing model restriction, these tuning parameters reduce predictor error and variance, leading to simpler models for validation. In conventional regression the number of components *K* is typically equal to the number of predictors *p* (i.e. $K = P$). However, practice has demonstrated to optimise the R^2 value and improve out of sample predictions this is best achieved when $K<P$. The CCR program initially optimises for K and then for P given the particular value of K (Magidson, 2013).

Lastly, the cross-validation process means the sample is randomly divided into equal folds between a minimum of 5 and maximum of 10 (in this case n=32 giving 8 folds). The last fold is set aside for validation testing and the model is trained on the remainder 1-X. This process is repeated, with the next highest set aside for validation testing. In the second round of validation the sample undergoes a new randomisation process, which is then repeated across all folds. The final model is, therefore, assessed on out of sample performance addressing concerns raised over poor levels of replication in published traditional regression models (Nuzzo, 2014). The dependence of cross-validation on model performance on new cases means that the regression model is not dependent upon conventional sample assumptions.

A strength of CCR is that it recognises repeat cases, therefore, creating a greater number of light measures to be tested. To establish the frequency of each predictor the model was set to run 500 rounds and 8 folds (folds must be between 5 and 10 with n being divisible by this number, e.g. 32 is divisible by 8) to give 4000 runs.

[13] Suppressor variables: i.e. an independent variable which, when added to the model, raises observed R^2 accounting for the residuals left by the model without it, and not due to its own association with the dependent variable.

3.5.3 CCR analysis strategy

Correlated component regression (CCR) linear modelling was used to explore which blue light exposure, illuminance levels and duration in light thresholds best predict sleep quality. To test the strength of associations between light exposures and durations in thresholds health and wellbeing covariates were added to the models, i.e. cognitive function, visual function, age and daytime physical activity level. Secondly, CCR binary logistic modelling was used to explore what variables best predict cognitive reaction time. The same light exposures, durations in threshold and health and wellbeing covariate variables were explored.

First, to assess the association between dependent sleep measures and independent blue light exposure, illuminance levels or durations of exposure a series of CCR linear regression models were run (variables were log transformed to achieve an even distribution). There were 4 dependent variables (DV) of sleep, which have been used in other studies (Shochat *et al.*, 2000; Zeitzer *et al.*, 2007; Hubalek, Brink and Schierz, 2010; Scheuermaier, Laffan and Duffy, 2010; Stone *et al.*, 2014; Crowley, Molina and Burgess, 2015) and include, 1) sleep onset latency (SOL), 2) sleep efficiency (SE), 3) total sleep time (TST) and 4) wake after sleep onset (WASO).

Secondly, to explore predictors of cognitive reaction time a series of CCR binary logistic regression models were run. Cognitive reaction time has been a reported in previous studies as a robust dependent measure in older people, particularly those who are experiencing visual impairment (Schmoll *et al.*, 2011).

Although CCR is unique in its ability to analysis data sets where the number of predictor variables can be greater than the number of cases it is still in a novel and evolving statistical analysis approach and care was taken in advoiding models overloads with variables. Therefore in order to produce more robust and stables results (i.e. limiting the number of predictors against the number of cases) the independent variable light measures were divided into 3 categories: 1) exposure at pre-set intervals across the day, 2) durations spent in lux thresholds and 3) duration spent in blue light thresholds. A

series of covariates were introduced into the regression analysis. These were age, cognitive function, daytime physical activity and measures of visual function (i.e. visual acuity and contrast sensitivity).

3.6 Ethics

Heriot-Watt University's School of Energy, Geoscience, Infrastructure and Society Research Ethics Committee and Insurance department approved this research. Information sheets and signed consent was a requirement for participation (Appendices I and J). For the study involving older people, those with the capacity to consent and understand the protocol were recruited. In addition the researcher met with the care home manager and next of kin to ensure that the potential participant(s) did understand the study purpose and protocol. In the exploratory study involving adolescents, both parental and participant consent were sought. The researcher also obtained the Enhanced Disclosure and Barring Service (DBS) check to work with school children.

3.7 Summary

To summarise, the chapter outlined the methodology, study design and the data analysis approach. In the following chapter (4) the protocol development relating to young people with autism and the preliminary findings are reported. Chapter 5 reports the pilot study and protocol development in older people, the characteristics of the group by season, associations between light and sleep/wake parameters and the within group differences (between season). In Chapter 6 there is a report of between group differences (based on cognitive ability) and predictors of sleep quality in older people.

Chapter 4 : Developing a protocol to explore blue light exposure in adolescents with autism spectrum disorder

"I'm a visual thinker, not a language-based thinker. My brain is like Google images."

- Temple Grandin

4.1 Introduction

In this chapter an exploratory study conducted in adolescents with autism spectrum disorder living in a residential school is presented. The chapter describes the development of a protocol to engage and communicate a study with a group facing sensory and emotional difficulties (objective 2). The subsequent methods used to recruit a study cohort are described. An investigative data analysis and preliminary findings are reported followed by a discussion of findings. Study limitations are considered and a proposed protocol set out for further study.

The research questions that will be addressed in this chapter are:

- Can a study protocol be developed to quantify blue light exposure, illuminance levels and sleep patterns in a group with sensory issues?
- What are the associations between blue light exposure, illuminance levels and sleep parameters?
- How does the structured routine of the school week compare to that of the home routine?

4.2 Aim of the exploratory study

The aim of this explorative work was to establish a workable study design through focus groups and interviews and to test the feasibility of the protocol in a small sample of adolescents with autism spectrum disorder (ASD)**.** A preliminary investigation would allow for testing the adequacy of the actiwatch equipment, help assess whether the

research protocol was realistic and workable in this population and identifying problems that might occur using the proposed methods. Moreover, it enabled an appraisal of the proposed recruitment methods, aided the development of research questions, estimate the time required to carry out the study and measurements whilst helping towards the design of a protocol for further study.

4.3 Developing the protocol

To ascertain the possibility of forming a study sample a focus group with staff (n=10) and individual interviews were conducted with parents (n=5). To help profile the sleep/wake cycle and to estimate the viability of working with a group of children or adolescents with ASD attempts were made to contact charities and special needs schools. Sleep Scotland, a dedicated parental and young people with sleep issues support charity and and a number of specialist schooling providers (New Struan School, Kaimes School and Falkland House School) were approached to participate in the development of the protocol and establish participants for the exploratory research. From the initial contact and attempts to engage interest, a cohort of staff was recruited at a residential school in rural Fife, Falkland House School, supporting boys with ASD and additional support needs. Subsequently, parents of potential participants were contacted via the school and interviewed individually. Following meetings with staff and parents potential participants were identified.

Prior to the recruitment session the researcher met with a leading paediatric consultant from the Royal Sick Kids Hospital, Edinburgh, with a specialist in neurodisability and autism spectrum disorder. This meeting enabled a professional appraisal of the proposed recruitment methods and exploratory protocol. Feedback from this meeting was positive and there was agreement that both the recruitment methodologies and proposed exploratory study design could be achievable in the chosen study population. However, a caveat was raised regarding the deep sensory issues that young people with ASD face, suggesting the actiwatch may prove to be difficult to tolerate.

Following this, the recruitment seminar was designed to be interactive and allowed opportunities for participants to ask questions. The researcher used the images from the storyboard to explain what the study was exploring without being to in-depth that participants might alter their behaviour (Appendix G). After the final step (6), blank graph paper, similar to the actiwatch output, was distributed to participants. The researcher drew an example of their actiwatch output and described their pattern as they drew it.

Researcher: *"I get up at 7am and like to run in the morning - so my activity is high, and if it's sunny and I'm outside then I'll receive lots of daylight. By 9am-10am I'm at my desk working. I'm at my desk most of the day and don't move much until I'm ready to go home. Generally, I'm a good sleeper. I go to bed around 11pm and fall asleep."*

Participants were asked what their routine look like. A few offered ideas such as –

Participant 1: *"I get up at 8am on schools days and have my breakfast, so I don't move much. On Thursdays we have PE for an hour so I'm moving loads then."*

Participant 3: *"Weekends? I do what I want when I go home. Sometimes I'm up until 2/3am on my computer or watching TV."*

They were then asked to draw out their activity and sleep pattern on the graph paper for a typical school day and another at the weekend. They interpreted their activity and sleep patterns and implied what the corresponding light levels might be like, i.e. if they were outside playing they would be active with high light levels and at night they were inclined to draw the opposite. This task was intended to allow potential participants better understand the function of the actiwatch (i.e. it simply records movement and light levels) and dispel fears that the equipment may be able to record personal details.

After completion of the information session, potential participants were invited to take part in the pilot study, they were provided with an information sheet and consent form (Appendices I and J). All of those present were happy to continue with the exploratory

protocol. In total 8 pupils gave written consent with additional consent sought from a parent (Appendix J). This study protocol met the requirements for Heriot-Watt University ethics board.

4.4 Method

4.4.1 Participants

The study participants were Scottish schoolboys (n=8) aged 13-18 years living in a residential school in Fife. For the sample the mean age was 16 years (SD=2). All descend from various regions of Scotland and reside at school Monday to Friday, returning to the parental or guardian home at weekends. Participants all had a diagnosis of ASD and had previously reported disruptions in their sleep cycle. In the cohort, 1 participant was using a melatonin dietary supplement to help with sleep. He was instructed to remain taking this as normal.

The study was conducted during April 2013. Participants wore the actiwatch for 5 days on their non-dominant wrist (i.e. with a view to capture 2 days at school and 2 days at the weekend). They were instructed to leave the watch uncovered for the duration of the study and to wear it 24-hours continuously (only to be removed when bathing or swimming). Participants were awarded a certificate of achievement for completing the study presented by the researcher at a school assembly.

4.4.2 Protocol

Before the start of the study participants were reminded of the protocol and again instructed to keep the light sensors uncovered as much as possible and remove if submerging in water. The methodologies used for recording personal light exposure, sleep/wake and activity patterns are reported in Chapter 3. In brief, devices were checked and calibrated to begin recording at 12noon on day 1. The researcher collected

them at the end of the 5-day study period at 12noon. Due to limited equipment (6 actiwatches) participants were split into two groups, 4 participants were measured in parallel on consecutive weeks. Participants completed a post-study questionnaire and one-to-one interview with the researcher. This was used to help interpret the actiwatch output and to allow for feedback that might be helpful towards establishing the full study protocol.

4.4.3 Study setting

The pilot study was conducted in a residential school setting in rural Fife (Figure 4.1). The building is located within the Falkland Estate in Fife and dates back to 1839. It is surrounded by rich woodland and nestles at the foot of the Lomond Hills. The building boasts a historical interior with large glazed windows and ceiling heights in excess of 3 metres. In the teaching areas the rooms are in line with typical classroom proportions e.g. approximately 9x10metres, still with large east or south facing aspects.

Figure 4.1 Falkland House School, Fife

4.5 Preliminary results

Descriptive statistics were used to explore the distribution of the data. Non-parametric tests were used to investigate preliminary relationships because the data was not normally distributed. A visual inspection of the actiwatch outputs and discussions with the cohort at the end of the study period indicated that 1 participant failed to wear the watch during the study period and 1 participant went home for the week and did not reside at school (see Table 4.1). Therefore, these 2 cases were excluded, leaving 6 datasets to be analysed.

To investigate possible associations between variables Spearman's rho bivariate correlations were explored for weekdays and weekend separately. To explore differences between weekdays and weekend a Wilcoxon signed-rank test was carried out on sleep and light measures. This was anticipated to highlight if relationships between sleep parameters and light exposure changed between school days and time at home during the weekend.

Table 4.1 Participant overview

ID	Age	TST (mins)	SE (%)	WASO (mins)	SOL (mins)	Wake time	Bedtime
1	15	562	74	27	94	09:11	23:49
2	18	423	80	63	24	08:58	00:10
3	14	378	67	56	125	10:25	00:38
4	15						
5	13	435	80	26	65	08:49	23:42
6	18	715	69	33	17	11:58	23:34
7	16	524	84	55	25	09:02	22:46
8	18	365	60	35	114	07:28	21:11

Note: grey hatch represents data incomplete participant removed from statistical analysis
TST= total sleep time, SE=Sleep efficiency, WASO=Wake after sleep onset, SOL=sleep onset latency

4.5.1 Can a protocol be successfully developed to explore blue light exposure in adolescents with ASD?

(1) Focus group outcomes

From the focus groups staff reported that sleep did not appear to be a problem whilst at school (i.e. students responded to set bedtimes and wake times). They did state that sleep disruption was of concern for some students prior to moving into the school. The group unanimously stated that parents reported their child had turned night into day, i.e. slept all day and spent most of the night awake. Although staff did not have concerns with sleep disruption they did indicate that some students still report difficulties in falling asleep or frequent night-time awakenings. It was also discovered that 2 students slept with the light on at night. Information from the focus group suggested 1 potential participant used a dietary melatonin supplement to modulate sleep. When asked about the use of technology the school expressed a strict policy on time allowed on devices. All technology or televisions must be switched off by 21:00 for the younger students (aged 10-14 years) and 22:00 for older students (15-18 years).

Staff members were questioned about possible methods to recruit participants, e.g. a written information sheet, diagrammatic representation of the study or a combination of these. The group stated that visual aids were beneficial and students responded well to graphical information and capable of following or comprehend text instructions. The researcher wished to investigate potential motivators that might help to engage participants. It was suggested that an award or recognition for participation would be considered an incentive. Staff members were keen to ensure participants were not incentivised through a monetary or gift reward. They felt that this could cause difficulties between students that did not participate or may potentially change behaviours during the study.

(2) Parent interview outcomes

Parents confirmed that before enrolment their child did not have good sleep quality or sleep hygiene (i.e. regulated bedtime and wake time or calming down time prior to sleep). They expressed that since attending the school their child had improved sleep

quality and reduced anxiety about sleeping. All parents interviewed said that at weekends and school holidays (i.e. non-residential time) their child would be free to have the sleep/wake pattern they wished. They were not expected to maintain a regular bedtime or wake up time. Some parents (n=2) suggested that this caused a recurrence of sleep problems in their child. When parents were asked about technology usage they had a mixed response. A parent of a younger child (aged 13 years old) stated he was not interested in gaming nor did he have a smartphone. Here light from technology was not an issue, however he did prefer to sleep with a small night light on. The details of this lamp are unknown in terms of illuminance level or blue spectral content. Parents of the older pupils noted that their child did own a smartphone, tablet or computer. Parents also stated that they did not perceive these as a cause of sleep disruption and that their child was able to use these when they wished. They stressed that they saw these as educational tools (e.g. reading books on tablet devices or doing homework online) and were not concerned about over usage or light exposure. This information suggested that in older adolescents light exposure at night could be a possible sleep disrupter as they may spend prolonged periods in front of bright backlit devices prior to bedtime.

(3) Participant feedback

As part of the protocol each participant was interviewed post study and completed a short questionnaire (Appendix K). This was used to establish parameters such as if they felt they slept better during the school week or weekend at home, what their daily routine was like and additional feedback on the protocol that might be useful to building a full study.

The first section asked questions in relation to sleep, i.e. approximate bedtime and wake time both during weekdays and weekends. Perception of sleep quality between weekdays and weekends was also asked. All participants reported very different bedtime and wake times between school week and weekends. All participants indicated a structured routine during the week and suggested they went to bed between 21:30 and 22:00 and woke between 07:30 and 08:00. Responses indicated a large range at weekends between bedtime 00:00 and 06:00 and wake time 07:00 to 12:00. When exploring perceived sleep quality (i.e. when do you feel you sleep better?) Findings

suggested that 3 participants felt they slept better during the school week, 2 participants said they slept better at home during weekends and 1 participant said they felt no difference between weekdays and weekends.

Participants were asked about their preferred activities in the morning and in the evening. The same choices were given for both times of day. In the morning activities 4 participants reported that they would prefer to spend time outside and 2 participants preferred indoors on computers or watching TV. No participants reported reading as a preferred activity. In the evenings 2 participants suggested that watching TV or using the computer was the preference and 4 participants would choose to be outside.

Some of the richest outcomes from this study were in the post-study conversations. Participants were engaged in an open-ended conversation, rather than a succession of structured questions. This was used to facilitate the opportunity for participants to offer personal feelings and attitudes towards the study. All participants agreed it had been a positive experience for them and would happily take part in any follow on studies.

A point of particular interest was the response given when asked what they enjoyed the most and what they did not enjoy.

Participant 1: *"Taking part was good – the watch made me realise what time it was. I never wear a watch. It was good to know what time it was."*

Participant 2: *"It made me feel part of something and I could talk to the other guys about stuff."*

Participant 5: *"The watch doesn't look great. If it was black then it would be really cool."*

Does this indicate the importance and potential benefit of other environmental cues for people living with ASD? Could customisation of the device help increase participant interest and reduce anxieties if the participant could have a degree of ownership of the

device, making it a more familiar object? In summary, the exploratory protocol was successfully administered in 6 participants, with no feedback to suggest objections to what had been expected during the study duration.

4.5.2 What are the associations between blue light exposure, illuminance level and sleep parameters?

To explore possible associations between sleep parameters and light during weekdays verses weekends a set of Spearman's rho bivariate correlation were explored. The time at school during weekdays was investigated separately from the time at home during weekends. This was intended to examine if relationships between sleep measures and light exposure changed between weekdays and weekends. Table 4.2 reports the correlation results for weekdays and Table 4.3 are the correlation results for the weekend.

(1) Weekday correlations between sleep measures and light

Correlations explored for weekdays suggested a significant negative association between blue light exposure 4 hours prior to bedtime and total sleep time (r_S=-.88, p=0.04). This association was also negative for sleep efficiency (r_S=-.77, p=0.019). Results indicate higher blue light exposure prior to bedtime was associated with fewer minutes asleep and lower sleep efficiency. Results indicated a significant positive association between blue light exposure 4 hours prior to bedtime and the time a participant went to bed (r_S=-.98, p=0.015), indicating higher blue light exposure in the evening was associated with a delay in time to bed.

Exposure to blue light prior to bedtime was not the only light measure to suggest interesting trends in this data. A similar pattern was found in the illuminance level prior to bedtime for the same 4 hour period. There was a significant negative association between the level of illuminance 4 hours prior to bedtime and sleep efficiency (r_S=-.76, p=0.046), i.e. higher levels of illuminance prior to sleep was associated with lower sleep

efficiency. The relationship was similar for bedtime (r_S=-.63, p=0.000), i.e. the higher levels of illuminance in the evening was associated with a later time to bed.

Finally, there was significant positive association between total sleep time and sleep efficiency (p=0.041), i.e. longer total sleep time was associated with higher sleep efficiency. There were no other statistically significant results.

Table 4.2 Spearman's rho correlations Weekdays

	Total sleep time	Sleep efficiency	WASO	SOL	Wake time	Bedtime	Morn BLE	Morn illuminance	Day BLE	Day illuminance	Pre-bed BLE	Pre-bed illuminance
Total sleep time	1											
Sleep efficiency	.77*	1										
WASO	.42	.72	1									
SOL	-.67	-.66	-.60	1								
Wake time	.60	-.02	-.08	-.14	1							
Bedtime	-.49	-.80	-.75	.49	-2.90	1						
Morn BLE	-.20	-.02	-.08	.60	.02	-.11	1					
Morn illuminance	-.42	-.11	.20	.60	.02	-.29	.82*	1				
Day BLE	-.85*	-.63	-.35	.75	-.65	.55	-.02	.20	1			
Day illuminance	-.67	.34	.17	.42	-.42	-.20	.82*	.82*	.25	1		
Pre-bed BLE	-.77*	-.83*	-.70	.59	-.49	-.89*	.17	-.02	.63	.50	1	
Pre-bed illuminance	-.63*	-.76*	-7.0	.61	-.42	-.98**	-.14	-.31	.73	0.09	.87*	1

**correlation is significant at 0.01 (2-tailed), * correlation is significant at 0.05 (2-tailed). WASO=wake after sleep onset, SOL=sleep onset latency, BLE=blue light exposure measure in $\mu W/cm^2$, Illuminance level measured in lux

(2) Weekend correlations between sleep measures and light

In the weekend data there was a significant negative association between sleep onset latency (i.e. the time taken to fall asleep) and sleep efficiency, suggesting taking longer to fall asleep may be associated with lower sleep efficiency (r_s=-.95, p=0.001). Furthermore, there was a significant positive association between the total sleep time and blue light exposure across the daytime (r_s=.82, p=0.023), indicating higher levels of blue light exposure across the daytime may be associated with longer periods of night-time sleep. No other statistically significant relationships were found in the weekend data (Table 4.3).

Table 4.3 Spearman's rho correlations weekends

	Total sleep time	Sleep efficiency	WASO	SOL	Wake time	Bedtime	Morn BLE	Morn illuminance	Day BLE	Day illuminance	Pre-bed BLE	Pre-bed illuminance
Total sleep time	1											
Sleep efficiency	-.16	1										
WASO	.17	.63	1									
SOL	-.07	-.95*	-.60	1								
Wake time	-.31	-.40	-.02	.37	1							
Bedtime	-.88*	-.37	-.02	.42	.60	1						
Morn BLE	.48	.23	-.20	-.31	-.74	.77	1					
Morn illuminance	.37	-.02	-.31	-.02	-.48	-.48	.82*	1				
Day BLE	.82*	-.39	.14	.28	-.48	.77	.82*	.88*	1			
Day illuminance	.75	-.32	-.21	.21	-.02	-.42	.48	.77	.85*	1		
Pre-bed BLE	-.11	-.57	-.17	.49	.20	.11	.31	.69	.49	.60	1	
Pre-bed illuminance	-.25	-.66	-0.8	.60	.25	.25	.20	.60	.37	.48	.98**	1

**correlation is significant at 0.01 (2-tailed), * correlation is significant at 0.05 (2-tailed). WASO=wake after sleep onset, SOL=sleep onset latency, BLE=blue light exposure measure in $\mu W/cm^2$, Illuminance level measured in lux

4.5.3 How does the structured routine of the school week compare to that of the home routine?

During the school week participants slept for a mean of 7 hours (422 minutes). The mean wake up time and time to bed were 07:44 and 00:14 respectively (Table 4.4). At the weekend participants slept for the same mean duration (7 hours). The mean wake up time and time to bed suggested approximately a 3-hour phase-shift i.e. 10:32 and 03:20 respectively (Table 4.4). Studies comparing adolescents with ASD to typically developing adolescents have found that people with ASD have a shorter total sleep time, e.g. typical adolescent=9.3 hours and ASD=8.9 hours (Polimeni, Richdale and Francis, 2005). In this study it was suggested to be even shorter than in previous work (an average of 7 hours of sleep). Furthermore, reports suggest adolescents with ASD experience a longer sleep onset latency (i.e. time it takes to fall asleep), indicating that it may take up to one hour to fall asleep (Krakowiak *et al.*, 2008). This appears to be reflected in the result for this pilot investigation (Table 4.4).

In a small sample (n=6) the reliability of statistically significant results would be minimal, however it does indicate a trend. To explore differences in mean outcomes between weekday verses weekend routine the Wilcoxon signed rank test was carried out. The results showed that wake up time and bedtime was statistically different between weekdays verses weekends (both at Z=2.20, p=0.028). Participants wake up time and bedtime were later at the weekends than during the school week. They woke approximately 2 hours 45 minutes later and had a bedtime 3 hours 5 minutes later at weekends (Table 4.4). It was expected that more circadian disruption would be present at weekends when participants might be freer to define their routine. However, it does propose they were able to shift their 'daytime period' by going to bed later and waking later. In a typically developing adolescent population reports indicate sleep may not change greatly between weekdays and weekends, with 2 days off not sufficient time to desynchronise the cycle (Hansen *et al.*, 2005). Research has also reported adolescents may lose as much as 2 hours of sleep during weekdays due to early school start times and at weekends sleep time may be 30 minutes longer (Hansen *et al.*, 2005). No other statistically significant results were found. However, there were trends in the expected direction for wake after sleep onset, i.e. there were more waking moments during the sleep cycle at weekends compared to during the week at school.

During the school week descriptive statistics suggested a mean morning blue light exposure of 10μW/cm^2 and mean daytime blue light exposure 76μW/cm^2. Weekend results suggested that morning blue light exposure of 49μW/cm^2 and mean daytime blue light exposure 44μW/cm^2. These results were not statistically different, but were in the expected direction i.e. mean morning blue light exposure was higher at weekends. For levels of illuminance results suggested that during the school week mean morning illuminance was 1240 lux and mean daytime illuminance was 1032 lux. At weekends the mean morning illuminance was 1416 lux and mean daytime illuminance was 2127 lux. Again results were not statistically different, but were in the expected direction.

Table 4.4 Mean (SD) and Wilcoxon signed-rank test results for weekday and weekend sleep and light statistics (n=6)

	Weekday mean, (SD)	**Weekend mean,(SD)**	**Wilcoxon signed-rank test (weekday to weekend)**
Total sleep time (mins)	422 (52)	422 (79)	Z=-.31
Sleep efficiency (%)	78 (4)	75 (9)	Z=-.13
Wake after sleep onset (mins)	38 (17)	60 (25)	Z=-1.36
Sleep onset latency (mins)	71 (55)	80 (62)	Z=-.52
Wake time	07:44 (31)	10:32 (2)	**Z=-2.20, p=0.028, r=-.45**
Bedtime	00:14 (75)	03:20 (5)	**Z=-2.20, p=0.028, r=-.45**
Morning blue light (μW/cm^2)	10 (8)	49 (64)	Z=-1.15
Morning illuminance (lux)	1240 (2560)	1416 (1197)	Z=-.52
Daytime blue light (μW/cm^2)	76 (84)	44 (46)	Z=-.31
Daytime illuminance (lux)	1032 (961)	2127 (2168)	Z=-1.15
Evening blue light (μW/cm^2)	0.3 (0.5)	0.6 (0.6)	Z=-.94
Evening illuminance (lux)	19 (39)	25 (25)	Z=-.94

Bold type indicates a statistically significant result

4.5.4 Case study: Evidence of circadian disruption in ASD

The degree of possible circadian disruption during time spent at home was most evident in participant 6. For the purpose of the data analysis described earlier in this chapter participant 6 was excluded. This was because he subsequently spent the study week entirely at home, therefore, his data was not reflective of a typical school week verses weekend routine. A visual inspection of the data raised interesting questions and a very different routine was observed in this participant. The circadian disruption is illustrated in Figure 4.2. To understand the output note three tones of blue, 1) dark blue defines "off wrist", i.e. the participant was not wearing the actiwatch, 2) mid blue indicates the participant was asleep and 3) light blue is the sleep latency period, i.e. intention to fall asleep but not in a sleep cycle.

On day 1 of the recording the participant went to bed at approximate 04:00 and woke the following day at 13:00. On day 2 there was a significant period of "off wrist" (14:00 to 22:00). This was followed by latency only period between 22:00 to 10:00 the following day (3). The participant did not go into the next sleep cycle until 19:00 on day 3, which lasted until 13:00 the next day, i.e. this participant sleep for approximately 18-hours continuously. Day 4 saw a short period of activity between 13:00 and 22:00. The next sleep cycle began at approximately 23:00 and ended at 11:00 the following day. Between day 4 (Saturday) and the return to school on day 6 (Monday) there was no information available, the watch status was "off wrist". The only day recorded at school was day 6 (Monday). The sleep cycle between day 6 and day 7 saw very short sleep cycle i.e. only 5-hours sleep between 03:00 until 08:00.

This output clearly displays an irregularity in the sleep/wake cycle compared to those participants who spent the week at school and weekend at home. Illustrated by Figure 4.3 is an alternative output from one participant that successfully completed the study. As a comparison it is clear that during the school nights (day 1 and 2) the participant had a regular bedtime and wake time. On days 3, 4 and 5 (i.e. weekend nights) there was a degree of change in sleep onset latency, bedtime and wake time. These outputs show differences depending upon the routine of participants, however, it does not provide sufficient evidence to imply that routine only is key to sleep regulation. In order to create a more secure evidence base this study protocol who need to be replicated in a

similar population, i.e. age, gender, spectrum of autism etc., to establish the extent that home routine is reflective of this pattern.

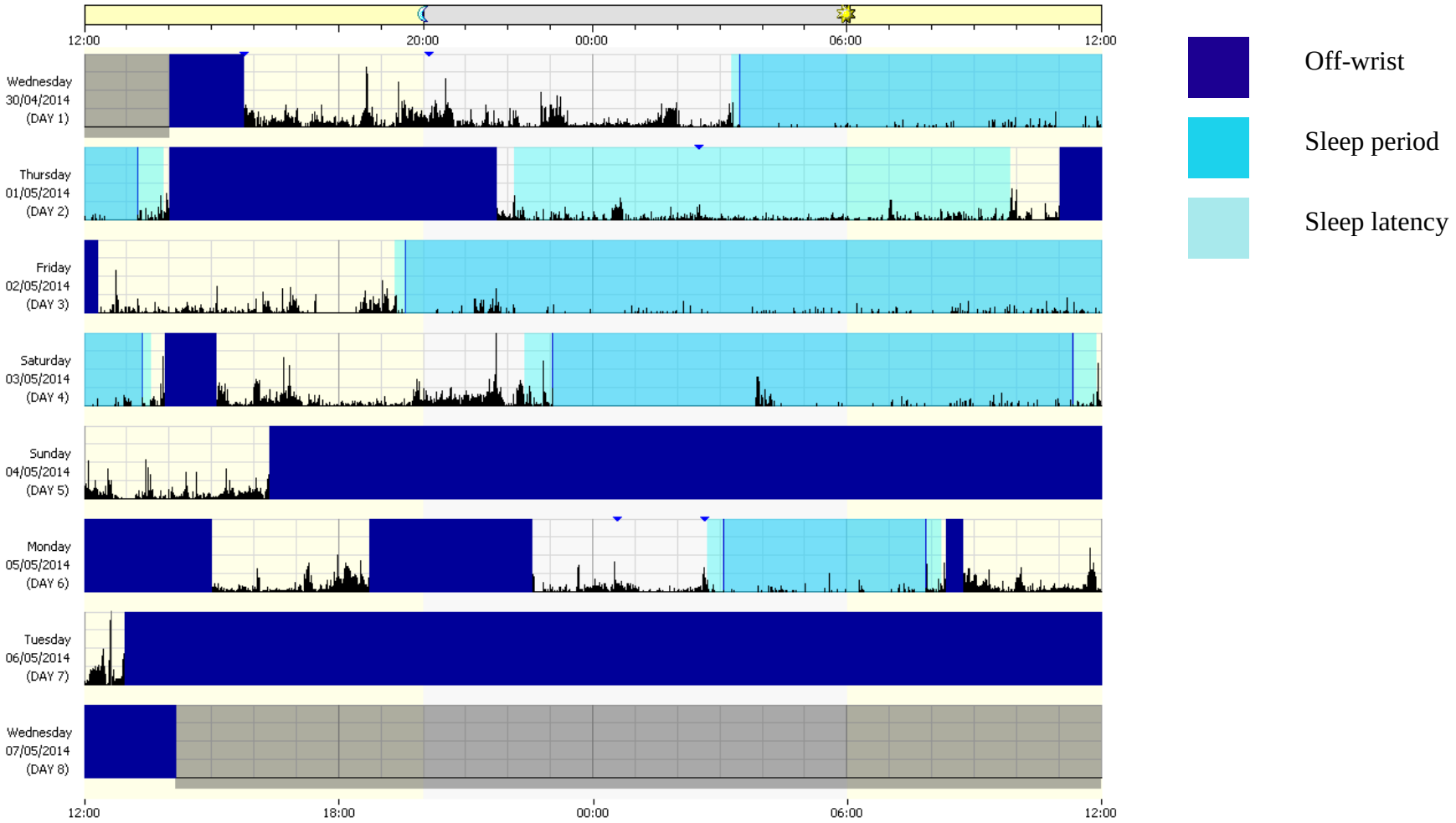


Figure 4.2 ASD Actigraphy output from participant with incomplete exploratory study protocol (all time at home)

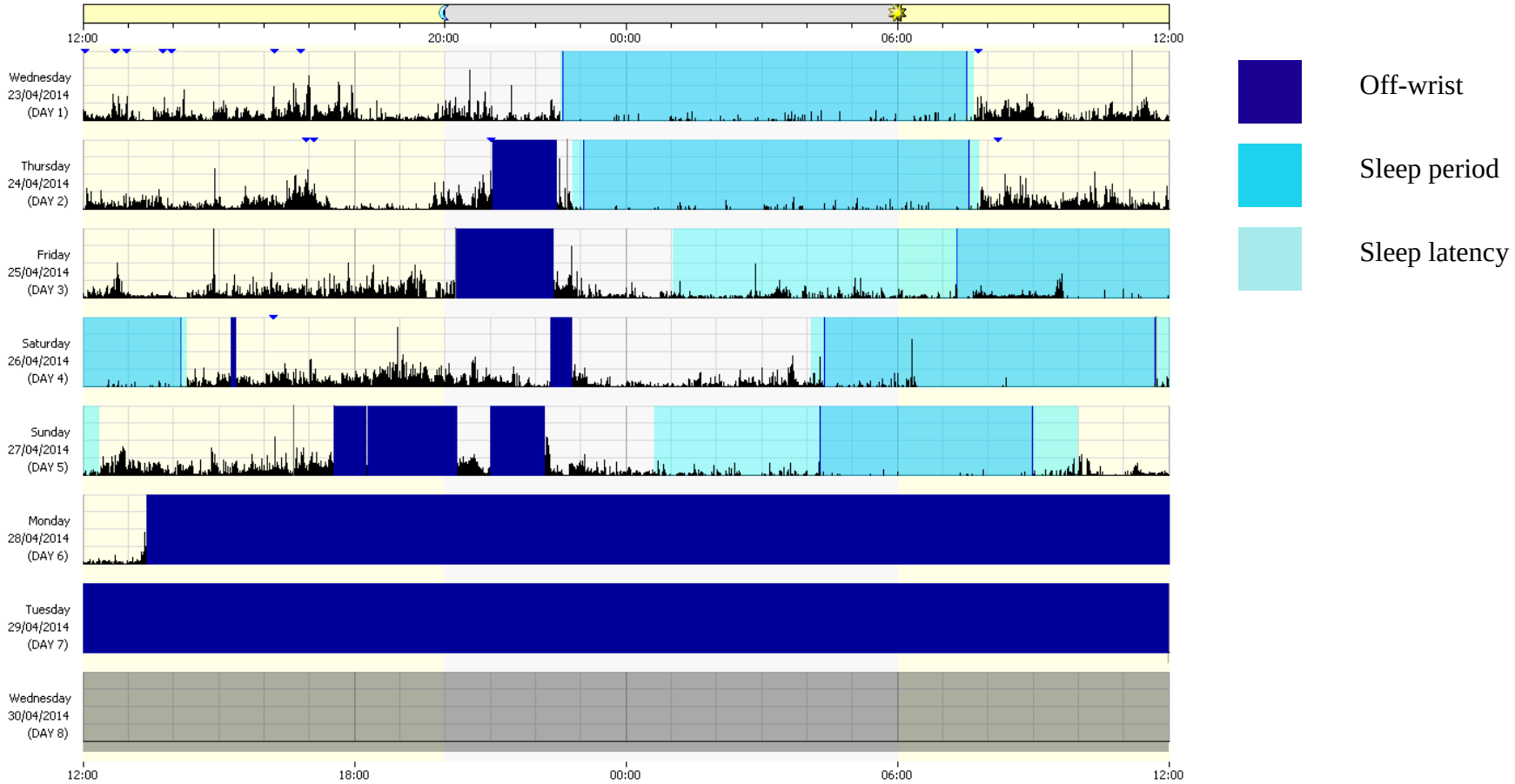


Figure 4.3 ASD Actigraphy output from participant with completed the exploratory study protocol

4.6 Summary of preliminary results

This exploratory study was innovative in its use of visual aids to engage and recruit participants. This put participants at ease and created an open environment to discuss (if they wished) the pros or cons of the study. The anecdotal comments from the feedback session were extremely useful in establishing a design for the main study. The key preliminary results were:

1) Sleep quality varies between weekday and weekends: time to wake and bedtime are statistically different between weekdays at school compared to weekends. During weekends there was a 3-hour circadian delay in bedtime and wake time. There were no other statistical differences in sleep parameters or blue light and illuminance measures. However, there were associations in the expected direction for mean wake after sleep onset (WASO), suggesting that sleep at weekends was more fragmented with wake bouts.

2) At weekdays there was an association between blue light exposure 4-hours prior to bedtime and lower sleep efficiency, a shorter total sleep time and a later bedtime. The same relationships, i.e. reduced sleep efficiency and later bedtime, were visible between the level illuminance pre-bedtime during the school week.

3) At weekends the spearman's rho correlations suggested there was an association between a longer time to fall asleep and lower sleep efficiency. Preliminary results also suggested that daytime blue light exposure may be associated with an increased in time asleep at night.

4) Feedback from participants, that successfully completed the protocol, indicated that this could be successfully implemented without changes to the design. The two participants that were unsuccessful in completing the protocol indicted that this was not caused by study design, i.e. one participant was at home and the other misplaced the watch at the start of the study period. Opinion also

suggested that the visualised recruitment method was effective in engaging participants.

4.7 Limitations

A limitation of the exploratory study was that it was carried out in small sample, in males only and in a residential setting. Although autism spectrum disorder and related conditions are more prevalent in males (Baron-Cohen *et al.*, 2011) that it not to say they are exclusive. A repeat study would benefit from a mixed gender cohort to investigate if there are differences in sleep quality between male and females living with ASD. Furthermore, sleep and light were explored here in a residential setting. Understanding the possible relationships between sleep and light exposure would benefit from different study locations comparing residential and home settings. It was evident from this study that the boundaries of the residential school structure may be helpful towards regulating a day/night pattern, to understand the extent of the effect a parallel group living at home would help to draw inferences.

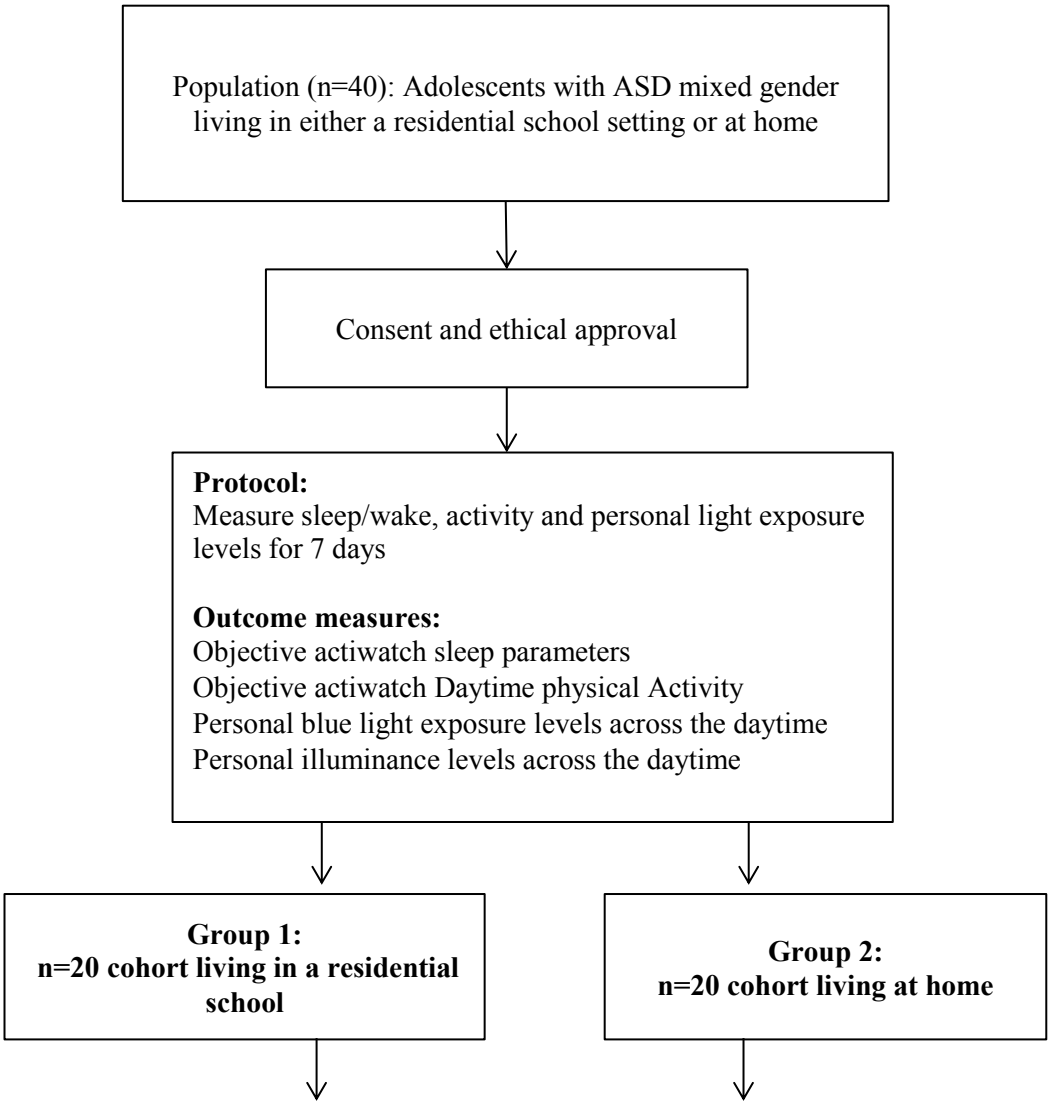
Another limitation of this study was the location of watch. As discussed previously (Chapter 3) understanding the associations between light and sleep are more accurately done by light measurements taken in the same plane as the eye. Therefore, in a full repeat study measurements would be more accurately taken if participants were able to tolerate wearing the light sensor at the lapel to capture light indecent at the same plane as the eye (i.e. vertical illumination) . Similarly, if the number of days recorded could be extended this would allow for a more accurate picture to be formed of a typical sleep/wake and light pattern of adolescents with ASD. Other studies have successfully recorded 8 to 12 nights of sleep in children or adolescents with ASD. Participants were stable in medical and behavioural conditions (Souders *et al.*, 2009). Souders and colleagues concealed the actiwatch sensor in a 6×6 cm soft cotton pocket in the upper sleeve–arm area of the child's nightwear. In other studies, such as that by Acebo *et al.* (1999) it has been suggested that a minimum of 5 analysable nights of data would provide an image of sleep patterns. In future research, a 7-day period would help to

profile the variability in sleep over the duration of a week and allow for days when data may be lost through lack on compliance with the protocol.

Lastly, it may be worth considering as a recruitment incentive, to allow customisation of the actiwatch (to a degree that does not interfere with the operation of the equipment). Simple measures such as interchanging the watchstrap or coloured stickers might encourage ownership and help towards reduced anxiety in wearing something unfamiliar.

4.8 Suggested study design

Building upon the preliminary data analysis and feedback from participants a recommended design for further study is illustrated in Figure 4.4. The modest evidence from this pilot suggested that total sleep time was not in line with current health recommendations and that blue light exposure prior to bedtime was associated with later sleep onset. What remains unknown is whether this pattern of sleep/wake and light exposure is typical in adolescents with ASD that live at home and if gender is of importance. To explore this, replication of the pilot study is needed. The study design addresses the same sleep/wake, activity and light patterns outlined in this thesis to be measured in adolescents with ASD that live at home and in a residential setting. The aim of the statistical analysis would be to investigate between group differences across the outcome measures e.g. *do sleep/wake and light exposure patterns differ between young people with autism living at home and those living in a residential school setting?*



Proposed RQ's;

1) What are the characteristics sleep/wake, daytime activity and light exposure of individual groups?
2) What are the associations between sleep/wake, daytime activity and light exposure patterns by group?
3) What are the differences in sleep/wake, daytime activity and light exposure patterns between groups and by time of the week?

Figure 4.4 Suggested design exploring light and sleep/wake patterns in adolescents with ASD living at home and in a residential school

4.9 Discussion

Can a protocol be successfully developed to explore blue light exposure in adolescents with ASD?

In this chapter the pilot demonstrated that it was feasible to administer the protocol in this population. Opinion suggested that the visualised recruitment method was successful in engaging and recruiting participants. To establish the protocol the researcher spoke with leading expert in the field of autism research. Concerns were previously raised suggesting that wearing an actiwatch would be difficult in this population. This study demonstrated through a clear description of the study design and protocol it was possible to administer an actiwatch in a cohort with complex sensory issues. Other interesting information that emerged was the statement made by one participant in the post-study feedback session - "*Taking part was good – the watch made me realise what time it was. I never wear a watch. It was good to know the time of day*." Could adolescents living with ASD benefit from environmental cues, such as wearing a watch? How do environmental zeitgebers help with sleep regulations in ASD? These anecdotes open new questions in the field of light and sleep studies for this specific population.

What are the associations between blue light exposure, illuminance and sleep parameters?

There is limited evidence available to compare differences in personal light levels adolescents and specifically those with autism. However, in this study results suggested that participants were likely to be receiving good light exposure over the morning and whole day period, both on school days and at weekends. The mean readings suggested this was over 1000 lux in both instances. As a reference from previous studies (Scheuermaier, Laffan and Duffy, 2010) this is a possible indicator that participants were able to spend time outdoors and might also suggest that the school building was well lit for both visual and non-visual purposes. Time outdoors in the morning hours helps towards circadian entrainment. Blue spectral irradiance was higher during the school week compared to weekends across the daytime. This would suggest that during the school week participants had more mean blue light exposure (76$\mu W/cm^2$). Without

further investigation and comparing study locations in terms of illumination levels and blue light exposure it is difficult to fully understand the extent of how much light adolescents with ASD might receive across the school day or during weekend break. Evening illuminance levels and blue light exposure were relativity low at both times of the week. However prolonged exposure to low-level light prior to sleeping has been reported as a possible disrupter of circadian rhythms (Burgess, 2013; Wood *et al.*, 2013; Chang *et al.*, 2015).

There were associations between blue light exposure 4-hours prior to bedtime and reduced sleep efficiency, short total sleep time and a later bedtime. The same relationships, i.e. reduced sleep efficiency and later bedtime, were visible between the level illuminance pre-bedtime. In this study it was unknown as to the sources of evening light exposure e.g. was it the time of the year the study was conducted (i.e. springtime when the days are beginning to grow longer) or alternatively from light emitting from indoor sources. It would be beneficial to repeat this study at different points across the year and document behaviour prior to sleep. This would indicate were seasonal variations in light exposure were influential and/or if sources were from electrical light or backlit devices.

The findings from this research raise many questions in relation to the circadian patterns of adolescent with ASD. Does the school routine help to regularise the sleep/wake pattern or cause further sleep deprivation? Is light prior to bedtime a circadian disruption? How do adolescents with ASD differ from typically developing in terms of light exposure patterns? These questions can only be further understood with more research exploring the relationships between sleep, autism and light exposure. What is still left unknown is to what extent routine has impact and how different the weekday to weekend is in comparison to non-residential pupils or indeed typically developing adolescents.

How does the structured routine of the school week compare to that of the home routine?

In this pilot study the sleep habits of participants appear to indicate, that independent of time of week, participants have long periods of wake before sleep onset, later bedtime, and decreased total sleep time. According to studies in typically developing adolescents these are common characteristics (Carskadon, 1990), but is those with ASD they are often more pronounced (Richdale and Prior, 1995). Preliminary results from this study appear to be in line with other research. As a comparison, Wiggs and Stores (2004) found in girls with a diagnosis of ASD (n=38,age range 5 to 16 years) that the mean sleep onset latency was 72 minutes (i.e. it took 1 hour 12 minutes to fall asleep), mean total sleep time was 8 hours 55 minutes, mean wake after sleep onset 39 minutes and sleep efficiency 79%. Results from this pilot study were similar (e.g. the mean sleep onset latency 71 minutes, total sleep time was 7 hours, mean wake after sleep onset 38 minutes and sleep efficiency 78%). In this sample of adolescent boys the total sleep time was approximately an hour shorter in comparison to girls. It would suggest that the adolescent males with ASD in this study were experiencing a greater degree of sleep disturbance. From this exploratory study the unexpected result was the few number hours sleep both during weekdays and at weekends. Preliminary results indicate that for this sample the total sleep time was only 7 hours per night.

According to current recommendations by the National Health Service (NHS), adolescents require 9 hours of sleep per night. This would indicate that participants in this study do not have sufficient hours of sleep at night, independent of day of the week. Despite verbal reports from both staff and pupils that bedtime was between 21:30 and 22:00 sleep cycles commenced, on average, 2 to 2.5 hours later at approximately midnight. It is difficult to determine what the cause of this was. It could be for example an excess of blue light from electrical sources, an undiagnosed irregularity in melatonin rhythmicity or signs of typical adolescent sleep behaviour. The early school start time may also be a contributing factor to lack of sleep, which has been suggested by other studies as possible cause of sleep deprivation in adolescents (Hansen *et al.*, 2005; Figueiro *et al.*, 2011a). Does this provide further support that adolescents with autism would benefit from a change in the school start time? Studies have found that

adolescents in mainstream schooling show improved academic performance in the afternoon compared to mornings and report more feeling of wakefulness compared to mornings (Carskadon, 1990; Hansen *et al.*, 2005). Merikanto et al (2013) found that a later time to bed, particularly after 23:30, indicated poor sleep quality, which was detrimental to school performance.

In this current pilot study academic performance was not measured, but the mean time to bed was after 23:30. Future studies may wish to investigate this parallel to sleep and light exposure in ASD. The Wilcoxon signed-rank test suggested there was a difference in bedtime and wake time from weekdays to weekends. Changes in sleeping patterns from weekdays to weekends may not be uncommon (Hansen *et al.*, 2005). Adolescents falling asleep later in this study is consistent with other work that suggest during pubescent years there is a natural delay in the circadian sleep phases, i.e. they tend to fall asleep later and wake later than children (Hagenauer *et al.*, 2009). Adhering to an early rises on school days and suffering for delayed sleep onset has been reported to be causing sleep deprivation in adolescents (Figueiro *et al.*, 2011a; Sharkey *et al.*, 2011). Would an adjusted start time suit adolescents sleep cycles better and specifically help those with existing sleep problems?

The preliminary results from the pilot did suggest that although participants may not sleep for long enough at night there was at least a presence of routinized sleep that appeared to be regulated by the school structure. Findings also suggested that sleep patterns did not change significantly between weekdays to weekends in respect of total sleep time, sleep onset latency and sleep efficiency, but that bedtime and wake time did change significantly. Hansen *et al*. (2005) reported no changes in sleep patterns between weekdays and weekends during the academic year in typically developing adolescents i.e. the continual school routine maintains a degree of regularisation to sleep/wake cycles with a two day weekend not sufficient time for the circadian system to phase-shift out of synchronicity. This might suggest that adolescents with ASD in this study were displaying similar patterns to typical adolescents during the school term, i.e. only two days off at weekends is not sufficient time to see a shift in circadian

rhythms. Further studies exploring both populations are required to confirm this hypothesis.

Perhaps the potential degree of disruption in adolescents' with ASD during non-academic time was highlighted in the case study (section 3.5.4) through the participant who spent the week at home. In comparison to those who successfully completed the study protocol there was a marked degree of circadian disruption in this participant. A visual inspection of the actigraphy output showed a fragmented sleep/wake cycle, where the participant was displaying long periods of wake during the night and the reverse during daytime (see Figures 3.4 and 3.5). Does this tell us that although participants may not be getting the required amount of sleep during week, the school routine does help towards maintaining a regular lifestyle pattern?

In summary, this exploratory study established a protocol recording light exposure and the sleep/wake pattern of adolescents with autism using an actiwatch. The exploratory data analysis suggested interesting trends that warrant further studies in a larger sample. This would allow for a more robust test to better understand if relationships are significant and/or where differences may occur between those living in a residential school setting compared to those living at home.

Chapter 5 : A seasonal comparison of blue light exposure, illuminance levels and sleep/wake patterns of older people

5.1 Introduction

This chapter presents an overview of the pilot study and protocol development in relation to older people living in a residential care home. The study was replicated in two seasons, summer and winter. The results reported here included a description of the health, wellbeing and light exposure characteristics of the group, an investigation of the associations between these characteristics by season and finally how these differed over time (objective 3). These explorations used different statistical parameters e.g. descriptive statistics describing the sample, correlations exploring associations between variables and a within group test (Wilcoxon signed-rank test) to detect changes over time.

This chapter addresses the following research questions:

- What are the seasonal health and wellbeing characteristics of the group?
- What are the associations between health, wellbeing and light variables?
- Do health and wellbeing outcomes differ between seasons, measured by sleep/wake, activity, mental wellbeing and cognitive ability?
- Does light exposure differ between season,s measured by blue light irradiance, illuminance level and durations in specific exposure thresholds?

5.2 Pilot study and protocol development

(1) Participants and protocol

The pilot study was brought to the attention of the Royal National Institute of Blind People (RNIB) and Crossreach Care facilities. These organisations are interested in better understanding the impacts of light on sleep quality in the older adult population they support. Participants were recruited after initial discussions with the care staff. The researcher met with participants to explain the protocol, answer any questions, deliver

an information sheet and obtain signed consent (Appendices I and J). Additional written consent was sought from the participant's next of kin. Participants were informed that they could leave the study at any point without prior notice.

The study was carried out during summer 2013. This tested the feasibility of the protocol and allowed for a consideration of limitations. The aim was to assess personal illuminance levels and investigate possible associations between sleep/wake and activity in older people living in residential care homes (n=7). Participants wore an actiwatch for 3 days, which recorded continuously individual light and sleep/wake patterns. Participants were assessed by the Mini Mental State Exam (MMSE) as an initial screening tool to provide an indication of their cognitive ability (i.e. normal cognitive function or potentially impaired cognition). Subjective sleep quality was measured by the Pittsburgh Sleep Quality Index (PSQI). Staff kept a sleep diary on behalf of the participant for the duration of the study.

(2) Preliminary data investigation and results

Due to the small sample size investigative analysis on 7 participants would not be powered to detect a statistical significance, but the pilot data suggested trends in the expected direction. Firstly, correlational data suggested 1) a negative association between onset latency of sleep (time to fall asleep) and mean daytime illuminance level i.e. higher daytime illuminance suggested a shorter sleep latency, 2) a negative association between sleep onset latency and sleep efficiency i.e. a shorter sleep latency indicated a higher sleep efficiency and 3) a positive association between sleep efficiency and mean daytime illuminance, i.e. higher daytime illuminance was associated with higher sleep efficiency. These results gave further cause to explore possible associations in a large sample.

(3) Post-pilot protocol development

Post-pilot study the researcher met with the care home mangers and participants to seek feedback. The staff reported that keeping a sleep diary on behalf of participants was burdensome to their working routine and often found they had forgotten to complete the diary on the same day. Participants were happy with the protocol, with 4 people from

the pilot happy to carry forward to the main study. During the pilot study advanced actigraphy equipment became commercially available, which was capable of capturing a spectrum of light at specific bandwidths. Finally, during the pilot study continued meetings with ophthalmological specialists and emerging research in this field suggested that a visual assessment would be advantageous in the study design.

A review of the limitations and further literature searching suggested the full study could be strengthened and was amended in the following ways. Firstly, use of an actiwatch gathering spectral irradiances in addition to illuminance levels. In the pilot study actiwatches, gathering illuminance level only were borrowed from the Sleep Centre at the Edinburgh Royal Infirmary Hospital. Additional funding secured from the Scottish Government (Care and Support Division – Sensory Impairment) enabled the purchase of new equipment, more advanced in capturing a spectrum of coloured light irradiances. Secondly, a visual assessment was incorporated. During the pilot study further evidence emerged supporting the argument that a visual assessment was now pertinent to lighting research, in particular studies involving older people. Therefore, ophthalmologists were consulted at the Princess Alexandra Eye Pavilion, Edinburgh, in order to develop a visual assessment. Thirdly, an additional measure of cognitive ability (i.e. cognitive reaction time) and assessing mental wellbeing were added to the study design. Schmoll *et al.* (2011) reported an association between visual function, reaction time and sleep quality suggesting these as covariates (Schmoll *et al.*, 2011). Similarly, mental wellbeing in older people and the links to seasonal variations in light was considered another possible covariate of sleep quality (McKee, Harrison and Lee, 1999; Jean-Louis, Kripke and Ancoli-Israel, 2000; Carvalho-Bos *et al.*, 2007). Fourthly, the data collection was extended to 4 days and two body-mounted sensors (one on the wrist and one at lapel level) were positioned. Finally, the sleep diary kept by the care home staff was not carried forward into the main study. Staff reported this to be an onerous task during the pilot study.

(4) Full study protocol and additional recruitment

The protocol set out above was replicated, with modifications, in full during summer (n=20) and winter 2014 (n=16). To increase awareness of the research and to explain

more effectively the study the storyboard (created for the ASD study) visualising the research and commitment required for participation was used (Appendix G). To boost participant numbers the researcher joined the Scottish Dementia and Clinical Research Network (SDCRN) and attended the Care Homes Scotland conference to promote awareness. The SDCRN is a network and data base established to spread a culture of clinical research across Scotland and help to improve recruitment from care home facilities that have expressed an interest in participating. From this initial attempt, facilities contacted via the SDCRN network did not wish to participate in the research due to the excessive number of requests. This was likely due to the network being in its infancy and as the network grows it will gain momentum and the number of interested and willing care home facilities will increase with time.

In addition, the researcher contacted numerous care home facilities across central Scotland to further the awareness of the research. Facilities that expressed an interest in participating were visited and coffee mornings to engage participants were held at 5 additional potential venues from the pilot study. An identical recruitment procedure was used, i.e. the researcher met with the care home manager and participant to explain the protocol and gain written consent (with the additional next of kin consent sought). Upon completion of the study a small gift for participation was offered (funded by Heriot-Watt University, School of Energy, Geoscience, Infrastructure and Society). After the initial summer data collection participants were revisited at intervals until the repeat winter study. This helped towards participant retention i.e. to ensure they remained interested in the research and did not feel forgotten after the initial summer study before the winter data collection began.

5.3 Method

5.3.1 Participants

The sample that took part in this research consisted of 20 participants in summer and 16 participants in winter (male=3, female=17 summer, and male=3, female=13 repeated in winter). The mean age of the cohort was 85 years (SD=7, range 72-99 year). The

reduced participant numbers in winter were accounted for by, 1 participant who passed away, 2 chose to withdraw from the process and a lost dataset for 1 further participant during download.

5.3.2 Protocol

Each participant completed the cognitive assessments, mental wellbeing scale, visual tests and personal questionnaire (see Chapter 3). These were carried out with the researcher on a one-to-one basis on the first day of the study. The actiwatch was worn at the wrist and lapel for 4 days continuously, capturing personal sleep/wake, physical activity and personal light exposure patterns.

5.3.3 Study setting

In total six study settings were used ranging in architectural design and layout, an overview is provided in Table 5.1. They included 1) a refurbished Victorian period property (built between 1837-1901), with traditional large glazed south facing communal areas (i.e. living and dining spaces) and private bedrooms all facing west (Figure 5.1, venue used in pilot study), 2) one single story prefabricated home constructed during the 1970's, window and room sizes were of a domestic scale with room orientation predominantly south facing (Figure 5.2), 3) setting 3a, b, c were all low rise domestic style buildings constructed approximately 1990, with smaller window dimensions that are typical of more recent architectural design. The communal rooms and bedrooms in these locations faced either south or west (Figure 5.3, 5.4 and 5.5) and 4) a new build assisted living facility completed in 2013 (Figure 5.6). The design of this was based on the model that residents had their own separate apartment and had the use of communal facilities such as a function room, lounge and dining area. Apartments and rooms were orientated to face all aspects.

All of the facilities were located in central Scotland (the city of Edinburgh, Glasgow and county of Fife). They were a range of privately run and state funded care homes.

The interior décor of all facilities was finished in a traditional pallet of colours and patterns.

Table 5.1 Overview of study settings and participant numbers

Study setting	Summer	Winter
Study setting 1: refurbished Victorian period properties, estimated construction between 1837-1901	8	6
Study setting 2: single story prefabricated home constructed during the 1970's	2	2
Study setting 3a: low rise domestic style buildings constructed approximately 1990	2	2
Study setting 3b: low rise domestic style buildings constructed approximately 1990	2	2
Study setting 3c: low rise domestic style buildings constructed approximately 1990	1	1
Study setting 4: a new build assisted living facility completed in 2013	5	3
Total	20	16

Figure 5.1 Study setting 1

Figure 5.2 Study setting 2

Figure 5.3 Study setting 3a

Figure 5.4 Study setting 3b

Figure 5.5 study setting 3c

Figure 5.6 Study setting 4

5.4 Results

5.4.1 What are the seasonal health and wellbeing characteristics of the group?

The analysis in this first section explores descriptive statistics by season for the repeat cohort (n=16). Mean scores and standard deviations (SD) were investigated. The standard deviation indicates the extent of deviation or spread of scores in the group as a whole. A small SD would suggest that all scores are very close to the mean and large score would indicate there is more variance in the scores. Table 5.2 provides an overview of scores for each participant.

Table 5.2 Participant overview

ID	Age	MMSE		SRT (milliseconds)		WEMWES		Visual acuity		Contrast sensitivity		PSQI		TST (mins)		SOL (mins)		SE (%)		WASO (mins)		Wake up		Bedtime	
		S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W
1	76	28	29	358	347	70	65	1.05	1.20	.36	.34	7	8	339	375	52	26	65	80	120	67	07.28	07.78	22.45	23.54
2	71	14	16	1006	1124	69	66	1.50	1.35	.20	.52	1	0	468	362	7	17	72	70	72	70	10.36	06.48	21.45	22.14
3	87	18	25	1027	1011	45	47	.45	.75	.64	.60	9	8	335	351	22	13	80	88	41	57	05.48	11.18	22.48	01.32
4	78	15	18	1193	688	62	66	1.20	.90	.54	.58	12	12	412	615	32	41	84	82	40	99	06.29	06.15	22.21	23.53
5	92	29	29	1046	330	61	62	1.35	.90	.14	.52	6	5	441	528	22	83	83	76	47	73	06.31	07.13	21.47	20.14
6	81	13	13	1279	1069	50	49	1.20	1.05	.38	.54	6	10	222	273	5	22	70	85	124	21	04.38	04.30	22.42	23.08
7	83	28		1053		51		1.05		.22		6		949		82		75		174		12.53		15.54	
8	80	19	17	1170	1026	51	54	1.05	1.05	.56	.20	8	8	382	247	56	81	76	27	45	86	06.27	07.78	22.10	18.15
9	79	25	22	481	396	46	47	1.50	1.05	.42	.54	4	6	487	421	40	17	88	56	19	14	06.37	06.59	21.25	22.26
10	86	28	29	620	547	44	37	1.35	1.05	.04	.42	5	5	464	375	45	99	87	70	19	41	07.34	06.17	22.45	22.20
11	92	28	24	692	674	45	53	.90	.90	.30	.56	4	4	507	625	0	52	83	74	34	131	09.10	05.59	22.48	23.04
12	98	19	19	744	995	49	46	.00	.60	1.00	1.00	4	4	408	424	13	18	85	80	45	81	07.08	07.30	23.09	22.42
13	91	18	12	868	1145	47	32	.90	1.05	.70	.72	3	2	321	287	7	14	86	71	36	75	07.22	09.41	01.07	02.55
14	93	14		620		52		.90		.80		1		454		7		89		40		06.50		22.23	
15	88	25	19	1004	1013	34	38	1.05	.90	.32	.70	2	8	92	74	3	98	48	67	7	35	08.43	10.27	04.58	20.18
16	92	29	30	437	538	53	32	1.35	1.50	.10	.20	7	10	324	318	24	3	79	87	28	38	07.55	06.49	01.16	00.42
17	78	28		1146		60		1.50		.20		9		331		134		51		37		10.16		00.59	
18	90	29	30	312	319	52	52	1.05	1.05	.42	.56	8	5	604	373	135	82	70	77	108	43	9.35	10.22	23.40	01.59
19	89	28		471		43		1.65		.12		14		484		0		94		25		07.56		23.24	
20	82	29	30	741	611	60	62	1.35	1.20	.12	.28	11	9	403	505	146	71	69	64	61	158	07.47	07.31	21.11	21.15

Note: grey hatch represents data incomplete participant removed from statistical analysis
TST= total sleep time, SE=Sleep efficiency, WASO=Wake after sleep onset, MMSE= mini mental state examination, SRT=short reaction time, WEMWEBS= Warwick Edinburgh Mental Wellbeing Scale

(1) Health and wellbeing characteristics

Table 5.3 summarizes the mean scores (and SD) for the suite of health and wellbeing measures in two seasons, these include mental wellbeing, cognitive function, sleep/wake parameters, daytime physical activity level and visual function. Overall, the cohort did not display large differences in mean scores across the suite of measures. Mental wellbeing (WEMWBS), MMSE, simple reaction time (SRT) and subjective sleep assessments (PSQI) were alike in both seasons. In both seasons the WEMWBS scores suggested the cohort had average mental wellbeing. This state of mental wellbeing was derived from a Scottish Government report by Davidson *et al*. (2009) who reported a mean score of 42–59 could be classified as average mental wellbeing. The PSQI scores suggested poor sleep quality (>5 poor sleep quality) (Buysse *et al.*, 1989) in both seasons. Measures of visual function followed this trend, although visual acuity (the ability to distinguish fine detail) in the right eye did appear reduced in winter (.51) and compared to summer (.39) (note a lower score indicates better visual acuity see Table 4.2). The key outcomes, which presented most change in mean scores, were sleep parameters and daytime physical activity level. Firstly, there was very limited seasonal changes in total sleep time, sleep onset latency, sleep efficiency, and minutes awake during sleep (WASO) (Table 5.4). Results suggested in winter that bedtime was approximately 20 minutes earlier (23:13 summer and 23.34 winter) and wake up time 20 minutes later (07:26 in summer and 07:50 winter). Secondly, daytime physical activity was higher in summer (454 active counts) compared to winter (174 active counts). Many of the mean scores suggested that there was a large deviation from the mean, particularly in MMSE (SD=6), and SRT (SD=309 milliseconds) and daytime physical activity (SD=143 active counts) in summer. This builds evidence that the cohort has a range of cognitive ability and physical activity levels. These differences, and the implications of cognitive ability, are explored later in the chapter for their associations and difference between seasons.

Table 5.3 Mean scores for health measures in two seasons

		Summer	Winter
		Mean (SD)	**Mean (SD)**
Wellbeing	WEMWBS	52 (9)	50 (11)
Cognition	MMSE	22 (6)	22 (6)
	SRT (milliseconds)	811 (309)	740 (309)
Sleep/wake	PSQI	6 (3)	6 (3)
	Onset latency (minutes)	38 (43)	46 (34)
	Sleep efficiency (%)	76 (10)	72 (14)
	WASO (minutes)	53 (35)	68 (38)
	Sleep time (minutes)	388 (119)	385 (139)
	Bed time	23:34 (2)	23:13 (2)
	Wake time	07:26 (1)	07:50 (2)
Activity	Daytime physical activity	454 (143)	174 (43)
Visual function	CS right	1.07 (.39)	1.03 (.21)
	CS left	.93 (.47)	.90 (.47)
	VA right	.39 (.25)	.51 (.20)
	VA left	.54 (.49)	.52 (.49)

(2) Light exposure characteristics

Table 4.5 summarises the mean scores (and SD) across the series of light variables. Results suggest that light recordings were much higher in summer than in winter. Specifically, morning illuminance (466 lux summer, 65 lux winter) and morning blue light exposure (24 $\mu W/cm^2$ summer and 3 $\mu W/cm^2$ winter) were higher in summer. Durations in morning bright light thresholds, equally, were longer in the summer compared to winter e.g. time >1000 lux was 46 minutes in summer and only 3 minutes in winter. Again, these differences are explored later in the chapter for the significance level and indeed for their relationship to cognitive ability and daytime physical activity.

Table 5.4 Mean scores for light exposures in two seasons

	Summer	**Winter**
	Mean, SD	**Mean, SD**
Morning illuminance (lux)	466 (894)	65 (59)
Morning blue light ($\mu W/cm^2$)	24 (57)	3 (4)
Daytime illuminance (lux)	18 (41)	38 (42)
Daytime blue light ($\mu W/cm^2$)	360 (634)	51 (44)
Evening illuminance (lux)	151 (2)	20 (15)
Evening blue light ($\mu W/cm^2$)	5 (8)	.5 (.5)
Morn duration >1000 lux	46 (56)	3 (8)
Morn duration >100 $\mu W/cm^2$	24,(33)	2 (0)

In brief, between seasons the greatest mean differences were in the temporality of sleep/wake (i.e. bedtime and wake up time), daytime physical activity level and across the suite of measures for light exposures and durations in thresholds.

5.4.2 What are the associations between health, wellbeing and light variables by season?

The Spearman's rho bivariate correlations investigated associations between health variables only and between health and light variables each by season. Firstly, the summer associations are presented followed by the winter associations.

(1) Health measures: Spearman's rho bivariate correlations (summer)

The PSQI had a positive correlation with sleep onset latency (r_S=.46, p=0.037) indicating a higher perceived level of sleep disruption was associated with a longer time to fall asleep. Furthermore, sleep onset latency was positively associated with the number of wake bouts (r_S=.44, p=0.049), i.e. taking longer to fall asleep was associated with more night-time awakenings (Table 5.5). Daytime physical activity level was negatively associated with morning wake time (r_S=-.77, p=0.000) i.e. a later time to rise was associated with lower daytime physical activity (Table 5.5).

There was a significant negative association between MMSE and simple reaction time test (r_S=-.46, p=0.039) i.e. a lower MMSE score was associated with a slower reaction time. MMSE was positively associated with sleep onset latency (r_S=.46, p=0.039) i.e. higher cognitive function was associated with a longer time to fall asleep (Table 4.6). Finally, MMSE was negatively associated with visual acuity in both eyes (right eye, r_S=-.63, p=0.003), left eye r_S=-.55, p=0.011) i.e. lower cognitive function is associated with poorer visual acuity. A positive association with MMSE and contrasts sensitivity was found (r_S=.58, p=0.007) suggesting higher cognitive function is associated with better contrast sensitivity (Table 5.5).

Table 5.5 Health measures: Spearman's rho bivariate correlations (summer)

	WEMWBS	MMSE	SRT	PSQI	SOL	SE	WASO	TST	Wake time	Bedtime	Physical activity	CS right	CS left	VA right	VA left
WEMWBS	1														
MMSE	.09	1													
SRT	.11	-.46*	1												
PSQI	.18	.37	0.9	1											
SOL	.44	.46*	-.02	.46*	1										
SE	-.35	-.18	-.24	-.15	-.33	1									
WASO	.59**	-.05	.26	.14	.44*	-.43	1								
TST	-.01	.24	-.31	-.03	.11	.39	.11	1							
Wake time	.04	.44*	-.30	-.11	.10	.31	-.03	.37	1						
Bedtime	-.23	-.04	-.31	.18	-.20	.30	.15	.40	-.20	1					
Physical Activity	.24	-.13	.18	.25	.03	.31	.11	-.16	-.73**	.05	1				
CS right	.21	.29	-.03	.28	.14	-.03	-.17	.14	.24	-.28	.11	1			
CS left	.50*	.58**	-.16	.33	.24	-.43	.23	.05	.45*	-.07	-.21	.49*	1		
VA right	-.08	-.63**	.16	-.23	-.11	.19	.15	-.13	-.49*	.21	.15	-.72**	-.68**	1	
VA left	-.44*	-.55*	-.16	-.31	-.37	.34	-.26	-.06	-.22	.12	.04	-.40	-.83**	.68**	1

**correlation is significant at 0.01 (2-tailed), *correlation is significant at 0.05 (2-tailed). WEMWBS=mental wellbeing, MMSE=mini mental state examination, SRT=simple reaction time, PSQI=Pittsburgh sleep quality index, SOL=sleep onset latency, SE=sleep efficiency, WASO=wake after sleep onset, SOL=sleep onset latency, TST=total sleep time, CS=contrast sensitivity, VA=visual acuity

(2) Health and light measures: Spearman's rho bivariate correlations (summer)

To best convey the associations between health, wellbeing and light variables, only those relationships suggested to be significant are reported in the correlation matrix (Table 5.6). These variables include total sleep time, wake up time and average daytime activity. Exploratory correlations with the PSQI found a positive association with all light variables. It had been expected that a negative relationship would be observed i.e. as morning blue light exposure increases perceived sleep disruption decreases.

Results suggest a negative association between total sleep time and duration of exposure to 0-20 μW/cm^2 (r_s=-.48, p=0.032), i.e. longer periods of time spent on lower blue light thresholds were associated with shorter total sleep times. Time to wake and the blue light threshold 20-60 μW/cm^2 were negatively associated (r_s=-.47, p=0.035), i.e. longer durations of time spent in a threshold of 20-60 μW/cm^2 were associated with earlier wake up times (Table 5.6).

There were positive associations between the daytime physical activity level and the duration of exposure within the thresholds of 600-1000 lux (r_s=.48, p=0.029) and 20-60 μW/cm^2 (r_s=-.62, p=0.033) during the morning interval. This would indicate that the duration of exposure and the blue spectral intensity in the morning hours was associated with higher daytime activity levels (Table 5.6).

Table 5.6 Health and light variables: Spearman's rho bivariate correlations (summer)

	TST	Wake time	Physical activity	Morn illuminance	Morn BLE	Evening illuminance	Evening BLE	Daytime illuminance	Daytime BLE	>1000 lux	600-1000 lux	200-600 lux	50-200 lux	>100 $\mu W/cm^2$	60-100 $\mu W/cm^2$	20-60 $\mu W/cm^2$	0-20 $\mu W/cm^2$
TST	1																
Wake time	.04	1															
Physical activity	.37	-.16	1														
Morn illuminance	-.33	-.22	.38	1													
Morn BLE	-.26	-.20	.36	.98**	1.												
Evening illuminance	-.24	-.33	.22	.27	.27	1											
Evening BLE	-.12	-.26	.31	.27	.27	.93**	1										
Daytime illuminance	-.10	-.20	.18	-.22	-.23	-.09	-.11	1									
Daytime BLE	-.09	-.19	.13	-.26	-.28	-.08	-.12	.98**	1								
>1000 lux	-.33	-.23	.26	.91**	.92**	.40	.38	-.07	-.10	1							
600-1000lux	-.38	-.32	.48*	.70**	.65**	.16	.17	.08	.03	.67**	1						
200-600lux	-.09	-.43	.35	.24	.17	.04	-.00	-.06	-.04	.18	.52*	1					
50-200lux	-.02	-.22	.16	-.14	-.18	.11	.06	.13	.06	-.15	.22	.27	1				
>100 $\mu W/cm^2$	-.17	-.03	.22	.80**	.83**	.31	.36	-.14	-.	.83**	.37	-.20	-.21	1			
60-100 $\mu W/cm^2$	-.34	-.30	.271	.84**	.81**	.48*	.45*	-.09	-.11	.87**	.59**	.31	-.22	.62**	1		
20-60 $\mu W/cm^2$	-.31	-.47*	.62**	.68**	.61**	.36	.41	-.13	-.15	.56**	.73**	.56**	.14	.36	.72**	1	
0-20 $\mu W/cm^2$	-.48*	-.13	.09	-.06	-.13	.17	.15	-.13	-.16	-.14	.13	.08	.49*	-.23	.02	.30	1

**correlation is significant at 0.01 (2-tailed), *correlation is significant at 0.05 (2-tailed). TST=total sleep time, BLE=blue light exposure measure in $\mu W/cm^2$, Illuminance level measured in lux

(3) Health measures: Spearman's rho bivariate correlations (winter)

Daytime physical activity level was positively associated with sleep efficiency, (r_s=.61, p=0.011), i.e. higher daytime activity levels are associated with higher in sleep efficiency. The simple reaction time (SRT) test was negatively associated with total time asleep, (r_s=-.51, p=0.041), i.e. longer sleep times were associated with a faster reaction time test (Table 5.7).

The winter correlations identified a similar pattern as those in the summer in relation to cognitive ability and measures of visual function i.e. higher cognitive function was associated with better visual function. No other health variables returned significant associations.

Table 5.7 Health measures: Spearman's rho Bivariate correlations (winter)

	WEMWBS	MMSE	SRT	PSQI	SOL	Sleep efficiency	WASO	Total sleep time	Wake time	Bedtime	Physical activity	CS right	CS left	VA right	VA left
WEMWBS	1														
MMSE	-.01	1													
SRT	-.11	-.84**	1												
PSQI	.10	.19	-.11	1											
SOL	.19	.24	-.31	-.00	1										
Sleep efficiency	-.10	.13	-.10	.30	-.42	1									
WASO	.46	-.05	.15	-.15	.11	-.14	1								
Total sleep time	.42	.35	-.51*	-.14	.17	.05	.50*	1							
Wake time	-.20	.16	-.01	-.08	.02	.11	-.06	-.41	1						
Bedtime	.44	-.26	-.00	.08	.15	.06	.15	.45	-.57*	1					
Physical Activity	.04	.19	-.32	.30	.02	.61*	-.24	.34	-.46	.31	1				
CS right	.10	.20	-.09	.12	-.20	-.22	-.17	-.25	-.14	-.10	-.23	1			
CS left	.29	.17	.00	.25	-.07	.99	.01	-.21	-.32	-.07	.00	.74**	1		
VA right	-.28	-.41	.32	-.32	-.13	.24	-.01	.03	.23	.07	-.01	-.73**	-.77**	1	
VA left	-.07	-.60*	.29	-.29	-.17	-.06	-.09	.07	-.02	.41	-.14	-.42	-.65**	.76**	1

**correlation is significant at 0.01 (2-tailed), *correlation is significant at 0.05 (2-tailed). WEMWBS=mental wellbeing, MMSE=mini mental state examination, SRT=simple reaction time, PSQI=Pittsburgh sleep quality index, SOL=sleep onset latency, SE=sleep efficiency, WASO=wake after sleep onset, SOL=sleep onset latency, TST=total sleep time, CS=contrast sensitivity, VA=visual acuity

(4) Health and light measures: Spearman's Rho bivariate correlations (winter)

The PSQI and daytime blue light exposure were negatively associated (r_s=-.61, p=0.011), i.e. perceived sleep disruption is lower if blue light exposure is higher across the daytime (Table 5.8).

The MMSE was positively associated with the duration of time spent within a threshold of 600-1000 lux (r_s=.50, p=0.039), i.e. higher cognitive function was associated with longer periods of time spent in bright light (Table 5.8).

Table 5.8 Health and light variables: Spearman's rho bivariate correlations (summer)

	MMSE	PSQI	Physical activity	Morn illuminance	Morn BLE	Evening illuminance	Evening BLE	Daytime illuminance	Daytime BLE	>1000 lux	600-1000 lux	200-600 lux	50-200 lux	>100 μW/cm^2	60-100 μW/cm^2	20-60 μW/cm^2	0-20 μW/cm^2
MMSE	1																
PSQI	.19	1															
Physical activity	.19	.30	1														
Morn illuminance	-.01	.46	.06	1													
Morn BLE	-.05	.35	.05	.85**	1												
Evening illuminance	.10	.15	-.09	-.04	-.25	1											
Evening BLE	-.13	-.45	-.27	-.27	-.21	.40	1										
Daytime illuminance	.35	-.05	-.43	-.29	-.40	.58*	.14	1									
Daytime BLE	-.19	-.61*	-.57*	-.61*	-.50*	.05	.37	.52*	1								
>1000 lux	.29	.51*	.15	.51*	.54*	-.11	-.49	.06	-.33	1							
600-1000lux	.50*	.49*	.13	.40	.49	-.08	-.50*	-.01	-.47	.76**	1						
200-600lux	.00	.27	.11	.64**	.89**	-.18	-.12	-.46	-.42	.40	.52*	1					
50-200lux	.00	.70**	.18	.52*	.25	.47	-.20	.15	-.47	.12	.05	.05	1				
>100 μW/cm^2	-.20	.62*	-.05	.65**	.51*	.22	-.02	-.15	-.34	.16	.08	.45	.61*	1			
60-100 μW/cm^2	.13	.19	-.05	.58*	.85**	-.33	-.24	-.25	-.32	.67**	.61*	.77**	-.06	.17	1		
20-60 μW/cm^2	-.14	.10	-.23	.59*	.75**	-.44	-.23	-.23	-.12	.54*	.27	.53*	-.04	.23	.77**	1	
0-20 μW/cm^2	-.02	.34	-.09	.54*	.67**	-.48	-.32	-.29	-.21	.54*	.25	.48	.05	.39	.65**	.87**	1

**correlation is significant at 0.01 (2-tailed), *correlation is significant at 0.05 (2-tailed). MMSE=mini mental state examination, PSQI=Pittsburgh sleep quality index, BLE=blue light exposure measure in μW/cm^2, Illuminance level measured in lux

5.4.3 Do health and wellbeing outcomes, measured by sleep/wake, activity, mental wellbeing and cognitive ability differ between seasons?

The next analysis investigated differences between seasons, summer and winter, in the repeat sample (n=16). The Wilcoxon signed-rank test was used to explore differences in health and wellbeing outcomes and light measures across seasons. Firstly, health and wellbeing measures were investigated and secondly blue light exposure, illuminance levels and durations in specific light thresholds.

(1) Within group differences for health measures (n=16)

The main finding from the within group analysis suggested daytime activity level was significantly different. The Wilcoxon signed-rank test indicated daytime activity was higher in summer (mean=454 average active count) than in winter (median=174 average active count). As expected, participants were more active during the summer season (Z=-3.51, p=0.00) (Table 5.9, Figure 5.7)

Results also suggested a significant difference between visual acuity measured in the right eye between summer (mean=.39 logMAR) and winter (mean=.54 logMAR). This indicated visual acuity decreased from the first measurement, (Z=-2.44, p=0.05) (Table 5.9).

Table 5.9 Differences in health measures, mean (SD) and Wilcoxon signed-rank test across seasons

		Summer	Winter	Wilcoxon signed-rank test
		Mean (SD)	**Mean (SD)**	**Summer to winter (n=16)**
Wellbeing	WEMWBS	52 (9)	50 (11)	z=-.45, p= .64
Cognition	MMSE	22 (6)	22 (6)	z=-.17, p= .86
	SRT	811 (309)	740 (309)	z=-1.08, p= .27
Sleep/wake	PSQI	6 (3)	6 (3)	z=-.53, p= .62
	Onset latency	38 (43)	46 (34)	z=-.62, p= .53
	Sleep efficiency	76 (10)	72 (14)	z=-.59, p= .55
	WASO	53 (35)	68 (38)	z=-1.29, p= .19
	Sleep time	388 (119)	385 (139)	z=-.10, p= .98
	Bed time	23:34 (2)	23:13 (2)	z=-.62, p= .53
	Wake time	07:26 (1)	07:50 (2)	z=-.72, p= .46
Activity	Activity count	454 (143)	174 (43)	**z=-3.51, p=0.00, r=-.87**
Visual function	CS right	1.07 (.39)	1.03 (.21)	z=-.81, p= .41
	CS left	.93 (.47)	.90 (.47)	z=-.66, p= .50
	VA right	.39 (.25)	.51 (.20)	**z=-2.44, p=0.01, r=-.61**
	VA left	.54 (.49)	.52 (.49)	z=-.56, p= .57

Bold type indicates a statistically significant result

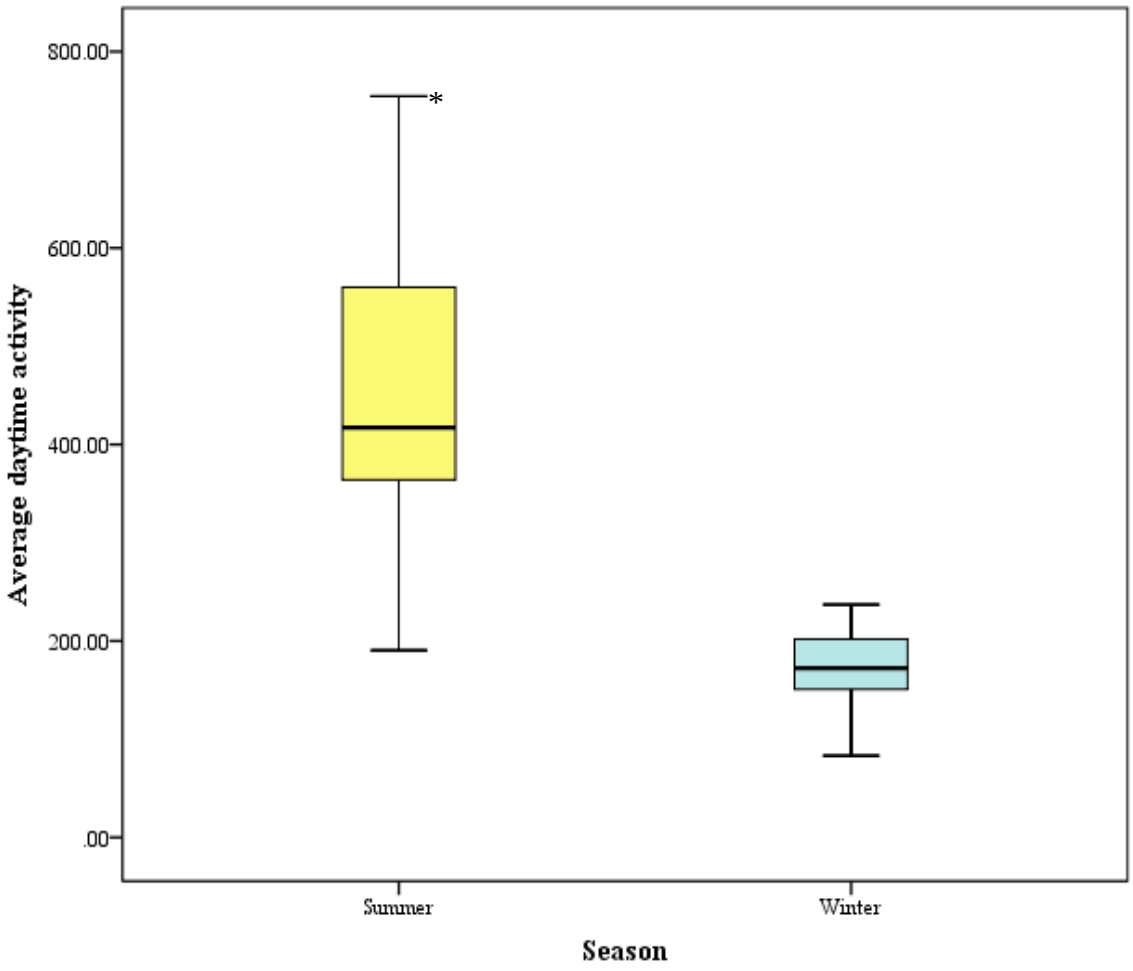


Figure 5.7 Difference in daytime activity level between seasons

5.4.4 Does light exposure differ between seasons measured by blue light irradiance, illuminance level and durations in specific exposure thresholds?

(1) Within group differences for light exposure and durations in light threshold measures (n=16)

Results indicated statistically significant seasonal variances on the suite of light measures (see Table 5.10 below). Morning blue light exposure (Z=-3.00, *p*=0.03) and morning illuminance level (Z=-2.98, *p*=0.04) were both significantly higher in summer. Similarly, participants spent longer durations in bright light thresholds in summer compared to winter (Z=-2.91, *p*=0.04). The corresponding blue light threshold of 100 $\mu W/cm^2$ was significantly different between seasons also (Z=-2.66, *p*=0.00). The duration of time spent in 1000 lux or greater has been defined in previous studies as an indicator of time outdoors (Scheuermaier, Laffan and Duffy, 2010). Results may be an important insight into the limited amount of time older people spend outdoors in the winter months (also see Figure 5.8, 5.9 and 5.10).

Table 5.10 Differences in light measures, mean (SD) and Wilcoxon signed-rank test across seasons

	Summer	**Winter**	**Wilcoxon signed-rank test**
	Mean, SD	**Mean, SD**	**Summer to winter (n=16)**
Morning illuminance (lux)	466 (894)	65 (59)	**z=-2.89, p= 0.04, r=-.72**
Morning blue light ($\mu W/cm^2$)	24 (57)	3 (4)	**z=-3.00, p=0.03, r=-.75**
Daytime illuminance (lux)	18 (41)	38 (42)	**z=-2.99, p=0.03, r=-.74**
Daytime blue light ($\mu W/cm^2$)	360 (634)	51 (44)	**z=-3.25, p=0.04, r=-.81**
Evening illuminance (lux)	151 (2)	20 (15)	**z=-3.15, p=0.02, r=-.55**
Evening blue light ($\mu W/cm^2$)	5 (8)	.5 (.5)	**z=-3.36, p=0.01, r=-.54**
Morn duration >1000 lux	46 (56)	3 (8)	**z=-2.91, p=0.04, r=-.72**
Morn duration >100 $\mu W/cm^2$	24,(33)	2 (0)	**z=-2.66, p=0.00, r=-.66**

Bold type indicates a statistically significant result

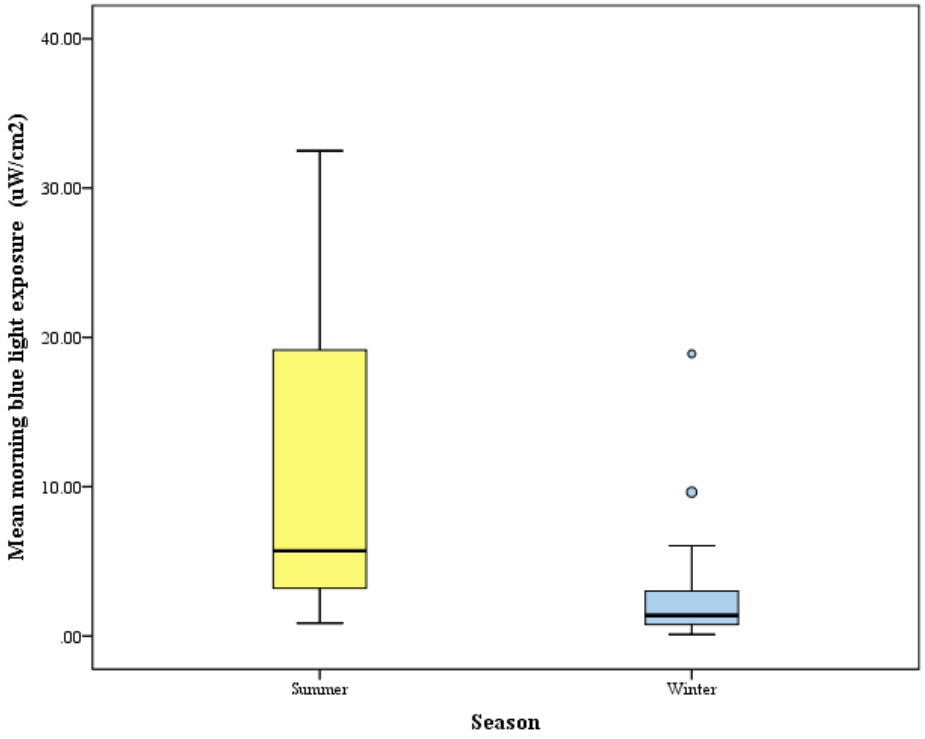


Figure 5.8 Seasonal differences in blue light exposure levels

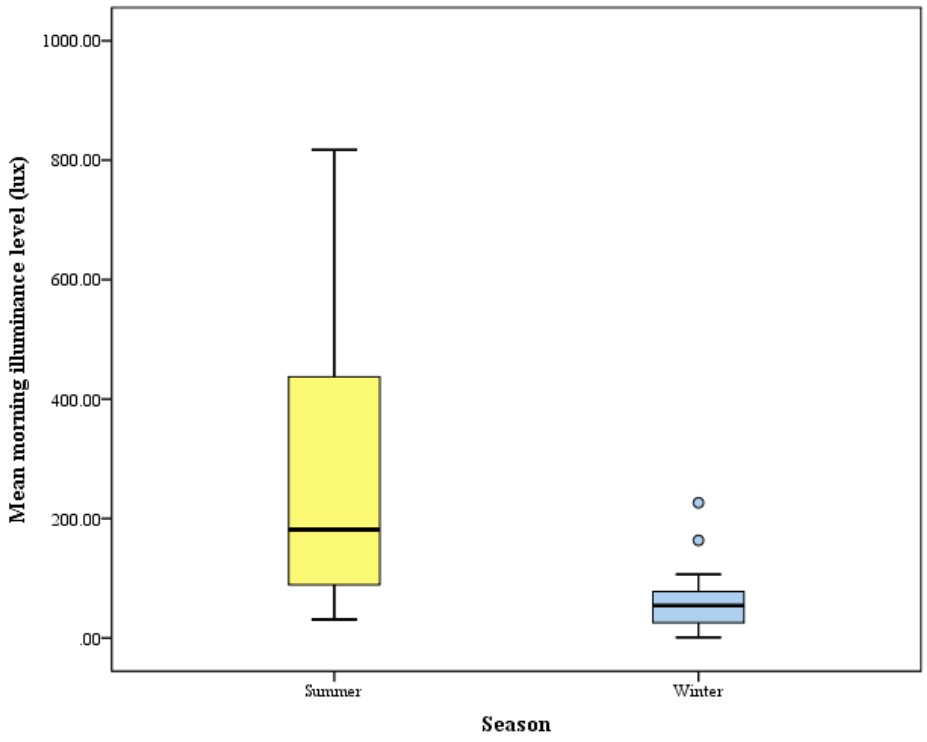


Figure 5.9 Seasonal differences in illuminance levels

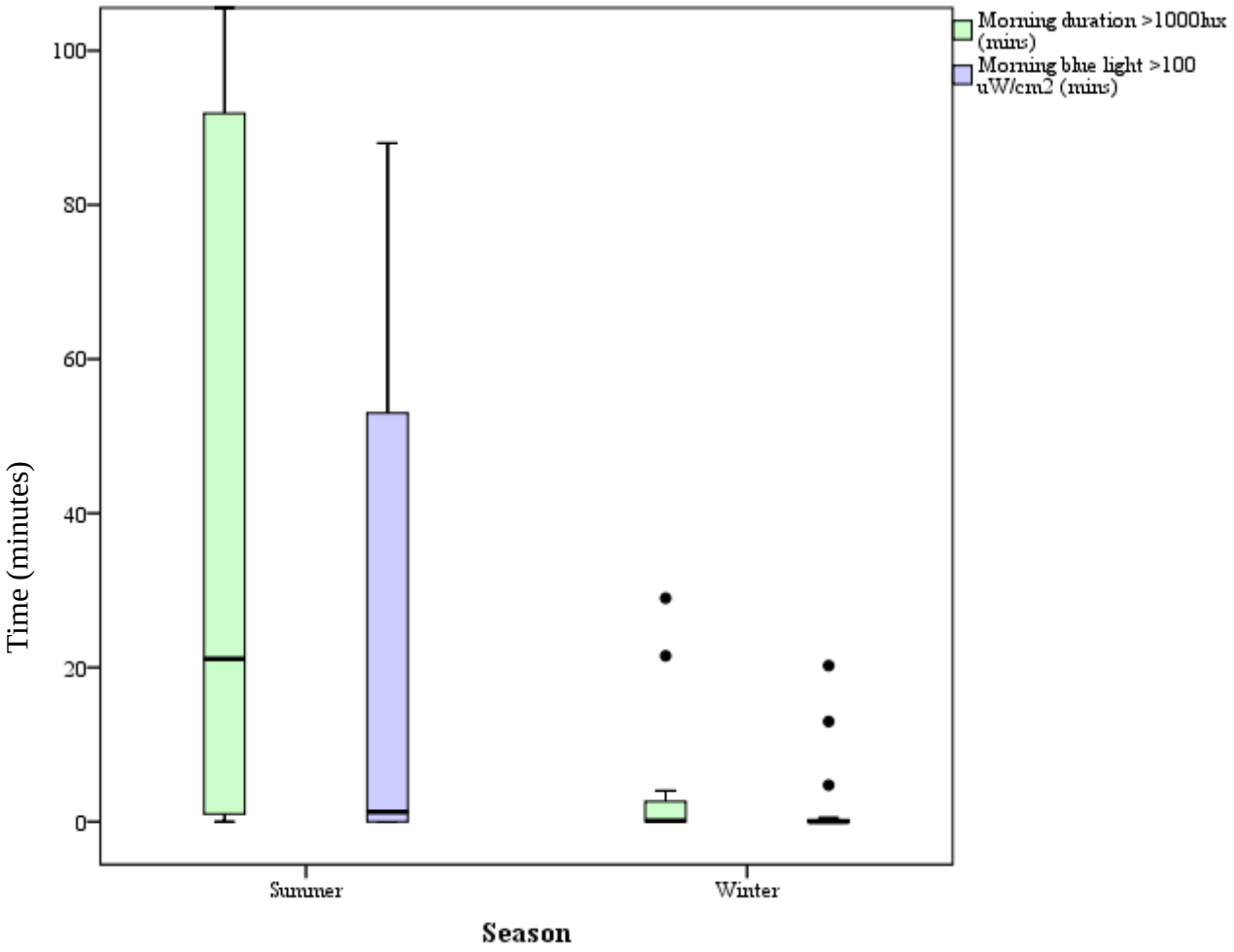


Figure 5.10 Durations in blue light (>100 µW/cm2) and illuminance thresholds (> 1000 lux)

5.5 Summary of results

(1) Characteristics of the cohort by season

The mean descriptive statistics suggested differences in scores between seasons most predominantly for bedtime, wake up time and daytime activity levels. The deviations from the mean also indicated possible differences could exist for cognitive ability. Likewise, all light measurements were higher in summer and again the standard deviations from the mean would suggest that participants had a range of light exposure levels, particularly in the summer months.

(2) Associations between variables (summer)

In summary, associations between cognitive function, sleep and visual performance were in the expected direction, although not all of these relationships were statistically significant. Higher cognitive function was negatively associated with a faster reaction time and better visual acuity and positively associated with contrast sensitivity. Higher cognition was not significantly correlated with higher mental wellbeing or sleep parameters, such as sleep onset latency or number of wake bouts.

Associations between the subjective sleep measure and objective sleep measures were in the direction expected, i.e. self-rating poor sleep quality lead to a decrease in objective sleep latency. Associations between daytime physical activity and wake time were in the direction anticipated, i.e. a later wake up time was associated with a decrease in daytime activity levels. Associations between cognitive measures and light variables were not significant. Expected results included a negative association between total sleep time 0-20 $\mu W/cm^2$ and a negative association between wake up time and 20-60 $\mu W/cm^2$. These findings suggest that spending longer periods in the morning in light lacking in blue spectral irradiance may be associated with less sleep at night, whilst increased durations in blue light may be associated with an earlier time to wake.

Finally, higher levels of daytime activity were associated with more minutes spent in illuminance thresholds of 600-1000 lux and 20-60 $\mu W/cm^2$. No other blue light exposure, illuminance levels or durations in thresholds met the expected associations.

(3) Associations between variables (winter)

In summary, higher cognitive function was associated with faster cognitive reaction time. Higher cognitive function was also associated with better visual acuity in the left eye only, other visual measures continued in the expected directions, but were not significantly associated. This result was unexpected, as the summer study had suggested associations with visual acuity in both eyes and similarly with contrast sensitivity. Faster cognitive reaction time was associated with total sleep time, this was as expected. Higher daytime physical activity was associated with sleep efficiency in the direction expected.

Associations between light exposure and cognitive function measures were in the expected direction for the duration of time spent in the ambient light threshold of 600-1000 lux.

(*4) Within groups differences*

- Between seasons the cohort had significantly higher daytime physical activity levels i.e. during the summer months this was higher.
- Results suggested across the cohort measures of visual acuity were poorer from first to second measure.
- Sleep measures did not change significantly between seasons. Although mean readings demonstrated a difference for sleep efficiency, total sleep time and number of awakenings.
- Wellbeing scores were not statically different from season to season.

5.6 Discussion

What are the seasonal health and wellbeing characteristics of the group?

The explorative descriptive means suggested the variables of most interest were bedtime, wake up time and daytime physical activity. Between seasons there appeared to be an earlier time to bed and later time to wake in winter. This sleep variance is in line with other seasonal sleep studies. Kohsaka *et al*. (1992) and Hubert, Dumont and Paquet (1998), reported total sleep time may be the same in both seasons, but the phase of the sleep cycle may advance in summer with an earlier wake up time. Likewise, daytime physical activity was higher in summer compared to winter, which is in line with current literature (Cheadle, 2006; Moschny *et al.*, 2011). There were mean differences across other sleep measures (e.g. sleep onset latency, wake after sleep onset and sleep efficiency) but these were less pronounced. Other health and wellbeing measures, such as subjective sleep quality (PSQI), mental wellbeing (WEMWBS), cognitive reaction time and visual function scored similarly in each season. The spread of scores in relations to MMSE suggested the cohort ranged in cognitive ability.

What are the associations between health, wellbeing and light variables?

Although differences in mean scores for objective sleep measure were not markedly different there were interesting associations emerging in the data. The Spearman's rho correlations for the summer data suggested a positive association between subjective self-rating sleep (PSQI) and objective measures of sleep onset latency. A higher perceived sleep disruption was associated with longer sleep latency, which was also positively associated with the total number of continuous wake bouts during the sleep cycle. These relationships may be common in an ageing population and are consistent with findings from a cross-sectional study by Middelkoop *et al*. (1996). The author reported (measuring subjective sleep quality) sleep disorders are common in older people and increasing was age associated with more frequent night-time awakenings ($p<0.001$) with females self-reporting significantly poorer sleep quality ($p<0.01$) and longer sleep onset latency ($p<0.01$). This current study poses further questions; *Does worrying about falling asleep delay sleep onset? Does taking longer to fall asleep cause frequent wake bouts during the sleep cycle?* The associations reported in this current

study help to build evidence of the possible links between perceptions of sleep quality and objective sleep performance in older people.

In addition, findings from the summer study suggested a positive association between daytime physical activity and wake up time, i.e. a later wake up time was associated with lower daytime activity. In the winter associations between sleep measures held a similar trend, but relationships were not significant i.e. a positive association between daytime physical activity and sleep efficiency. This finding, in conjunction with current evidence, highlights that in order to consolidate sleep in older people measures should be taken to promote daytime physical activity and reduce long periods of sedentary behaviours (Kuck, Pantke and Flick, 2014; Chennaoui *et al.*, 2015). If activity were combined with time outdoors would further benefits to sleep quality be observed?

In each season explorations suggested no associations between mental wellbeing (WEMWBS) and other health measures or light variables. It was expected that sleep quality parameters such as sleep efficiency or fewer night awakenings would be associated with better mental wellbeing. Other studies in older people have suggested that mental wellbeing may be strongly correlated with a robust rest/activity rhythm (Carvalho-Bos *et al.*, 2007).

This study found interesting associations between the MMSE, visual acuity and contrast sensitivity. In the summer correlations there was a significant negative association between both right and left visual acuity measures and MMSE, suggesting better cognitive function was associated with better visual acuity. Similarly, there was a significant positive association between MMSE and contrast sensitivity in the left eyes, posing the same association (Dhillon and Lascaratos, 2009; Schmoll *et al.*, 2011; Nylén *et al.*, 2014). These simple correlations raise many interesting questions and support existing evidence of the relationship between cognition, vision and sleep quality in older people (Sander *et al.*, 2015). There is already evidence to suggest an association between declining cognitive function and poorer visual function (Salthouse *et al.*, 1996; Clemons, Rankin and McBee, 2006; Fleur and Salthouse, 2014). Clemons and colleagues reported that poorer visual function was associated with a lower MMSE

score (i.e. potential cognitive impairment) (p<0.05). However, current literature suggests differences in circadian patterns based on cognitive function and ageing older people (Czeisler and Dumont, 1992; Fetveit and Bjorvatn, 2006). Therefore, it would seem sensible for future studies to explore three measures; 1) light exposure, 2) objective sleep patterns and 3) visual function, to establish circadian patterns and the quality of care home environments for older people.

Do health and wellbeing outcomes differ between seasons measured by sleep/wake, activity, mental wellbeing and cognitive ability?

Result from the within group analysis suggested a significant difference in daytime physical activity level between seasons, i.e. participants had higher daytime physical activity levels in summer compared to winter. This finding is supported by reports that humans are more active in the summer months (Cheadle, 2006; Moschny *et al.*, 2011). Furthermore, Sumukadas *et al*. (2009) stated not only seasonal difference can influence physical activity levels, but length of day and hours of sunshine can have a profound effect on older people. In this research length of day or hours of sunshine/daylight were not analyzed, although in future studies it may be a valuable exercise to conduct, particularly the influence of weather patterns and hours of sunshine. The area of interest in this study was an exploration of time and duration of exposure and the possible associations with sleep and/or physical activity measures. Unexpectedly, objective measures of sleep quality (e.g. total sleep time, sleep onset latency, wake after sleep onset, sleep efficiency, wake up time and bedtime) did not differ significantly between seasons. Based upon the works of Kohsaka *et al*. (1992), Hubert, Dumont and Paquet (1998) and Figuerio *et al*. (2012) seasonal differences in sleep patterns were expected to be more pronounced. For example a phase-shift in bedtime and wake time was expected. Although, a later bedtime and earlier wake time in summer was present in this study it was not significantly different. Not only were there no significant differences in objective sleep outcomes, but also in subjective self-reporting sleep quality (PSQI). The mean PSQI score was 6, this was true in both seasonal measures (a score >5 is considered poor sleep quality). In this particular cohort all participants felt they had poor sleep quality. It was expected that self-reported sleep quality would be better in summer. Anderson *et al*. (2014) found that self-reported abnormalities in the sleep/wake

cycle were associated with a decline in cognitive function. This association will be explored between groups based on cognitive ability in the following chapter (5). It may be that changes in sleep parameters are dependent upon cognitive ability and not only season.

Finally, results for visual function outcomes suggested, for the repeat cohort (n=16), from summer to winter measures of visual acuity did not change significantly, but contrast sensitivity did (i.e. the ability to distinguish between objects). Contrast sensitivity was lower in winter than summer. Changes in this measure may be a genuine decline in visual functioning, but could also be caused by personal factors such as differing mood or alertness and concentration ability on the day of assessment, thus resulting in the participant reading the chart differently. Alternatively, unavoidable inconsistences such as sitting further away from the test chart, the angle of the test boards (these had to be propped up in various fashions with items present in the room, e.g. chairs), lower light levels or more glare from windows in the room may have contributed to this change. In future studies the following adaptation could help to improve consistency, for example an internally illuminated box chart, would give a more consistent brightness for reading, limiting glare from the glossy surface of the chart and maintaining a fixed angle at which to view the chart.

Does light exposure differ between seasons measured by blue light irradiance, illuminance level and durations in specific exposure thresholds?

As expected, light exposure recordings made in this research were significantly different between seasons, i.e. the morning (p=0.03), whole day (p=0.04) blue light and morning (p=0.04), whole day (p=0.03) illuminance levels were significantly higher in summer than in the winter. These findings are consistent with the cross-sectional study by Thorne *et al*. (2009), who also reported a significant difference in seasonal light across the daytime (p=0.0002) and blue spectral contribution of light (p=0.0006), i.e. these were greater in summer compared to winter. Overall, the readings recorded in winter for this research were much lower than those in summer. However, even the summer readings were low and are reflective of the existing work (Shochat *et al.*, 2000; De Lepeleire *et al.*, 2007; Sinoo, van Hoof and Kort, 2011). This research has indicated that

the cohort living in care homes did not receive high levels of illuminance in either season. This highlights a need to improve lighting provisions in care homes, particularly in northern countries where natural light is limited in winter months.

In this cohort the mean duration of time above 1000 lux was 46 minutes during the summer and only 3 minutes during the winter. This result was statistically different. Because the durations above 1000 lux in winter was very low, it would be reasonable to assume that for most participants time outdoors was very limited. There is the caveat that clothing could have covered light sensors. It is not uncommon for people (independent of age) to spend fewer minutes during the daytime in light >1000 lux, particularly amongst those living at higher latitudes (Cole *et al.*, 1995; Hubert, Dumont and Paquet, 1998). However, the findings here would suggest there is a need to facilitate more time outside and/or to create indoor environments that can mimic qualities of spending time outdoors i.e. better quality lighting.

In summary, correlations indicated interesting trends between cognitive ability, sleep quality parameters and daytime physical activity levels. It was suggested that higher cognitive function was associated with a faster reaction time, and better visual acuity. Results also suggested that higher levels of daytime physical activity were associated with higher sleep efficiency. It was also reported that higher daytime physical activity levels were associated with longer durations in brighter light illuminance thresholds (600-1000 lux). Between seasons investigations indicated sleep/wake patterns did not differ significantly, but daytime physical activity levels were, i.e. physical activity levels were much higher in summer. Light exposures and durations in thresholds were also significantly different between seasons, i.e. these were much higher and longer in summer.

Chapter 6 : Between group analysis based on cognitive ability and exploring predictors of sleep quality in older people

6.1 Introduction

This chapter presents the findings of the between group analysis examining the differences in health, wellbeing and light exposures based on cognitive ability and investigates possible predictors of sleep quality (objective 4). The cohort was divided into two groups using the MMSE (described in the previous chapter). A set of nonparametric Mann-Whitney U tests was used to explore the differences between groups. It was the intention in this chapter to investigate predictors of sleep quality and to better understand the potential impacts of individual discriminants such as age, cognition, visual function and activity level. A new form of high dimensional correlated component regression modelling was used for this analysis.

This chapter addresses the following research questions:

- How do health and wellbeing outcomes, measured by sleep/wake, activity and mental wellbeing differ between groups and by season?
- Does light exposure, measured by blue light irradiance, illuminance level and durations in specific exposure thresholds, differ between groups and by season?
- Does light exposure (blue light exposure, illuminance level or duration in light thresholds) predict sleep quality (measured by total time asleep, sleep efficiency or sleep onset latency) and cognitive reaction time?

6.2 Method

To investigate differences, the sample was split using the MMSE. Results identified two groups, 1) score of >23 categorised as normal cognitive function or 2) score of <19 categorised as potentially impaired cognition. In summer (n=20) the cohort divided into: 1) normal cognitive function=12 and 2) potentially impaired cognition=8, in winter

(n=16) the cohort divided into: 1) normal cognitive function=9 and 2) potentially impaired cognition=7. Health and wellbeing, measured by mental wellbeing (WEMWBS), simple reaction (SRT), visual function, sleep parameters and daytime physical activity levels were investigated. Light exposures and durations in specific thresholds were explored between groups by seasons. For the purpose of these tests the summer group were analysed with 20 participants and the winter data with the reduced number of 16 participants (Table 6.1 provides an overview of participants).

Table 6.1Participant overview

ID	Age	MMSE		SRT (milliseconds)		WEMWES		Visual acuity		Contrast sensitivity		PSQI		TST (mins)		SOL (mins)		SE (%)		WASO (mins)		Wake up		Bedtime	
		S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W
1	76	28	29	358	347	70	65	1.05	1.20	.36	.34	7	8	339	375	52	26	65	80	120	67	07.28	07.78	22.45	23.54
2	71	14	16	1006	1124	69	66	1.50	1.35	.20	.52	1	0	468	362	7	17	72	70	72	70	10.36	06.48	21.45	22.14
3	87	18	25	1027	1011	45	47	.45	.75	.64	.60	9	8	335	351	22	13	80	88	41	57	05.48	11.18	22.48	01.32
4	78	15	18	1193	688	62	66	1.20	.90	.54	.58	12	12	412	615	32	41	84	82	40	99	06.29	06.15	22.21	23.53
5	92	29	29	1046	330	61	62	1.35	.90	.14	.52	6	5	441	528	22	83	83	76	47	73	06.31	07.13	21.47	20.14
6	81	13	13	1279	1069	50	49	1.20	1.05	.38	.54	6	10	222	273	5	22	70	85	124	21	04.38	04.30	22.42	23.08
7	83	28		1053		51		1.05		.22		6		949		82		75		174		12.53		15.54	
8	80	19	17	1170	1026	51	54	1.05	1.05	.56	.20	8	8	382	247	56	81	76	27	45	86	06.27	07.78	22.10	18.15
9	79	25	22	481	396	46	47	1.50	1.05	.42	.54	4	6	487	421	40	17	88	56	19	14	06.37	06.59	21.25	22.26
10	86	28	29	620	547	44	37	1.35	1.05	.04	.42	5	5	464	375	45	99	87	70	19	41	07.34	06.17	22.45	22.20
11	92	28	24	692	674	45	53	.90	.90	.30	.56	4	4	507	625	0	52	83	74	34	131	09.10	05.59	22.48	23.04
12	98	19	19	744	995	49	46	.00	.60	1.00	1.00	4	4	408	424	13	18	85	80	45	81	07.08	07.30	23.09	22.42
13	91	18	12	868	1145	47	32	.90	1.05	.70	.72	3	2	321	287	7	14	86	71	36	75	07.22	09.41	01.07	02.55
14	93	14		620		52		.90		.80		1		454		7		89		40		06.50		22.23	
15	88	25	19	1004	1013	34	38	1.05	.90	.32	.70	2	8	92	74	3	98	48	67	7	35	08.43	10.27	04.58	20.18
16	92	29	30	437	538	53	32	1.35	1.50	.10	.20	7	10	324	318	24	3	79	87	28	38	07.55	06.49	01.16	00.42
17	78	28		1146		60		1.50		.20		9		331		134		51		37		10.16		00.59	
18	90	29	30	312	319	52	52	1.05	1.05	.42	.56	8	5	604	373	135	82	70	77	108	43	9.35	10.22	23.40	01.59
19	89	28		471		43		1.65		.12		14		484		0		94		25		07.56		23.24	
20	82	29	30	741	611	60	62	1.35	1.20	.12	.28	11	9	403	505	146	71	69	64	61	158	07.47	07.31	21.11	21.15

Note: grey hatch represents data incomplete participant removed from statistical analysis
TST= total sleep time, SE=Sleep efficiency, WASO=Wake after sleep onset, MMSE= mini mental state examination, SRT=short reaction time, WEMWEBS= Warwick Edinburgh Mental Wellbeing Scale

6.3 Results

6.3.1 How do health and wellbeing outcomes, measured by sleep/wake, activity, mental wellbeing and visual function, differ between groups and by season?

(1) Between group difference for health measures (summer, n=20)

Results suggested that time to wake differed significantly between groups normal cognitive function (mean=8:02am) and potentially impaired cognition (mean=7:02am), suggesting those with potentially impaired cognition woke earlier (U=17.00, p=0.01) (Table 6.2 and Figure 6.1). No other objective sleep/wake parameters, subjective sleep quality or daytime physical activity level were found to be significantly different. Findings also suggested the simple reaction time test was significantly faster in the normal cognitive function group (mean=632 milliseconds) compared to the potentially impaired cognition group (mean=1041 milliseconds) (U=21.00, p=0.03), (Table 6.2, Figure 6.2). Likewise, visual acuity differed significantly in the right eye only, normal cognition (mean=0.24 logMAR) or potentially impaired cognition (mean=0.57 logMAR), i.e. those with normal cognition had better visual acuity in the right eye (U=8.50, p=0.002) (Table 6.2). Measures of contrast sensitivity were not found to be significantly different.

Table 6.2 Differences in health measures, mean (SD) and Mann-Whitney U (summer)

		N=20	NC, n= 12	PIC, n= 8	
		Mean (SD)	**Mean (SD)**	**Mean (SD)**	**Mann-Whitney U**
Wellbeing	WEMWBS	52 (9)	51 (10)	53 (8)	U=43.50, z=-.34, p=0.72
Cognition	MMSE	23 (6)	27 (1)	16 (2)	**U=.00, z=-3.77, p=0.005, r=-0.84**
	SRT (milliseconds)	813 (304)	632 (265)	1041 (189)	**U=21.00, z=-2.08, p=0.03, r=-0.46**
Sleep	PSQI	6 (3)	6 (2)	6 (3)	U=37.00, z=-.8, p=0.395
	Sleep onset latency (mins)	41 (47)	52 (53)	20 (18)	U=31.50, z=-1.27, p=0.2
	Sleep efficiency (%)	77 (12)	75 (13)	79 (6)	U=36.00, z=-.92, p=0.35
	WASO (mins)	56 (42)	49 (40)	57 (31)	U=35.00, z=-1.00, p=0.31
	Sleep time (mins)	421 (166)	449 (212)	388 (83)	U=32.00, z=-1.23, p=0.21
	Bedtime	23:03 (3)	23:17 (3)	22:47 (1)	U=41.50, z=-.50, p=0.61
	Wake time	08.05 (2)	8.08 (1)	7.02 (1)	**U=17.00, z=-2.39, p=0.01, r=-.53**
Activity	Average active count	421 (148)	425 (153)	493 (30)	U=30.00, z=-1.38, p=0.16
Vision	CS right eye	1.11 (.38)	1.2 (20)	.90 (51)	U=24.00, z=-1.87, p=0.06
	CS left eye	.97 (.44)	1.0(.46)	.75 (45)	U=23.00, -1.94, p=0.05
	VA right eye	.37 (.25)	.24 (14)	.57 (25)	**U=8.50, z=-3.05, p=0.002, r=-.68**
	VA left eye	.52(.44)	.43 (48)	.68 (49)	U=28.00, z=-1.54, p=0.12

Bold type indicates a statistically significant result

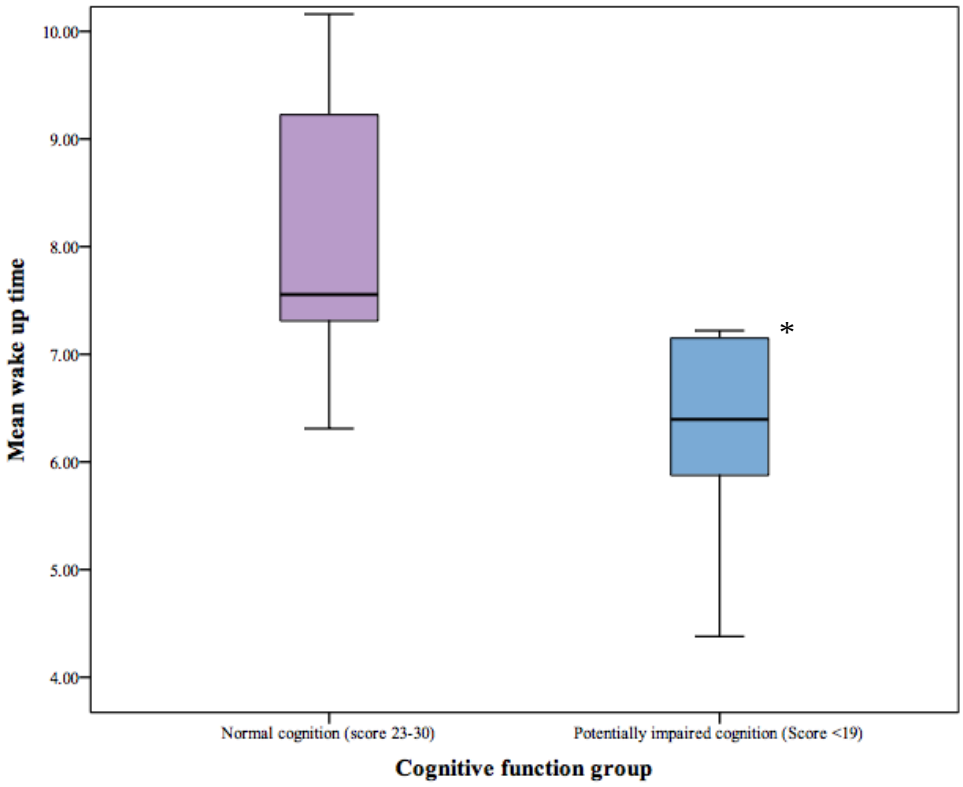


Figure 6.1 Between group differences for mean wake up time (summer)

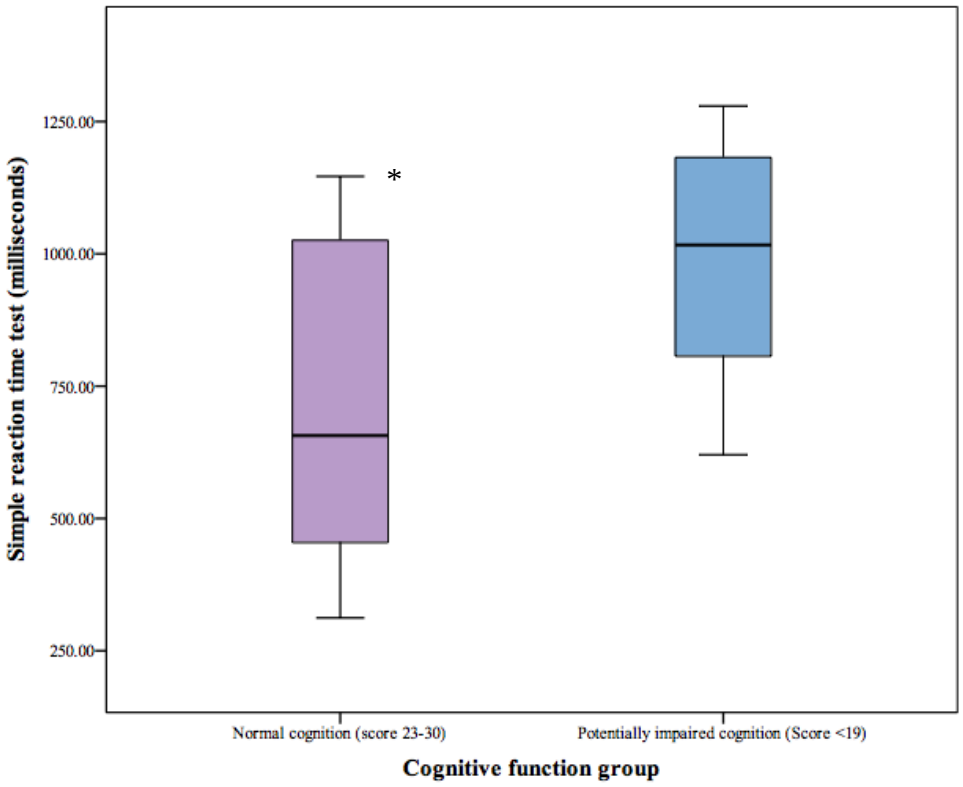


Figure 6.2 Between group differences for simple reaction time test (summer)

(2) Between group difference for health measures (winter, n=16)

In winter, results followed a similar trend to summer. For health measures i.e. objective sleep/wake parameters, subjective sleep quality, daytime activity and mental wellbeing or contrast sensitivity, no statistical differences between groups were recorded. The same significant differences was present for the simple relation time test (U=2.00, *p*=0.02) (Table 6.3, Figure 6.3). Visual acuity differed significantly in the left eye, suggesting this was better for those with normal cognitive function (mean=.39 logMAR) compared to those with potentially impaired cognition (mean=.78 logMAR) (U=13.00, *p*=0.05) (Table 6.3).

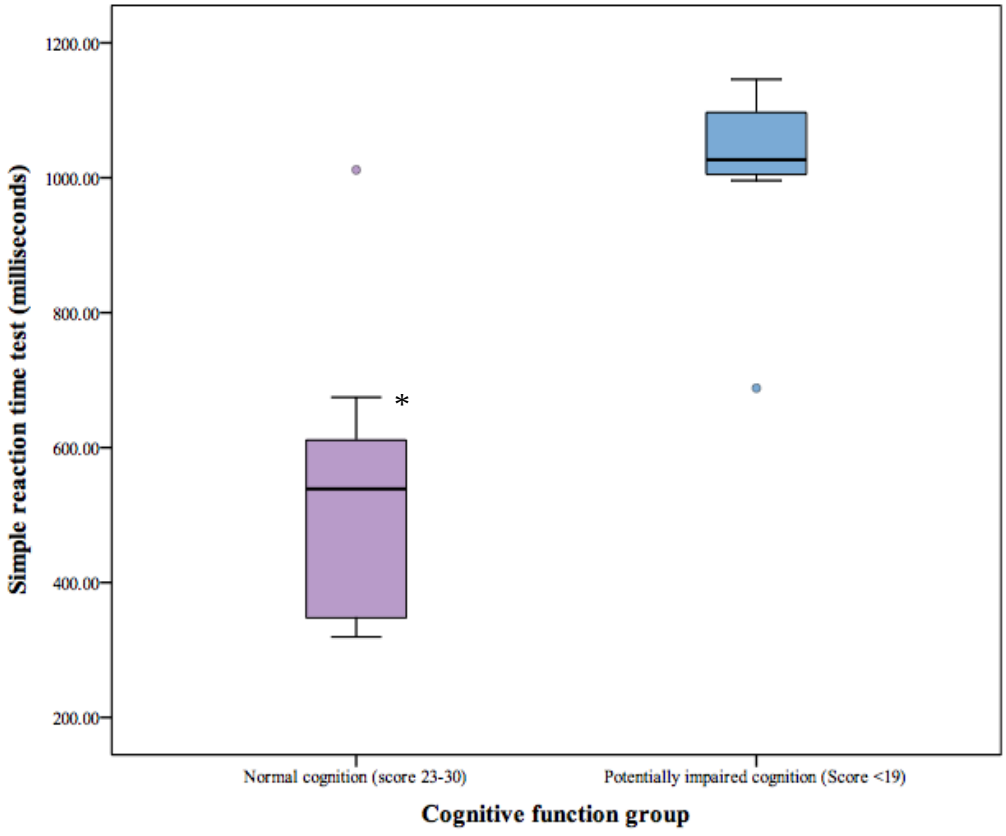


Figure 6.3 Between group differences for simple reaction time test (winter)

Table 6.3 Differences in health measures, mean (SD) and Mann-Whitney U (winter)

		N=16	**NC, n= 9**	**PIC, n= 7**	
		Mean (SD)	**Mean (SD)**	**Mean (SD)**	**Mann-Whitney U**
Wellbeing	WEMWBS	50 (11)	50, (11)	50, (12)	U=30.50, z=-.10, p=0.91
Cognition	MMSE	22 (6)	27(3)	16 (2)	**U=0.00, z=-3.35, p=0.01, r=-8.4**
	SRT (milliseconds)	740 (309)	530 (222)	1009 (152)	**U=2.00, z=-3.12, p=0.02, r=-.74**
Sleep	PSQI	6 (3)	6 (2)	6 (4)	U=30.00, z=-.16, p=0.87
	Sleep onset latency (mins)	46 (34)	49 (35)	41 (34)	U=28, z=.-37, p=0.71
	Sleep efficiency (%)	72 (14)	75 (10)	69 (19)	U=28, z=.-37, p=0.71
	WASO (mins)	68 (38)	69 (46)	67 (28)	U=27.00, z=-.47, p=0.63
	Sleep time (mins)	385 (139)	430 (100)	326 (167)	U=16.00, z=-1.64, p=0.10
	Bedtime	23:13 (2)	23:07 (1)	22:29 (2)	U=25.00, z=-.68, p=0.56
	Wake time	07.50 (2)	8.00 (1)	7.38 (2)	U=29.50, z=-6.88, p=0.83
Activity	Average active count	174 (43)	182, (27)	163, (57)	U=24.00, z=-.42, p=0.42
Vision	CS right eye	1.03 (.21)	1.0 (.21)	.98 (.22)	U=25.50, z=-.65, p=0.51
	CS left eye	.90 (.47)	.98 (.41)	.79 (.55)	U=27.50, z=-.43, p=0.66
	VA right eye	.51 (.20)	.44 (.14)	.60 (.24)	U=17.50, z=-1.48, p=0.13
	VA left eye	.52 (.29)	.39 (.25)	.69 (.26)	**U=13.00, z=-1.96, p=0.05**

Bold type indicates a statistically significant result

6.3.2 Does light exposure, measured by blue light irradiance, illuminance level and durations in specific exposure thresholds, differ between groups and by season?

(1) Between group difference for light exposure and durations in light threshold measures (summer, n=20)

Results for between group differences for light exposure and durations in light thresholds yielded mostly non-significant differences (Table 6.4). Across the suite of measures only one was reported to be statistically difference. The duration of time spent in the blue light threshold of 20-60 $\mu W/cm^2$ was suggested to be shorter in the normal cognitive function group (mean=17 minutes) compared to the potentially impaired cognitive function group (mean=73 minutes) (U=22.50, p=0.04). This result is difficult to interpret, as there is little empirical evidence of durations in blue light irradiance thresholds. However, if we considered evidence and relationships to other illuminance thresholds duration (Shochat *et al.*, 2000), we might assume that participant with potentially impaired cognition spent longer durations in less blue light exposure compared to those with normal cognition.

Table 6.4 Differences in light measures, mean and Mann-Whitney U (summer)

		N=20	**NC n=12**	**PIC n=8**	
			Mean (SD)	**Mean (SD)**	**Mann-Whitney U**
Light exposure at pre-set time periods	Morning mean illuminance (lux)	402 (806)	558 (1185)	347 (311)	U=27.00, z=-.476, p=0.7
	Morning mean blue light ($\mu W/cm^2$)	20 (51)	32 (76)	13 (12)	U=28.00, z=-.370, p=0.87
	Evening mean illuminance (lux)	127 (202)	158 (242)	143 (205)	U=29.00, z=-.265, p=0.63
	Evening mean blue light ($\mu W/cm^2$)	4 (7)	6 (8)	5 (7)	U=25.50, z=-.636, p=0.84
	Daytime mean illuminance (lux)	20 (39)	164, (141)	11 (921)	U=22.00, z=-1.00, p=0.28
	Daytime mean blue light ($\mu W/cm^2$)	23 (39)	12 (21)	30 (53)	U=22.00, z=-1.00, p=0.28
Morning durations in lux thresholds	Morning duration above 1000lux (mins)	46 (58)	33 (41)	63 (70)	U=22.50, z=-.954, p=0.47
	Morning duration 600-1000lux (mins)	27 (31)	17 (18)	48 (42)	U=22.50, z=-.954, p=0.11
	Morning duration 200-600lux (mins)	90 (69)	75 (47)	140 (81)	U=15.00, z=-1.74, p=0.05
	Morning duration 50-200lux (mins)	194 (200)	201 (231)	216 (227)	U=25.00, z=-.688, p=0.39
Morning durations in blue irradiance thresholds	Morning duration above 100$\mu W/cm^2$(mins)	20 (30)	27 (36)	19 (30)	U= 45.00, z=-.239, p=0.81
	Morning duration 60-100 $\mu W/cm^2$(mins)	9 (19)	4 (6)	19 (29)	U= 32.00, z=-1.25, p= 0.21
	Morning duration 20-60 $\mu W/cm^2$ (mins)	34 (64)	17 (15)	73 (99)	**U= 22.50, z=-1.97, p=0.04, r= -.44**
	Morning duration 0.5-20 $\mu W/cm^2$ (mins)	304 (143)	325 (148)	328 (104)	U= 43.00, z=-.38, p=.70

Bold type indicates a statistically significant result

(2) Between group difference for light exposure and durations in light threshold measures (winter, n=16)

When exploring winter data across the suit of light measures it was suggested no statistical differences between groups existed (Table 6.5).

Table 6.5 Differences in light measures, mean (SD) and Mann-Whitney U (winter)

		N=16	**NC n=9**	**PIC n=7**	
		Mean (SD)	**Mean (SD)**	**Mean (SD)**	**Mann-Whitney U**
Light exposure at pre-set time periods	Morning mean illuminance (lux)	63 (59)	66 (64)	63 (57)	U=31.00, z=-.05, p=0.95
	Morning mean blue light ($\mu W/cm^2$)	3 (4)	2 (2)	4 (6)	U=29.00, z=-.25, p=0.79
	Evening mean illuminance (lux)	20 (15)	21 (14)	17 (17)	U=25.00, z=-.68, p=0.49
	Evening mean blue light ($\mu W/cm^2$)	.5 (.5)	.48 (.42)	.71 (.62)	U=26.00, z=-.58, p=0.56
	Daytime mean illuminance (lux)	38 (42)	51 (51)	20 (16)	U=19.00, z=-1.32, p=0.18
	Daytime mean blue light ($\mu W/cm^2$)	2 (2)	1 (2)	2 (3)	U=24.00, z=-.79, p=0.42
Morning durations in lux thresholds	Morning duration above 1000lux (mins)	3 (8)	4 (9)	3, (8)	U= 25.50 z=-.67, p=0.49
	Morning duration 600-1000lux (mins)	3 (5)	5 (6)	.60 (1)	U= 16.00, z=-1.68, p=0.09
	Morning duration 200-600lux (mins)	33 (40)	31 (32)	35, (52)	U=26.50, z=-.53, p=0.59
	Morning duration 50-200lux (mins)	145 (152)	126 (74)	170 (222)	U=26.50, z=-.53, p=0.87
Morning durations in blue irradiance thresholds	Morning duration above $100\mu W/cm^2$(mins)	2 (0)	2 (6)	2 (4)	U= 29.50, z=-.27, p=0.78
	Morning duration 60-100 $\mu W/cm^2$(mins)	8 (30)	1 (2)	18 (45)	U= 30.00, z=-.19, p=0.84
	Morning duration 20-60 $\mu W/cm^2$ (mins)	8 (13)	.9 (12)	6 (14)	U= 22.50, z=-.96, p=0.33
	Morning duration 0.5-20 $\mu W/cm^2$ (mins)	273 (190)	218 (132)	344 (238)	U= 23.00, z=-.90, p=0.36

Bold type indicates a statistically significant result

(3) Are seasonal changes consistent across cognitive function groups?

A Wilcoxon signed-rank test was carried out to explore if within sub-groups (normal cognitive function or potentially impaired cognition) there were differences from season to season, i.e. do those with normal cognitive function have the same seasonal changes as those with potentially impaired cognition. Reported in the previous chapter (4), across the repeat cohort the only health and wellbeing measure to differ significantly between seasons was daytime physical activity. Further investigation revealed this was independent of cognitive ability, i.e. both groups normal cognitive function (Z=-2.66, p=0.005) and potentially impaired cognition (Z=-2.63, p=0.05) had significantly higher daytime physical activity levels in summer. Results also confirmed that objective sleep/wake parameters, subjective sleep quality and mental wellbeing did not differ between seasons for either cognitive function group. Finally, results suggested that for those with normal cognitive function measures of visual acuity (right eye, Z=-2.55, p=0.05) and contrast sensitivity (left eye, Z=-2.04, p=0.05) improved from summer to winter. This difference was only present for the normal cognition.

6.3.3 Does light exposure (blue light exposure, illuminance level or duration in light thresholds) predict sleep quality (measured by total time asleep, sleep efficiency or sleep onset latency)?

For the purpose of these tests the repeat cohort (n=16) were used and readings coded depending upon season. Discussed in Chapter 3, CCR regression modelling recognises repeats cases and creating a sample size of n=32, therefore, creating a greater number of light measures to be tested. Table 6.6 summarises results, followed by a report of models of most interest e.g. 1) morning blue light exposure as a predictor of total sleep time, 2) Daytime activity as a predictor of sleep efficiency and 3) visual function as a predictor of night-time awakenings. To estimate differences in the strength of associations between sleep quality parameters and 1) light exposures, 2) durations in illuminance thresholds and 3) durations in blue light thresholds individual runs were carried out.

Secondly, to explore predictors of cognitive reaction time a series of CCR binary logistic regression models were run. Cognitive reaction time has been a reported in previous studies as a robust dependent measure in older people, particularly those who are experiencing visual impairment (Schmoll *et al.*, 2011). Table 6.10 summarises the findings.

The Spearman's rho correlations (reported in Chapter 5) identified potential relationships between sleep parameters and light measures. For example total sleep time was negatively associated with longer periods in low blue light irradiance thresholds (0-20 μW/cm^2) (r_s=-.48, p=0.032), daytime activity levels were positively associated with longer durations in bright illuminance levels (600-1000 lux) (r_s=.48, p=0.029) and wake uptime was negatively associated with daytime activity level (r_s=-.77, p=0.035). Whilst in winter correlations suggested a positive association between daytime activity and sleep efficiency (r_s=.61, p=0.011) and a negative association between MMSE and durations in bright illuminance thresholds of 600-1000 lux (r_s=-.50, p=0.039). This helped to identify potential dependent sleep variables and independent light variables for regression modelling.

A guide to interpreting CCR output

The CCR results should be interpreted in the following way. In each table under 'fit' there is a report of the R^2 values, i.e. the total variance in the model. Below this are the standard coefficients for each tuning parameter of correlated component (*K*) and list of predictors (*P*) and the corresponding standard coefficient for each. In the 'predictor table' there is a list of the predictors in rank order. Finally, each output is accompanied by a graph, providing a visual interpretation of the number of predictors, which make up the model. The dark line on the graph indicates the optimum number of predictors (i.e. the peak in the line). If only one predictor is present the graph will start at the peak (i.e. single predictor) and begin to descend immediately.

Table 6.6 Summary overview of CCR Linear Regression models

DV	Predictors	Result: Predictors (rank order)	Comments
Sleep onset latency (SOL)	Light exposure + discriminants	Morning blue light (1)	(1) Results in opposite direction, i.e. higher morning BL is associated with longer SOL
	Illuminance durations + discriminants	VA left (1)	(2) Results in opposite direction, i.e. better VA is associated with longer SOL.
	BLE durations + discriminants	Contrast sensitivity left (1) VA left (2)	(3) Results in opposite direction i.e. better CS and VA re associated with longer SOL.
Sleep efficiency (SE)	Light exposure + discriminants	MMSE (1) Average activity (2)	(1) Results in opposite direction i.e. poorer cognitive function and higher activity are associated with higher SE. Although this relationship was found in the Mann-Whitney U summer results.
	Illuminance durations + discriminants	Age (0.11) MMSE (-0.59)	(2) Results in opposite direction i.e. higher age and lower cognitive function are associated with higher sleep efficiency.
	BLE durations + discriminants	Average activity (0.40) VA left (0.29)	**(3) Reported in text ***
Total sleep time (TST)	Light exposure + discriminants	Morning blue light (1)	**(1) Reported in text ***
	Illuminance durations + discriminants	CS left (1)	(2) Results in opposite direction as hypothesised, i.e. as morning light duration decreases sleep time increased.
	BLE durations + discriminants	Average activity (1) Morning blue 0-20 $\mu W/cm^2$ (2)	(3) Higher daytime activity associated with longer TST. Relationship with 2nd predictor BLE opposite direction.
Wake after sleep onset (WASO)	Light exposure + discriminants	MMSE (1) Average activity (2) CS right (3)	(1) Not as expected, higher cognitive function and better CS also associated with more awakenings.
	Illuminance durations + discriminants	MMSE (1) Average activity (2)	(2) Lower activity associated with more awakenings, Not as expected, higher cognitive function also associated with more awakenings.
	BLE durations + discriminants	CS left (1) VA right (2)	**(3) Reported in text ***

(1) Predicting total sleep time

The CCR model output shows a one-predictor solution as illustrated by Figure 6.4 below, i.e. the addition of other predictors to the model reduces the strength of the prediction. This single predictor is identified as *mean morning blue light exposure*, (i.e. the average blue light exposure a participant received in the morning interval 08:00-12:00). This is identified under 'standard coefficient' and 'predictor table'. In Table 6.7 below the model fit can be classified as small effect size (Cohen, 1988) (i.e. the value of R^2 is 0.10). The standard coefficient is 0.02 in a positive direction, indicating that total sleep time was associated with higher blue light exposure in the morning. The predictor table shows *morning blue light* is present in 2454 times out of 4000 regression runs.

Table 6.7 Predicting total sleep time

	Training	**Cross-Validation**	**SE**
Fit R^2	0.00	0.10	0.08
Std. Coefficient			0.02

Predictors	**Std. Coefficient**	**CC1**
Mean morning blue light exposure	0.02	1

Predictor Table	
Predictor	All
Mean morning blue light exposure	2454

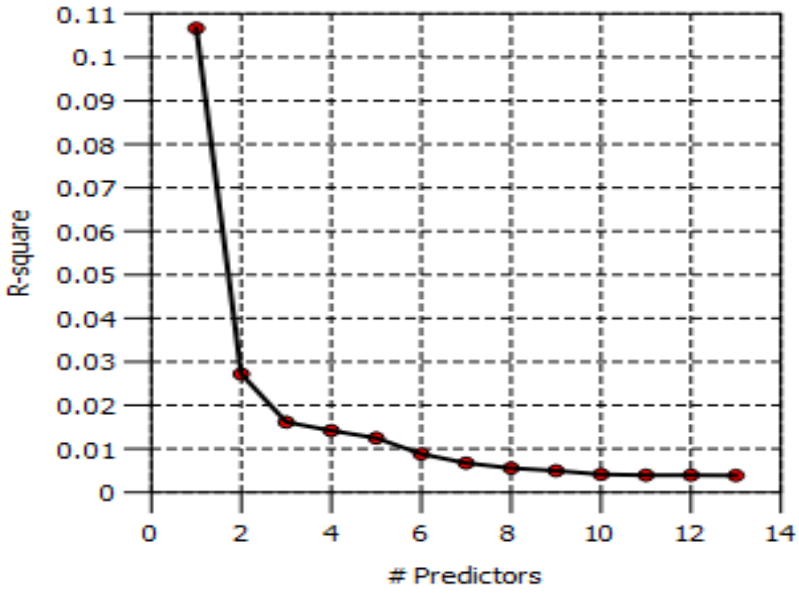


Figure 6.4 Predictor graph: Total sleep time

(2) Predicting sleep efficiency

The CCR model output shows a two-predictor solution as illustrated by Figure 6.5 below. These predictors are identified as *average daytime activity level* and *visual acuity (right eye).* In Table 6.8 below the model fit can be classified as small effect size (Cohen, 1988) (i.e. the value of R^2 is 0.04). The standard coefficients indicate that higher sleep efficiency was associated with higher daytime physical activity level=0.40 (coefficient in the positive direction) and better visual acuity=-0.29 (standard coefficient in the negative direction). The predictor table shows, in rank order, the top predictor was average daytime activity, which is present in 3735 times and visual acuity present 3499 times out of 4000 regression runs.

Table 6.8 Predicting sleep efficiency

	Training	**Cross-Validation**	**SE**
Fit			
R^2	0.20	0.04	0.02
Std. Coefficient		0.47	0.03

Predictors	**Std. Coefficient**	**CC1**	**CC2**
Daytime physical activity	0.40	0.92	-0.79
Visual acuity right eye	-0.29	0.57	0.49

Predictor Table

Predictor	All
Daytime physical activity	3735
Visual acuity right eye	3499

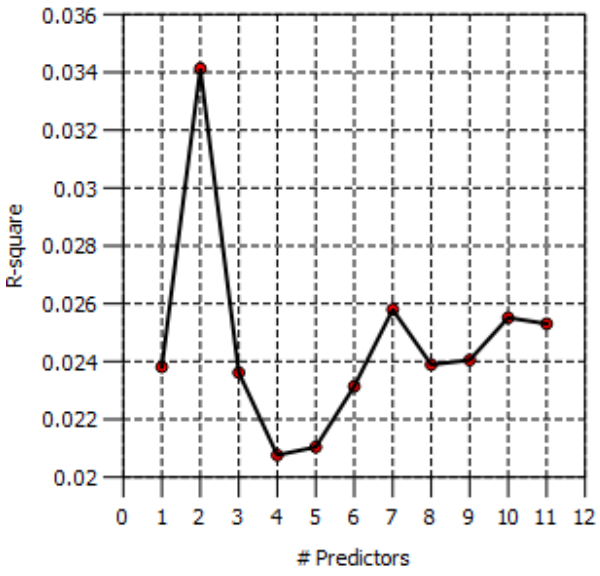


Figure 6.5 Predictor graph: Sleep efficiency

(3) Predicting wake after sleep onset (WASO)

The CCR model output shows a two-predictor solution as illustrated by Figure 6.6 below. These predictors are identified as *contrast sensitivity (left eye)* and *visual acuity (right eye).* In Table 6.9 below the model fit can be classified as small effect size (Cohen, 1988) (i.e. the value of R^2 is 0.02) (Cohen, 1988). The standard coefficients indicate that fewer night-time awakenings was associated with better contrast sensitivity=-0.14 (coefficient in the negative direction) and better visual acuity=0.27 (coefficient in the positive direction). The predictor table shows the top predictor is contrast sensitivity, which was present in 3613 times and visual acuity present 2966 times out of 4000 regression runs.

Table 6.9 Predicting wake after sleep onset (WASO)

	Training	**Cross-Validation**	**SE**
Fit			
R^2	0.24	0.02	0.01
Std. Coefficient		0.83	0.62

Predictors	**Std. Coefficient**	**CC1**	**CC2**
Contrast sensitivity left eye	-0.14	-0.06	-0.17
Visual acuity right eye	0.27	0.02	0.28

Predictor Table

Predictor	All
Contrast sensitivity left eye	3735
Visual acuity right eye	3499

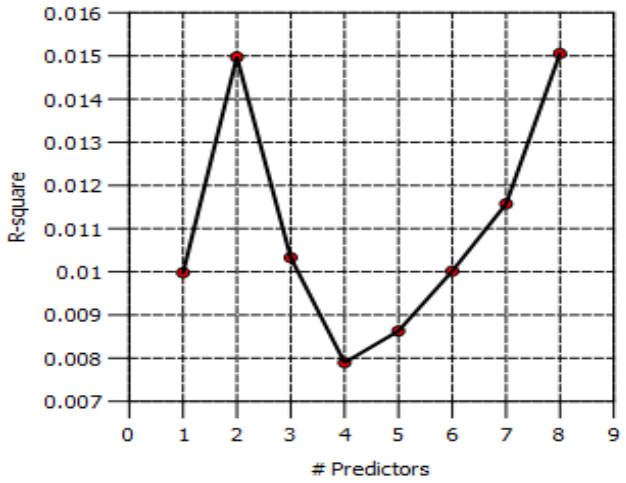


Figure 6.6 Predictor graph: Wake after sleep onset (WASO)

6.3.4 Does light exposure predict cognitive reaction time?

(1) Exploration of light and control discriminants as predictors of cognitive reaction time

An additional CCR binary logistic analysis was carried out to explore whether light exposure, durations in light thresholds or control discriminants could predict cognitive reaction time. The simple reaction time test was used as the dependent variable. A log transformation was attempted to create an even distribution in the data, but proved to be unsuccessful. Therefore, the median was used to split the data into two groups 1) fast and 2) slow. These scores mapped with the results from the MMSE assessment, i.e. those with normal cognitive function were below the median (faster reaction time) whilst those with potentially impaired cognition were above (slower reaction time). The results of this are reported in Table 6.10. In summary, morning blue light exposure, older age and poorer visual function were top predictors of slower cognitive reaction times.

Table 6.10 Summary overview of CCR binary logistic regression models exploring predictors of cognitive reaction time

DV	Predictor	Results Predictors (in rank order)	Comments
Simple reaction time, fast/slow	Light exposure + discriminants	Age (1)	Older age was associated with a slower reaction time.
	Illuminance durations + discriminants	VA right (1)	Poorer visual acuity (VA) associated with a slower reaction time.
	BLE durations + discriminants	VA right (1) Morning blue light (2)	Poorer VA and longer durations in lower level BLE are associated with a slower reaction time

6.4 Summary of results

(1) Between groups differences by season

In summary, the groups differed significantly in wake up time in summer only, i.e. those with potentially impaired cognitive function woke significantly earlier compared to those with normal cognitive function. In both seasons visual acuity was significantly different, i.e. those with normal cognitive function had better visual acuity compared to those with potentially impaired cognition. No other significant differences existed for sleep/wake, daytime physical activity, and mental wellbeing in each season. By season, the between group differences, across the suite of light measures, yielded mostly non-significant results. However, in the summer analysis the duration of time spent in a blue light threshold of 20-60 $\mu W/cm^2$ was significantly different, i.e. participants with normal cognitive function group spent less time in this threshold compared to those with potentially impaired cognition.

(2) Predicting sleep quality and cognitive reaction time

- Total sleep time was predicted by one variable, morning blue light exposure. The value of R^2 explained 10% of the variance in the model. This indicates that the morning blue spectral content of light may contribute to the total sleep time and the relationship held when controlling for other factors (i.e. age, activity level or visual function).
- Sleep efficiency was predicted by daytime physical activity and visual acuity. The values of R^2 explained 4% of the variance in the model. Again, the R^2 value is small, but an important indication that increased daytime activity levels may be associated with better sleep efficiency.
- The number of awakening after sleep onset (WASO) as predicted by visual acuity and contrast sensitivity. The values of R^2 explained 2% of the variance in the model and an important indication that visual function may play a part in consolidating sleep at night.
- The binary logistic CCR models exploring cognitive reaction time suggested that older age and poorer visual function as top predictors of slower cognitive reaction time.

6.5 Discussion

A series of between groups tests, either, 1) normal cognition or 2) potentially impaired cognition investigated differences across a range of health and wellbeing measures and light exposures. Results returned both interesting outcomes in line with current literature, but similarly identified unexpected relationships. The between group analysis explored difference by season, i.e. where did differences occur depending upon cognitive ability across the suite of health, wellbeing and light measures. A new regression modelling technique investigated light exposures and durations in thresholds as predictors of sleep quality, (measured by total sleep time, sleep onset latency, sleep efficiency and wake after sleep onset), whilst controlling for individual covariates such as cognitive ability, age, daytime physical activity etc.

How do health and wellbeing outcomes, measured by sleep/wake, activity and mental wellbeing differ between groups and between seasons?

Investigations of sleep parameters suggested only a significant difference in wake up time during the summer study, i.e. participants with potentially impaired cognition woke significantly earlier than those with normal cognitive function. This is in line with Wolkove *et al*. (2007) stating that older people tend to go to sleep earlier in the evening but also to wake earlier and that this can be exacerbated by changes in cognitive functioning. No other sleep parameters, in either season, were found to differ significantly between cognitive ability groups. This is contrary to reports from Moe *et al*. (1995) stating wake after sleep onset was significantly different ($p<0.005$), i.e. people with lower cognitive ability spent much longer periods awake during the night-time (n=116) and Geda *et al*. (2004) stating the presences of sleep disturbance is approximately double in persons with declining cognition compared to healthy controls (normal=514, mild cognitive impairment=54). The findings in this thesis are more consistent with Corchrane *et al*. (2012) who reported those with 'intact' cognitive ability did not differ from those with a decline in cognitive ability across a suite of similar sleep parameters (such as wake after sleep onset, total sleep time, bedtime and wake up time). This current study explored these sleep parameters in people living in residential care homes, Corchrane and colleagues examined people still living

independently (n=26). The authors postulated differences in cognitive ability did not seem to be explained solely by alterations in sleep patterns. This is also consistent with the study conducted by Schmoll *et al.* (2011) that reported improve light transmission through the eye, post-cataract surgery, may be beneficial to cognitive functioning. The findings in the thesis support this, the CCR binary logistic models suggested older age and poorer visual acuity as predictors of a slower reaction time. Further studies are needed to examine the wider underlying causes of circadian disruption, for example the influence of cognitive functioning or degeneration in the SCN (described in Chapter 1) (Hattar *et al.*, 2002; Lupi, Semo and Foster, 2012; Coogan *et al.*, 2013; Silver, 2014) or indeed more tangible associations such as daily routine, level of physical activity or the physical environment (i.e. care home verses independently living) (Duffy and Dijk, 2002; Anderiesen *et al.*, 2014). It may be possible that the care home routine at night is equally disruptive upon sleep quality independent of cognitive ability. Without further investigation and recordings of the care home routine at night it is not possible to infer a causal relationship at this time.

Much like the patterns of sleep/wake, daytime physical activity levels were not found to differ significantly between groups in either season. This is contrary to other studies that reported lower activity levels in those with a decline in cognitive function compared to healthy older adults (Ancoli-Israel *et al.*, 2002; Ravaglia *et al.*, 2008; de Bruijn *et al.*, 2013; Blondell, Hammersley-Mather and Lennert Veerman, 2014). In the previous chapter (4) results indicated a drop in daytime physical activity between seasons i.e. this was much lower in winter. In this cohort daytime physical activity levels changed by season but not within cognitive function groups. If season has a significant effect on daytime physical activity levels does this highlight that measures should be taken to promote physical activity in care homes, in particular facilitating more time outdoors in winter? It is not uncommon for levels of physical activity to differ with seasonality and that weather may be a barrier to performing activity (Cheadle, 2006). The results from this study, demonstrating a decrease in daytime physical activity level, coupled with existing literature (Cheadle, 2006; Moschny *et al.*, 2011) calls for research to explore interventions, particularly in the winter months and for those with limited mobility as a means of promoting better sleep quality.

The between group analysis suggested a statistical difference in reaction time, i.e. those with normal cognitive function responded quicker to the reaction time test. This relationship remained statistically significant in both seasons. This is consistent with other research, which has reported better cognitive function, measured by MMSE was associated with a faster cognitive reaction time (Pirozzolo *et al.*, 1981; Gordon and Carson, 1990). Future studies may wish to replicate both measures (MMSE and SRT) as a robust account of cognitive ability within a study population.

Lastly, visual assessments carried out for this study confirmed that all participants had low vision to some degree in both seasons. Stated previously, low vision is an indication of a visual impairment, thus impeding light transmission through the eye to the ipRGC, which helps circadian synchronisation (Turner, Van Someren and Mainster, 2010). The exact degree of light impediment was not known for this study. In order to fully understand the level of impediment a participant would require a more thorough eye examination. An ophthalmologist would be essential to the study design, with the ability to explore the eye in greater detail, e.g. grading the density of a cataract, establishing the severity of any eye disease (e.g. macular degeneration), measuring pupil retraction and ocular movement as well as determining the health of the external eye and internal eye. The protocol tested visual acuity and contrast sensitivity in both seasons. Results suggested in the summer study that visual acuity was significantly different in the right eye, whilst in the winter study this relationship was found in the left eye (i.e. those with normal cognitive function had better visual acuity). The findings are consistent with other research reporting a decline in cognitive function was associated with a decline in visual function (Rizzo *et al.*, 2000; Dhillon and Lascaratos, 2009; Schmoll *et al.*, 2011). The change in relationship from left to right eye had not been expected. Reasons for this difference may be as a result of the in-situ method, for example the lighting conditions in the room may cause the test board to be illuminated differently at each measure, the test board was positioned at inconsistent distances causing the participant to read the chart differently, or the participant's mood, alertness or concentration were different between measures, again, causing them to read the chart differently. This indicates scope to improve the in-situ methodology (this is discussed in more detail in Chapter 7).

It is also possible that the outcome is genuine and visual function was different at the second measure. This thesis does, however, demonstrate it is possible to conduct an in-situ visual assessment in this population, advancing the field of lighting studies. This research opens a new field in studies with older people, highlighting the need to measure cognitive function and vision simultaneously. In both seasons there was no statistical difference between groups (normal cognitive function or potential cognitive impairment) for measures of contrast sensitivity. Relationships followed a similar trend indicating better cognitive function was associated with better contrast sensitivity.

Does light exposure, measured by blue light irradiance, illuminance level and durations in specific exposure thresholds differ between groups and between seasons?

The analysis of light exposure also returned interesting results. This study found that the summer mean morning illuminance level was 402 lux and the blue spectral irradiance reading was 20 $\mu W/cm^2$. In winter this decreased to a mean morning illuminance level of 63 lux and 3 $\mu W/cm^2$ blue light irradiance. The summer illuminance readings are in line with findings from a previous work conducted in a similar population by Shochat *et al*. (2000). The author reported a mean daytime light exposure of 485 lux and described this as a low level of illumination. It would, therefore, be reasonable to draw a similar conclusion here and suggest that participants did not receive a great deal of blue or bright light in the morning interval (in either season). The between group test suggested in summer only the duration in the blue light threshold of 20-60 $\mu W/cm^2$ was significantly different, i.e. those with potentially impaired cognition spent longer in lower blue light thresholds. There were no significant differences for measures of illuminance at pre-set times across the day, nor were durations in illuminance thresholds significantly different in either season between groups. It is important to be mindful that other study limitations, such as sensors covered by clothing or that corneal measures were not recorded, may have been responsible for low light readings (Shochat *et al.*, 2000). As there is little evidence to compare the blue light irradiance measures with other published work it is difficult to draw inferences. However, it may be sensible to assume that blue spectral irradiance was low in both seasons. Similarly, differences in cognitive ability did not appear to be a factor in differences in illuminance levels or blue

light exposure, i.e. the cohort as a whole were experiencing poor lighting quality at important times of the day for circadian entrainment.

The opportunity to spend long periods of time in higher illuminance levels and higher blue spectral irradiance levels was more prevalent during the summer than winter. Results yielded that this was not statistically significant between groups, i.e. both croups spent limited amounts of time in bright light, particularly during the morning period. These findings may be to be expected as they follow published cross-seasonal studies, such as the works of Guillemette *et al*. (1998), Graw *et al*. (1999) and Bellia *et al*. (2014) that reported personal light exposure to be greater in the summer season. In this cohort the mean duration of time above 1000 lux was 40 minutes during the summer and only 3 minutes during the winter, there was no significant differences between groups in either season. This would suggest participants spent very limited amounts of time in bright light during the winter season and even in summer the duration of exposure was short. This has important implications for the care policy of older people highlighting a deficit in good light exposure and an area where improvements can be made.

Does light exposure (blue light exposure, illuminance level or duration in light thresholds) predict sleep quality (measured by total time asleep, sleep efficiency or sleep onset latency) and cognitive reaction time?

The Spearman's rho correlation set grounds to explore potential light measures as predictors of sleep. In Chapter 4 the correlations suggested associations between sleep and daytime physical activity. In the CCR analysis results implied that mean morning blue light exposure was the top predictor for total sleep time. This held true when control variables (i.e. cognitive function, visual function, daytime activity level and age) were added. Results have interesting implications. Firstly, 'light' as a predictor of sleep quality is consistent with other studies (Shochat *et al.,* 2000; Hubalek, Brink and Schierz, 2010). Previous work has only suggested illuminance levels as predictors. In this current study results indicated morning blue light exposure was the top predictor ahead of illuminance levels or indeed durations in light thresholds. This brings new evidence to the lighting research field indicating that the level of blue spectral irradiance

delivered in the morning interval (08:00-12noon) was associated with total sleep time. Research is required to explore this relationship further and investigate associations between blue spectral irradiances and sleep parameters. Emerging literatures supports the hypothesis that the blue spectral component of light is equally important when considering a lighting design scheme (Bellia *et al.*, 2014). The results of this thesis continue to support this argument and proved further evidence that it is no longer appropriate to simply design lighting schemes to lux levels alone.

Equally, results postulated an interesting narrative between sleep, activity, visual function and blue light exposure. For other sleep parameters i.e. sleep efficiency or time awake at night different predictors emerged. Regression results suggested for sleep efficiency daytime physical activity level was the top predictor. Whilst for minutes awake at night (WASO) a two-predictor solution, i.e. visual acuity and contrast sensitivity was suggested. Other studies have reported that light levels may predict night-time awakenings (Shochat *et al.*, 2000) when controlling for cognitive function, but have not accounted for other predictors such as physical activity or visual function. These results generate new concepts when exploring sleep patterns of older people e.g. physical activity and visual function may be related to sleep quality in older people in a residential care setting.

In this study measures of cognitive function did not predict sleep outcomes. In previous work, regression modelling has indicated that level of cognitive function may be a predictor of daytime napping and decreased daytime wakefulness (Shochat *et al.*, 2000). When controlling for cognitive function, light exposure and illuminance durations pervious work has found that light has a stronger association with night-time sleep (Shochat *et al.*, 2000). This current thesis appears to be consistent with this, i.e. morning light exposure was associated with the duration of sleep at night. Therefore, it may be that a decline in cognitive ability has a more profound effect upon daytime/daily functioning rather than night-time sleep disruptions. Additional studies are required to investigate relationships between cognitive ability and night-time sleep and to document the daily routine in in relation to this also.

The current thesis did not find an association between sleep onset latency and predictor variables in the anticipated direction. The Spearman's rho correlations suggested a positive association with the PQSI (self-rated sleep quality) i.e. a higher perceived level of sleep disruption was associated with taking longer to fall asleep. It may be that sleep onset is affected more by physiological measures such as feelings of worry or stress (Freedman and Sattler, 1982) rather than the physical impediment of light through the eye or the brightness of the daytime environment. Other studies have suggested that periods of insomnia (e.g. taking longer to fall asleep) may be caused by underlying health conditions or as side effect of medication (Wolkove *et al.*, 2007). Exploring these factors was beyond the remit of this study, but future research may wish to investigate this in line with sleep onset latency. There is also the possibility that the sample size did not have adequate power to detect a statistical significance. Further discussions of the limitations are reported in Chapter 7.

Summary

These results suggest there are large variations in light exposure levels in this particular sample (i.e. mean morning lux summer=402 lux and winter=63 lux or mean morning BLE summer=20 $\mu W/cm^2$ and winter=3 $\mu W/cm^2$). However, the mean in both seasons suggests overall that light levels and blue light irradiance were low (Shochat *et al.*, 2000). Research has inferred that care homes may not be adequately lit and that residents experience very low levels of illuminance during the daytime (Bakker, Iofel and Lachs, 2004; De Lepeleire *et al.*, 2007; van Hoof *et al.*, 2009; Sinoo, van Hoof and Kort, 2011). Moreover, research has indicated that low levels of illuminance may be associated with a disrupted sleep cycle and that higher illumination levels could alleviate some of the symptoms associated with poor sleep quality particularly in those with a decline in cognitive function (Lovell, Gevirtz and Ancoli-Israel, 1995; Ancoli-Israel *et al.*, 2002; 2003; Fetveit, Bjorvatn and Skjerve, 2003; Fetveit and Bjorvatn, 2004; Sloane *et al.*, 2007; Riemersma-van der Lek, Swaab and Twisk, 2008; van Hoof, Schoutens and Aarts, 2009; Figueiro *et al.*, 2014). It would be appropriate to suggest there are opportunities to supplement indoor lighting, particularly during the winter, for those who are less likely to spend time outdoors and specifically older people in a care home environment. The caveat, this should not been seen as alternative to spending time

outside as this brings many other benefits to people beyond circadian entrainment and sleep consolidation, i.e. a source of vitamin D, fresh air and opportunities for social encounters.

Exposures to these other environmental and social factors are also of key importance to circadian entrainment and overall general wellbeing. In previous works, exposure to bright light has been demonstrated to help stabilise a disrupted circadian pattern and reduce symptoms associated with declining cognitive function and poor sleep (Campbell, Dawson and Anderson, 1993; Koyama, Matsubara and Nakano, 1999; Fetveit, Bjorvatn and Skjerve, 2003; Fetveit and Bjorvatn, 2004; Barrick *et al.*, 2010; McCurry *et al.*, 2011). Therefore, a simple and inexpensive intervention such as supplementing low light levels, ensuring regular time outdoors and boosting physical activity could help to alleviate symptoms of poor sleep quality.

Research has demonstrated that blue light present in the environment from different sources can impact on sleep both in a positive (Ancoli-Israel *et al.*, 2003) and negative way (Cajochen *et al.*, 2011; Figueiro, Lesniak and Rea, 2011; Wood *et al.*, 2013) and confirms that our sleep wake cycle can be affected by light transmission through the eye (Czeisler, Allan and Strogatz, 1986; Czeisler, Kronauer and Allan, 1989; Berson, 2003; Kessel *et al.*, 2010). Kessel *et al*. (2010) stated that ageing was associated with a gradual decrease in the transmission of visible light through the eye, particularly at short wavelengths (i.e. blue light). Visual assessments in line with personal light exposure and sleep/wake patterns, specifically, in older people are very limited. This research attempted to address the lack of knowledge around light exposure, sleep and vision by incorporating in-situ measures of visual acuity and contrast sensitivity. The findings from this research indicate it is possible to assess visual function in older people, but that accuracy in doing so could be improved.

The low level lighting, which appeared consistently across the two seasons measured here, is a potential reason why no change in sleep parameters was found between groups. Although light was significantly different between seasons it may be that the continual low levels were not effective upon the circadian rhythms to cause a greater

seasonal change in sleep parameters. Likewise, this may be why no significant differences were observed depending upon cognitive ability, i.e. receiving inadequate light exposure was not a consequence of a decline in cognitive function alone. Further research, into the seasonal variations of light exposure in a care home setting and the associations with sleep quality of older people are required to investigate further the possible impact of cognitive function and the quality of lighting provisions in care homes.

Chapter 7 : Conclusions and Discussion

"I believe the way people live can be directed a little by architecture."

- Tadao Ando

This research focused on the associations between blue light exposure, illuminance levels and sleep quality. The overarching aim was to explore these associations in two populations that may be more susceptible to circadian disruption and/or irregularities in light exposure pattern, i.e. young people aged 13-17 years with autism and older people aged 72-99 years. The thesis demonstrated – albeit in small samples - that there was an association between morning blue light and measures of sleep efficiency in older people and that higher blue light exposure prior to bedtime was associated with delayed sleep onset in adolescents with ASD. The studies controlled for a range of covariate health variables, such as cognitive function, mental wellbeing, visual function and daytime activity levels. Although no causal relationship can be inferred by these studies the associations generate important questions in relation to assessing sleep and the possibilities that other health and environmental factors can contribute to the regulation of circadian rhythms and sleep quality.

This current research predominantly used quantitative measures to explore associations between blue light exposure, illuminance levels and sleep/wake patterns. The quantitative element consisted of measuring light and activity through the use of actiwatches, visual function and validated psychological scales assessing cognition function and wellbeing. The thesis also incorporated a qualitative approach (i.e. focus groups and one-to-one interviews) to establish a workable protocol in adolescents with ASD.

The purpose then of this final chapter is not to repeat the findings relating to the main research questions, but rather to bring together key conclusions that emerged from this thesis and address the research objectives. The integration of these findings includes strategic recommendation, which should be of interest to policy relating to older people

and in a broader sense those living with sensory issues. Additionally, it provides a reflection of the limitations and strengths of this thesis, the contribution to the field and directions for future works.

7.1 Addressing the objectives

In summary, the research objectives were:

1. Establish a methodology to explore BLE, illuminance and sleep/wake patterns in two populations with sensory issues.
2. Develop a workable protocol to investigate BLE, illuminance and sleep/wake patterns in young people with autism.
3. Investigate within group differences and associations of light, sleep/wake and health and wellbeing measures in two seasons.
4. Investigate between group differences of light, sleep/wake and health and wellbeing measures. Do light or health measures predict sleep parameters?
5. To make evidence informed conclusions and recommendations.

To address the research objectives quantitate and qualitative methods were used. The first objective stated above was addressed in Chapter 3 describing a novel methodology employing a quantitative measure of blue light irradiance, illuminance levels and sleep/wake patterns recorded by an actiwatch (objective 1). This device was successfully administered in two populations. A series of light measures investigated were described, these included mean exposures at pre-set intervals (morning, daytime and evening) and durations in blue light and illuminance thresholds in the morning interval. The thesis established a new set of blue light thresholds derived from existing empirical evidence relating to illuminance thresholds. The actiwatch successfully recorded sleep/wake and activity parameters, proving to be tolerable in populations with complex sensitivities.

Secondly, Chapter 4 reported the development of a workable protocol to measure sleep patterns and light exposure in young people with ASD (objective 2). A visual aid was

developed to communicate the study protocol and help towards recruitment of participants. Preliminary findings from the ASD pilot study suggested that between weekdays to weekends that bedtime and wake time were significantly delayed. Correlations suggested exposure to blue light prior to bedtime was associated with a delay in sleep onset.

Thirdly, Chapter 5 reported a within group analysis exploring seasonal differences in older adults (objective 3) indicated daytime physical activity was significantly higher in summer than in winter, no other sleep/wake or health and wellbeing measures differed between seasons. Similarly, mean light exposures and durations in bright light thresholds, particularly in the morning interval, were significantly higher in summer than winter. Correlations, by season, suggested self-rating poor sleep quality was associated with longer sleep onset time, daytime physical activity was associated with earlier wake up times and longer periods in bright light in summer. Statistically significant associations with cognitive ability or cognitive reaction time were not reported in summer. In winter relationships were less pronounced, suggesting only higher daytime physical activity was associated with better sleep efficiency. Higher cognitive ability was associate with longer periods in bright light in winter.

Fourthly, Chapter 6 addressed the between group analysis, by season (objective 4). The results suggested in summer wake up time and visual acuity differed significantly between groups (normal cognitive function and potentially impaired cognition). A new correlated component regression modelling technique was introduced to investigate possible predictors of sleep parameters. Results suggested morning blue light exposure (a predictor of total night-time sleep), daytime activity level (a predictor of sleep efficiency) and visual function (a predictor of minutes awake during the night) might contribute to sleep quality. Lastly, throughout each chapter the analysis has considered the result in order to make evidence informed conclusions and recommendations (objective 5).

7.2 Key conclusions of this research

7.2.1 Individual and environmental attributes associated with sleep quality

Across both studies, results indicate combinations of factors are associated with sleep regulation. For older people regression modelling suggested that different predictors might exist for different sleep quality parameters, including a range of human physiological factors (visual acuity, physical activity etc.). Results indicated morning blue light exposure (a predictor of total night-time sleep), daytime activity level (a predictor of sleep efficiency) and visual function (a predictor of minutes awake during the night) were predictors of sleep quality. These associations suggest covariates (e.g. visual function and physical activity) are currently under explored in light and sleep quality studies of older people.

This research is consistent with previous work, which has reported a combination of health and/or lifestyle choices may be associated with sleep quality (Luik *et al.*, 2013). Luik *et al*. (2013) measured a series of socio-demographics, mental health (i.e. cognitive function and depression level), lifestyle (i.e. caffeine, alcohol, smoking, body mass index (BMI)) and sleep parameters (i.e. actiwatches and sleep diaries) in older people aged 62±9.4 years (n=1734). Results from this study indicated that older age was associated with more fragmented periods of daytime activity ($p<0.02$). Although, in this current thesis mental wellbeing was not associated with sleep quality, depressive symptoms have been reported to be associated disrupted circadian rhythms and sleep quality characteristics (Tsuno, Besset and Ritchie, 2005; Carvalho-Bos *et al.*, 2007; Germain and Kupfer, 2008). Therefore, results from this thesis and findings currently published point to a growing need to explore a wide range of health and lifestyle factors in relation to sleep quality.

In young people with ASD, the results suggested sleep onset was delayed at weekends and the total hours of sleep at night was less than recommend by current NHS sleep guidelines, i.e. age 12-13 years require 9 hours, 15 minutes, age 14 years and older require 9 hours sleep (http://www.nhs.uk/Livewell, accessed 9/10/2015). In Chapter 3

the case study actigraphy data suggested when in a routinized situation (i.e. during the school week for adolescents with ASD) participants displayed a regular sleep pattern, e.g. maintained the same bedtime and wake times, but that total sleep time was below recommendations. At weekends, however, whilst participants slept for a similar duration of time, there was a significant difference in bedtime and wake up time (an approximate 3 hours phase-shift). These findings corroborate with research by Hansen *et al*. (2005), Moore and Meltzer (2008) and Au *et al*. (2014), suggesting current school timetables may be a hindrance to sleep quality. Future research is needed to confirm the impacts of changing the school day and the relationship sleep quality, school performance and how light exposure might play a role. This suggests the need for temporality as an important factor in the study design. Light exposure, along with other bodily functions, lifestyle choices and temporality are likely to be contributing to sleep quality at all ages.

7.2.2 Timing, duration and colour of light exposure

This thesis identified a gap in lighting research relating to time and duration of blue and/or bright light that it was associated with sleep quality. The studies explored blue light exposure, illuminance levels and durations in thresholds across a 24-hour cycle, for 4 days and in two seasons. Firstly, in relation to timing, findings suggested that mean morning blue light exposure (08:00-12noon) was associated with sleep efficiency. This is consistent with other works suggesting morning light is important to sleep regulation (Okumoto *et al.*, 1998; Koyama, Matsubara and Nakano, 1999; Yamadera *et al.*, 2000; Fetveit and Bjorvatn, 2006). In this current study, associations were not reported for whole day exposure, however, previous research has demonstrated that good lighting across the daytime may have the same benefits to sleep quality (Riemersma-van der Lek, Swaab and Twisk, 2008). In this thesis regression modelling suggested morning blue light had the strongest association with sleep efficiency over level of illuminance or indeed the duration of time in thresholds. However, this is not to say that illuminance levels or durations of exposure are not important, as several other studies have reported associations with sleep quality (Shochat *et al.*, 2000; Ancoli-Israel

et al., 2003; Sharkey *et al.*, 2011; Friedman, 2012). It does, however, indicate that the blue spectral content of light is likely to be important for promoting sleep quality. Additional explorations of blue spectral irradiance thresholds are required, due to the limited amount of literature presently available.

Results in relation to adolescents with ASD suggested that blue light of low intensity 4 hours prior to bedtime was associated with a delayed sleep onset. Although the sample size was too small to determine the accuracy of this association, the relationship was in line with previous studies (Dewan *et al.*, 2011; Chang *et al.*, 2012). In this research it was not possible to detect the precise source of this light emission (e.g. daylight, electronic devices or indoor artificial light). However, it generates questions about pre-bedtime light exposure patterns and how these might affect the ability to fall asleep. This is particularly pertinent if the light is being emitted from electronic backlit devices and how usage should be monitored prior to bedtime. It is important to better understand blue light exposure in adolescents, a population who are already experiencing changes in their circadian rhythms, i.e. later sleep onset, later wake up times and require longer sleep durations (Hagenauer *et al.*, 2009), whilst growing up in a digital age where much of daily communication is carried on electronic devices via the internet.

Secondly, duration of exposure is equally important and remains under debate. This research demonstrated the morning interval 08:00-12noon, i.e. 4 hour exposure duration was important for sleep quality. Other studies have reported shorter durations (i.e.08:00-11:00 or 09:30-11:00) (Okumoto *et al.*, 1998; Koyama, Matsubara and Nakano, 1999; Yamadera *et al.*, 2000; Fetveit, Bjorvatn and Skjerve, 2003) may equally prove to be associated with improved sleep quality. Contrary to this other studies have reported improvements are observed only after whole day exposure to bright light (Riemersma-van der Lek, Swaab and Twisk, 2008). The existing body of research has simply explored levels of illuminance and not focused on the blue spectral component of light - although short-wavelength light has been documented to be most effective upon the circadian system and sleep timings. To continue identifying the optimum duration of morning blue light exposure further studies are required. Researchers may choose to

interrogate the lighting designs varying in blue spectral content and duration of morning exposure, whilst exploring the associations with sleep quality and circadian rhythmicity.

Thirdly, colour of light and indeed interior surfaces might also contribute to the amount and quality light received at the eye. This is because much of the light that reaches our eye is reflected from surfaces. The spectral composition of light sources might influence appearance and ambience in a room. The colour-correlated temperature (CCT) is an indication of how warm or cold light might appear, i.e. positioned in either the yellow/red part of the spectrum of the blue/green area. In Chapter 6 there was a discussion of CCT lamps defining low Kelvin (K) temperatures as warm and higher K as cool (Boyce and Cuttle, 1990; Davis and Ginthner, 1990; O'Conner and Davis, 2005; Vogels and Bronckers, 2009). Therefore, when considering the pattern of natural daylight one should assume that indoor light should reflect this in terms of CCT. For example, morning light should reflect higher CCT lamps (bluer, brighter light) and evening light lower CCT lamps (warmer red/yellow, softer light). Research has also reported that higher CCT lamps (i.e. bluer outputs) were found to appear brighter with lower lux levels compared to lamps with lower (yellower) CCT (Chellappa *et al.*, 2011; Iskra-Golec, Wazna and Smith, 2012). There is also evidence to suggest that a person's melatonin suppression response might saturate at particular higher intensity light levels, yet this is still to be scientifically confirmed (Smith, Revell and Eastman, 2009; Bellia, Bisegna and Spada, 2011). These findings pose the questions as to how artificial light is effectively used indoors, both in terms of circadian entrainment, health, as well as energy performance and sustainability.

The lighting community does recognise the need to advance lighting with a circadian agenda. In Chapter 6 a novel artificial daylight concept was described (Chapter 6, section 6.2, see section 6.3, CoeLux), demonstrating a shift towards mimicking daylight indoors. Lighting research and technology appears to be making a step change in understanding methods and indeed the necessity to produce light sources of a spectral distribution close to that of daylight. An important note at this stage is again to reinforce the need to be exposed to natural daylight, which provides a free and effective way of boosting lighting levels. Whilst advances in lighting design are needed – particularly in

a care home context – artificial and electric indoor lighting should not become an accepted long-term solution or alternative to vital time outdoors.

The concept that our interior environment may be related to the non-visual performance of the eye is an emerging topic. A new study by Bellia *et al*. (2015) suggests that the spectral irradiance at the eye, photoreceptor stimulation, hue and chrome values vary significantly with different combinations of wall and lighting scenes and this has the potential to affect the non-image forming response. Specifically, the authors suggest rooms decorated in yellow hues might be likely to require greater amounts of light to achieve circadian response. They found that cooler coloured walls (such as light or pale blue and violet) reflected shorter wavelength light i.e. 450-480nm range. This study suggests exciting advances in terms of interior colour choice and the importance to circadian entrainment. The pattern of light across the day is fundamental to daily human functioning. It is desirable that an artificial light pattern should mimic, as closely as possible, the diurnal pathway of daylight. This will inevitably help to entrain the circadian clock and as a consequence the sleep/wake cycle.

7.2.3 Relationship with the built environment

In this research only light exposure was explored, however the effects of the built environment upon human health and wellbeing are not limited to light exposure. In the previous two sections (7.2.1 and 7.2.2) the concepts of other factors contributing to sleep quality were introduced. The discussions focused on possible physiological contributors and concept of delivering light exposure at the correct timing and durations across the daytime. This section explores the physical environment and introduces the idea that other indoor environmental factors could be related to sleep quality, circadian efficiency and by extension health and wellbeing. If light has the power to influence human physiology it is not unreasonable to assume that other indoor environmental factors such as air quality (i.e. adequate ventilation, sustained humidity levels and limited air pollutants), acoustics (i.e. sound absorption to reduce reverberation, limit noise transfer between rooms and ensure correct balance between indoor and outdoor

noise), thermal comfort (i.e. relating the indoor temperature) or water quality (although this is the least likely to be associated with sleep) may also affect sleep quality (Garre-Olmo *et al.*, 2012).

Studies investigating indoor environment quality (commonly phrased as IEQ) often measure this against human performance i.e. stress, work efficiency, concentration, mental alertness, or fatigue (Lamb and Kwok, 2016) or indeed building energy performance (Fisk, Black and Brunner, 2011; Singh *et al.*, 2011; Nimlyat and Kandar, 2015). It now seems timely to research this at a human physiological level and examine the impacts upon health and wellbeing indicators. It would be difficult to isolate all variables affecting a person's sleep, e.g. daily social interactions, sensitivities to sights, sounds and smells or underlying health conditions. However, this opens a novel field of research exploring IEQ measures in relation to human health and wellbeing indicators such as sleep quality.

Evidence exists to infer acoustics (noise), temperature and designs limiting social interactions in buildings may affect particular aspects of quality of life (Schnelle *et al.*, 1999; Garre-Olmo *et al.*, 2012; Wong *et al.*, 2014). Specifically, low quality of life assessments have been linked to higher indoors temperatures, higher noise levels and low social interactions, whilst low lux levels were associated with increased signs of negative affective mood (Garre-Olmo *et al.*, 2012). Complimentary to this poor quality of light (i.e. low lux levels) has been associated with poorer sleep quality (Zeitlhofer *et al.*, 2000) and lower mental wellbeing (Jean-Louis, Kripke and Ancoli-Israel, 2000). Therefore, it is sensible to assume that indoor environment quality may be associated with both quality of life and quality of sleep. Future research should consider incorporating other environmental factors, such as acoustic performance, air quality and/or a critique of spatial design in relation to facilitating social interactions into the study design as it is possible that sleep quality are affected by these too.

7.3 Implications for the built environment

(1) Interior design strategies

In collaboration with Heriot-Watt University's interior design programme, findings from this research were delivered as part of the 'Illusion of Memory' design project. These included: 1) season may contribute to physical activity levels and design should facilitate promoting activities; 2) morning light exposure is fundamental to promoting wakefulness and can contribute to sleep quality; 3) the visual; system differs across the life course and in particular older people should be exposure to much higher levels of illuminations across the daytime; 4) designs should enable older people to engaging socially and to spend time outdoors in safe and engaging spaces.

The interior design project created new design layouts for a residential care home. One proposal demonstrated how destination, interaction with nature and daylight could be integrated into design. Illustrated in Figures 7.1 and 7.2 are two design strategies, which would serve to enable a connection between nature, destination and view for older people. Figure 6.4 illustrates the potential of the 'indoor/outdoor' garden where residents could experience nature and good daylight, in a safe environment. Figure 6.5 illustrates the potential for a courtyard area, which would be flooded with natural daylight.

Figure 7.1 Illusion of memory: indoor garden to facilitate social engagement, Campbell, K. (2015)

Figure 7.2 Illusion of memory: nature's courtyard, Campbell, K. (2015)

In the current research there was diversity in the quality of spaces, both communal rooms and private bedrooms, across the care homes. Figures 7.3-7.6 demonstrate the range of good and poor lighting scenarios that were observed in the study locations. Figure 7.3 demonstrates a well-lit bedroom with a large window, allowing significant daylight penetrations, light coloured décor, a view out and seating placed for good light exposure. In contrast Figure 7.4 shows a setting where the bedroom was cluttered with heavy furniture and a dark colour scheme. Curtains hung over the window, furniture obscured a view out and daylight entering the room. Figures 7.5 and 7.6 are two contrasting examples for communal areas. Figure 7.5 identifies a dining are with good lighting and easy access to a garden area. Again the décor is light in colour and the room uncluttered for easy navigation. By contrast, Figure 7.6 shows a living room setting using the same lighting design, but a much darker interior décor. This demonstrates the choice of colour and its ability to reflect light is equally important as the as the room appears darker (compared to Figure 7.5)[14]. Similarly, the furniture is

[14] A limitation of these photographs is that they were taken with a smartphone, which may have affected the light quality in the photograph.

orientated with the back to the window, which reduces the amount of light hitting the eye and fails to benefits from a view into the garden area. This research highlights the inconsistency in lighting provision for older people living in care homes. There may be a lack of knowledge within care providers about the benefits of good lighting for older people. It also shows that there is added complexity in achieving good lighting and a décor that promotes better quality of light. Allowing people to personalise a space and achieve a sense of homeliness is often down to personal preference. Therefore, although light coloured décor, good daylight penetration and uncluttered space may be desirable, they may not be of personal preference.

Figure 7.4 Example of well-lit bedroom

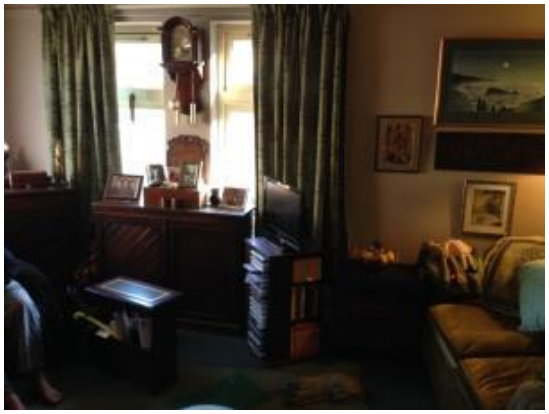


Figure 7.3 Example of poorly-lit bedroom

Figure 7.6 Example of well-lit dinning are

Figure 7.5 Example of décor affecting light quality

(2) Solutions in place

Although there are many strategic design changes that can be made to create environments that better suit biological functioning (i.e. orientating rooms with the path of the sun), these may not always be possible. Not all residential care homes are newly built and in the UK they may be a renovated period property (as was used in this study). There are simple solutions that can be implemented in an existing setting. The key focus is to maximise daylight in the building, as this is a free source of light and using electric sources to supplement this.

In the Stirling University Dementia Services Centre lighting guide (Marshall, 2001; McNair *et al.*, 2010) they introduced simple strategies, with a specific focus on those living with dementia related diseases, to improve lighting in care homes. These lighting considerations are also appropriate for older people living in care homes in general. Basic steps include ensuring that window-dressings, such as curtains or blinds, are fully open during the daytime hours and in particular during the morning period. Where possible, these should be pulled past the frame of the window to maximise light penetration through the window area available. Again, reasonable care should be taken to ensure that strong daylight does not cause people to overheat or suffer eyestrain from glare. This could be controlled with diffused blinds or external shading devices and sensors (Figure 7.7). What is important is that building occupants have a 24-hour light/dark cycle. Being exposed to 24-hour diurnal pattern of light will help to normalise circadian patterns and thus promote regulated sleep/wake cycles (as well as other bodily functions).

Much of the light that reaches the eye is reflected from other sources, e.g. from vertical and horizontal surfaces. Therefore, consideration must be given to the colour of walls, furnishings and flooring. Bellia *et al*. (2015) suggest rooms decorated in yellow hues are likely to require greater amounts of light to achieve a circadian response, whilst rooms decorated in cooler colours reflect more short wavelength light. It is recommended that walls, furnishings and rooms surfaces would be best in light colours (McNair *et al.*, 2010). This creates brighter rooms with more light reflection. It is also important for these to be of a matt finish to reduce glare and reflectance from surfaces and to offer

different tones of colour to help distinguish objects. This is because ageing causes the perception of colour to differ (Ishihara *et al.*, 2001) due to age-related changes, i.e. yellowing lens and narrowing pupil. Tone is based on distinguishing light from dark, therefore the more defined the differences in tonal colour the easier it is to identify objects and remain orientated (e.g. light coloured walls and darker coloured flooring, or door and doorframe distinguishable from the rest of the wall through choice of colour). The colour should also reflect the orientation of the room. For example rooms that face predominantly north would benefit from warm tones of colour as north-facing spaces will receive no bright sunlight. Cooler hues may exacerbate the feeling of reduced sunlight in north facing spaces.

The maintenance of supplementary electric light sources is also of importance in ensuring that indoor lighting is as effective as possible. At particular times of the year in the U.K., when the hours of daylight are reduced and sunlight exposure is limited, electric luminaires are the main source of light available to people indoors. Replacing broken or fused luminaires and cleaning them regularly, will ensure that rooms are constantly adequately lit. This is also true of windows, cleaning and maintaining external space close to windows is essential. A clean window will allow more daylight penetration than one which is dirty or masked by overgrown external foliage for example.

Figure 7.7 is an illustration of a window setting, which brings together the key aspects of architectural and interior design that might help to promote natural light exposure, which could help towards regulating the sleep/wake cycle and create a greater sense of wellbeing.

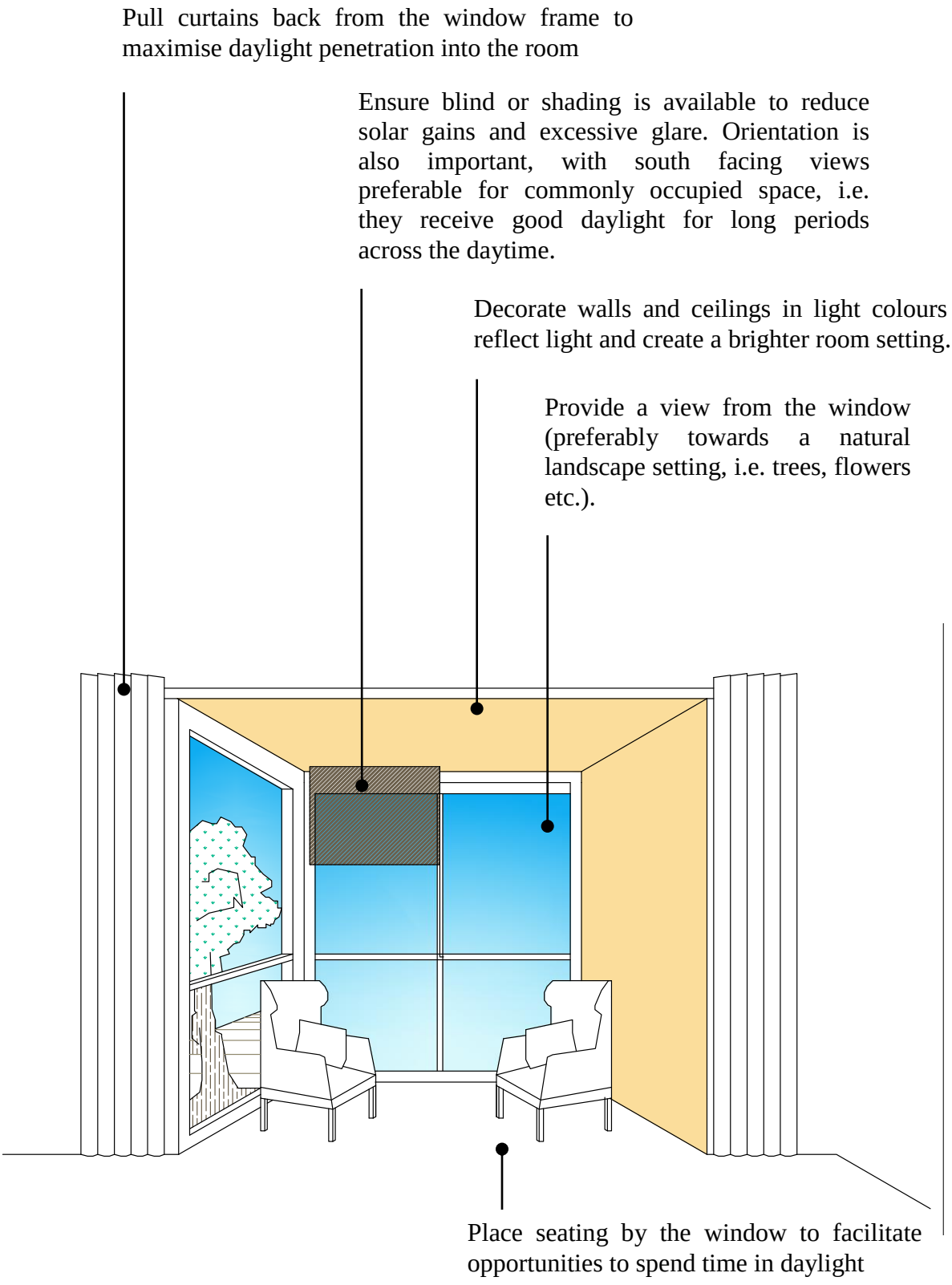


Figure 7.7 Schematic of care home window setting

(3) Broader applications

Although these recommendations are predominantly focused on older people and a care home setting at northern latitudes the core concepts are applicable across the life span and of course to other architectural settings. Other countries, such as those in the Mediterranean or closer towards the equator, experience different problems with light e.g. heat gains from the sun. Here the issue becomes one of cooling buildings rather whilst balancing good daylight distribution. Similarly, these countries offer a kinder climate, lengthier summers with time outdoors available more often (care should be taken in direct sunlight). The key message to remember is that internal spaces should have the best possible access to daylight and that rooms should be orientated towards the path of the sun as a response of either function and the requirements of building occupants. Light is an important design element for all building settings and across the life span. Outlined in the Box 7.1 below are the key recommendations that are applicable across the life span.

Insights from this work are applicable to a range of other target groups, such as provision of better lighting in hospitals or hospices where people are often unable to go outside, schools or universities, where young people spend long duration of time in classes during the morning hours, or in working populations where lighting also plays an important role across the daytime. The guidelines discussed here strongly suggest that designers should aim to develop a human-centred approach to lighting solutions in buildings.

Box 7.1 Broader applications in the built environment

1) **Maximise bright light exposure in the morning hours** – post-wake exposure to light helps synchronise the body clock and entrain the 24-hours circadian pattern. The best source of this is to spend time outdoors. In winter when light is more limited electrical sources (such as lamps with a colour correlated temperatures of 5000 K and above) would be a helpful substitute.

2) **Reduce light exposure at night-time** - to promote the production of melatonin, which aids sleep, light exposure (in particular light high in blue spectral content) should be limited prior to bedtime. Bedrooms should reduce exposure from light as much as possible to ensure restful sleep. Heavy curtains or blackout blinds could be used to exclude light pollution from external sources (i.e. bright light in summer or excessive light from street lighting).

3) **Orientation** – where possible rooms ought to face the required circadian direction (i.e. bedrooms with morning light exposure). The positioning of furniture towards windows with a stimulating view would be helpful for both circadian entrainment and also for general wellbeing.

4) **Outdoors** – designs should always facilitate easy access to outdoors, be these gardens, balconies or terraces. There is no substitute for going outside into daylight to help circadian entrainment. Time outdoors brings additional health and wellbeing benefits, such as fresh air and a source of vitamin D (Humble, 2010).

5) **Introduce environmental cues** – beyond light as a synchroniser for daily rhythms access to other environmental cues are also important. Time of day, ambient air temperature, noise and acoustic levels all play a role in determining the time of day and entraining circadian rhythms. Creating light and view filled destinations in rooms would facilitate access to environmental cues.

7.4 Implications for policy makers

The findings from this research, although related to two specific populations, still have relevance to people at different stages across the life course. Maintaining a regular sleep/wake pattern, ensuring good sleep hygiene, engaging in social interaction and exposure to environmental zeitgebers (i.e. a cue given by the environment, such as a change in light or temperature) are vital to all individuals and not limited to older adults or indeed young adolescents.

This research indicates that older people may be receiving inadequate light exposure at important times of the day (i.e. morning lux levels were low). Results also suggested that light exposure and duration in bright light were limited in both seasons. Statistical analysis revealed an association between morning blue light exposure and sleep parameters and daytime activity levels (e.g. higher blue light exposure was positively associated with sleep efficiency and daytime activity levels). Preliminary findings pertaining to adolescents with ASD suggested higher levels of blue light exposure prior to bedtime were associated with longer sleep onset latency and routine may play a part in regulating the sleep/wake pattern. These recommendations are pertinent to the general population, i.e. good sleep hygiene will help towards better sleep quality. The recommendations in Box 7.2 will be applicable to both older people living in a care home setting and more widely to those living with sensory impairments.

Box 7.2 Broader applications across the life span

1) **Morning bright light is fundamental to regulating the sleep wake cycle.** The evidence gathered in this research and taken together with the larger body of research exploring light exposure in humans, suggests that morning bright light post wake is fundamental to regulate and resynchronise circadian rhythms. Where persons have a reduced capacity to seek out bright light independently, it should be a prerequisite of the care routine to encourage exposure throughout the morning hours and indeed into the afternoon period.

2) **Artificial indoor lighting is not a substitute for time outdoors.** Following on from point 1, it should be stressed that time outdoors is the most effective and important source of light exposure to all humans. Beyond circadian entrainment it offers additional and vital health benefits, such as a source of vitamin D. A recent meta-analysis suggested that lower vitamin D concentrations are associated with a decline in cognitive function (Balion *et al.*, 2012). Therefore, for older people at risk of or already displaying a decline in cognitive function, time outdoors is imperative to maintaining healthy daily functioning.

3) **Activity levels may be associated with improved sleep quality.** In this research there was a positive correlation between sleep efficiency and daytime activity level. This is consistent with other studies (Alessi *et al.*, 1995; Alessi *et al.*, 1999). Therefore, in addition to bright morning light exposure it would be sensible to introduce physical activity into a person's day to improve sleep quality the following night.

4) **Limit blue light exposure at night.** Excessive light at night may be contributing to sleep disruption (Wood *et al.*, 2013). Preliminary findings in this research and from the wider context, suggest higher light levels or prolonged exposure may cause sleep disruptions. The care environment and hospitals should be mindful of this and seek to limit light exposure in bedrooms to promote a sense of relaxation and sleepiness. Ensuring curtains or blinds are of a fabric heavy enough to block light from outside. Where possible light emitting technology should be removed from the bedroom and use of red light sensors to allow night-time mobility to the bathroom.

5) **Create social and environmental interactions.** In this research an emerging theme was the importance of routine and access to environmental information (i.e. consistent routine, daily activity level). Care policy should be centred on accessing time of day, such as clocks, spending time outdoors in the morning, regularising mealtimes, promoting awareness of changes in light levels across the day and ensure social interaction to help towards maintaining a regular sleep/wake pattern.

6) **Holistic view in improving the quality of sleep and the environment.** It is important to recognise that sleep quality and the residual effects may be caused and affected by other environmental factors. Air quality, views or access to green space, noise exposure and acoustics, smells and colour of walls, may all be contributing factors that influence poor or indeed improved sleep quality. It is important to be mindful that although higher light levels are needed in care homes so too is good air quality, a reduction in excessive noise and a calming uncluttered colour scheme.

7) **Different lighting requirements occur across the life course.** Specifically, older people, those experiencing a decline in cognitive function or living with low vision require brighter lighting levels and/or help to ensure better light exposure.

8) **Better lighting has residual benefits to all building occupants.** Not only does better quality lighting improve the lives of persons with sensory and/or visual limitations, it also serves to promote better sleep and potential health improvements for all building occupants. For example a care home with better lighting may help staff to carry out their job with easier navigation of spaces and help maintain their own circadian rhythms when bound indoors for long periods during the daytime.

9) **Consider a lighting "routine".** The need for a regulated diurnal light exposure pattern was discussed throughout this thesis. Where possible indoor lighting should be varied across the course of the day, i.e. ceiling mounted luminaires in a cooler brighter colour temperatures (e.g. 10,000 K) would be best utilised in the morning hours and earlier afternoon. Whilst the lighting should be changed in the later afternoon and evening to more ambient task lighting centred in warmer colour temperatures (2000 K). Light during the sleep period should be blocked from bedrooms as much as possible and care staff should consider the use of red light sensors at night to limit circadian disruption.

7. 5 Strengths and limitations of the research

7.5.1 Key strengths and original contribution

The key strengths of this thesis are in, 1) confirming an association between blue light exposure and sleep parameters and establishing blue light illuminance thresholds, 2) quantitatively assessing sleep and light simultaneously, 3) the effective incorporation of a visual assessment in older people, 4) successful engagement of participants in sensor data capture with complex sensory and cognitive issues, 5) utilising a novel regression technique to capitalise on the sample size and 6) the implications for the built environment.

(1) Confirming an association between blue light exposure and establishing thresholds of blue light exposure

This research confirmed an associated between sleep quality measures and light exposure. Specifically, results suggested morning blue light was associated with better sleep efficiency and prolonged exposure to blue light at night was associated with delayed sleep onset. These findings bring new insights, to the field of lighting studies, as they identify that the blue spectral component of light, in a natural setting, is important for sleep quality. The current body of work identified new avenues for research by establishing a series of blue irradiance thresholds to be explored in relation to sleep measures. The work here postulates that the duration of blue light exposure is an important requirement for circadian entrainment, yet few studies have investigated this in a fieldwork setting. The thresholds parameters were derived from evidence of associations between illuminance thresholds (lux levels) and sleep quality (Hubalek, Brink and Schierz, 2010; Rea *et al.*, 2010; Bellia, Bisegna and Spada, 2011). The blue light thresholds were based on Hubalek and colleagues' strategy of aligning blue light thresholds with illuminance thresholds by a factor of 100, i.e. 600-1000 lux became 60-100 $\mu W/cm^2$. The thresholds described in this research, therefore, advance the limited availability of empirical evidence exploring blue light irradiances. Future studies may wish to identify different threshold cut-off points or look at alternative durations across the daytime and explore the associations with sleep quality.

(2) Quantitatively assessing sleep and light exposure patterns

The actiwatch is a novel piece of equipment typically used in medical and clinical studies. Here the equipment and outcome measures were applied to research with a social and design agenda, demonstrating to be a successful measure of sleep and light. The actiwatches were easily administered in two populations with sensory difficulties and proved not to be intrusive, resulting in sustained wearing and limited removal. Outcome measures provided a robust quantitative measure of sleep and activity with detailed information beyond a subjective assessment alone. However, the subjective sleep assessment did compliment the findings and suggested an interesting narrative between actual sleep performance and personal feelings of sleep quality. An advantage of the actiwatch is its ability to gather multiple sleep parameters with a sophisticated algorithm allowing these to be isolated and explored individually. The incorporated light sensor reduces the number of devices to be worn by participants, which was helpful in a population with complex sensitivities. The results enabled evidenced based recommendations to be made, from both a design practice and policy perspective. This thesis also highlights the value and continued need for interdisciplinary research. The study protocol was developed and designed through medical and engineering literature, as well as consultations with leading medical professionals. The outcomes of this thesis, therefore, have implications for both the medical and engineering communities, whilst being applicable to the design community.

(3) Incorporating a visual assessment in older people

Incorporation of a visual assessment in lighting studies is now vital in advancing the field. Future studies, which aim to investigate associations between sleep and light exposure, particularly in a residential care home, need to consider the potential impediment of light transmission through the eye in order to develop more sophisticated lighting designs. Research is slowly recognising the explicit need to assess visual function in parallel to sleep and light exposure (Sander *et al.*, 2015), yet comparable studies are limited. Primarily, lighting standards are written with the standard observer at age 45 (CIE, 1983). However, one could argue that with an expanding ageing population the standard observer is now much older, e.g. age 65 years and older. In

recent studies it has been suggested that the absorption peak for melanopsin transmission decreases by approximately 72% from the age of 10 years to the age of 80 years (Kessel *et al.*, 2010). It is now relevant to create a range of lighting standards that are more specific in terms of age, sensory requirement and architectural location.

(4) Engaging participants in sensor data capture with complex sensory issues

The successful recruitment of people with complex sensory issues provides key insights into groups that may be experiencing sleep problems, yet may be limited in their abilities to improve sleep quality. The methodology used to engage participants and convey the required commitment of a study protocol showed a sensitive approach that could be easily replicated by other researchers. The use of graphic enabled a clear dialogue for both young and older people to follow. Moreover, the continued connection with the researcher throughout the duration of the data collection period proved a valuable tool in maintaining enthusiasm, limiting participant fatigue, and ensuring that participant's understood the value of their time. This allowed the principal investigator to express the vital role of participation in research and how in doing so a catalyst for changing and improving environments for all can be created.

(5) Introducing novel regression modelling techniques

The CCR regression modelling technique will progress research carried out in studies where recruitment of participants may be difficult, limiting sample size or similarly where the number of measured outcomes exceeds the number of participants. This method capitalised on the findings in a small sample. The CCR modelling technique is designed to address collinearity between variables and manage a greater number of predictor variables than sample size. In this research a large number of lighting variables were recorded. In this case it would not be uncommon to observe multiple-collinearity. CCR addressed this issue and generated a sounder interpretation of associations between light and sleep variables. Similarly, the programmes capacity to handle repeat cases maximised the data by using both seasonal light measurements to create a larger dataset. The results from regression modelling corroborated findings from other studies using traditional regression techniques, but raised new and important questions and suggested a combination of factors may be responsible for sleep quality in

older people, e.g. daytime physical activity and visual function (Shochat *et al.*, 2000; Hubalek, Brink and Schierz, 2010; Luik *et al.*, 2013).

(6) Application in the built environment

The focus of this thesis was to explore associations between personal blue light exposure, levels of illuminance and the sleep/wake cycle. The findings from this current research support this argument and suggest that morning (08:00-12:00) blue light exposure was associated with the total amount of sleep at night in older people. The findings for thesis research and the recommendations outlined in section 7.3 should help to inform meaningful and practical architectural design and lighting solutions. This thesis places a strong emphasis that the architectural response and procurement of design must reflect and respond to the diurnal path of light. In Box 7.4 below is a summary of the key strengths and contributions of this research.

Box 7.4 Summary of key strengths and contributions

1) **Confirming an association with morning blue light and developing a set of blue light thresholds.** The results strengthen the existing argument that morning light exposure can impact upon sleep quality and that adequate exposure is necessary to promote circadian entrainment.

2) **Quantifying sleep/wake patterns.** Demonstrated in this research was the ability to administer body-mounted, objective measures of sleep/wake and light patterns in people with complex sensitivities.

3) **Incorporating a visual assessment.** It is now necessary to incorporate a visual assessment in to lighting studies in order to progress the knowledge of the eyes role in creating better lighting environments.

4) **Data capture in two populations with sensory issues.** This thesis demonstrated it was possible to engage people with sensory sensitive in a study protocol with body-mounted sensors by delivering the protocol requirements in an understandable graphical representation.
5) **Capitalising on a small sample with novel regression modelling techniques.** The thesis took a novel approach to maximising the data available and ensuring more robust statistical analysis can be carried out in studies with small samples.

6) **Evidence based implications for the built environment.** The thesis described simple design strategies, which could be employed at design inception of ‘in place’ in existing facilities.

In summary, the findings here complement the existing body of work in relation to the lighting provisions in care home facilities for older people, whilst broadening this to look at the blue spectral component and visual function. The thesis addressed the inherent need to include a visual assessment in future lighting studies and posed the questions that lighting requirements must fit with age, visual capacity, architectural setting and sensory and/or cognitive functioning. The thesis identified a novel area of research, which is largely under explored, testing the feasibility of a protocol in adolescents with autism spectrum disorder. It is one of the first to postulate a relationship between, ASD, sleep/wake and light exposure patterns with a suggested study outlined. The thesis took a practical perspective by yielding conclusions and recommendations based on the evidence from the studies conducted and from the wider literature in the field. The conclusions and recommendations will be of interest to architects, lighting designers and social care policy makers, providing an important insight into the need to ensure sufficient light exposure in order to support a healthy sleep/wake pattern.

7.5.2 Limitations

The main limitation to this study was the small sample size. Although other studies have used a similar sized cohort and have reported significant findings (Van Someren *et al.*, 1997; Shochat *et al.*, 2000; Fetveit, Bjorvatn and Skjerve, 2003; Fetveit and Bjorvatn, 2006), it would still be beneficial if the sample were larger for statistical analyses, including conventional regression analysis. Studies conducted in a care home environment, with older people, could result in low participant numbers for a variety of reasons, e.g. morbidity rates are high or management are reluctant to participate. In this study there were anecdotal observations made during the recruitment session that indicated potential participants saw little benefit in taking part. Attempts to address this issue included: offering a small gift for participation, regular visits from the researcher from study start (summer) to end (winter), handwritten letters of thanks and an explanation that participating in research serves as a catalyst for change, which benefit the wider society. When working with older people, particularly those already living in

a supported environment, there is the increased likelihood of participant mortality. This was an issue in this research, resulting in the loss of one participant. Similarly, participant fatigue can be problematic, here two participant lost interest in the study and chose to withdraw.

Perhaps the most challenging aspect of recruitment (that may have hindered the sample size) was sourcing willing care homes and participants. The care home manager and the support staff were reticent to participate and would not permit a speculative recruitment session. Several facilities approached for this study expressed that they receive an overwhelming number of requests to take part in research. This may be expected, as research in older people, particularly those experiencing cognitive or other decline, is very topical. Therefore it is not unreasonable to find potential participants, or those facilities that support them, to be hesitant. This work sets a precedent for other researchers to follow when sample size is limited. It also highlights the need to find sites where research fatigue is not a problem.

Equipment related limitations included the location of the light monitoring sensor and the calibration of the light sensitive cells. At present light monitoring devices used in older people and those with a cognitive impairment have been mounted on the wrist or worn at the lapel (Shochat *et al.*, 2000; Ancoli-Israel *et al.*, 2003; Figueiro *et al.*, 2012). A common criticism of light and sleep studies is that wrist measurements are the least accurate in establishing the amount of light that might be reaching the eye. Sensors are often covered by clothing and predominantly record light on the horizontal plane due to the orientation of the arm. In this study the sensor was worn at the lapel and was recording light on the vertical plane in line with the eye. Although there is a more suitable device known as the daysimeter (Bierman, Klein and Rea, 2005), which is mounted on spectacles, this was not considered viable in the study population for several reasons. Not all participants in this study wore spectacles and there were several that were frail. Therefore, to expect non-prescription spectacles to be worn as a means of mounting a sensor was considered an onerous task. The creators of the daysimeter device have mounted the sensor in a similar fashion (on the lapel or as a neck pendent) in an older population living in a residential care (Figueiro *et al.*, 2012). It was felt that

a lapel worn device would be less likely to be removed or swapped from person-to-person. At the start of the study participants and staff were instructed to keep the lapel sensor uncovered and to ensure it was swapped daily from clothing. Upon collection of the device on the final study day no participant was found without the devices. The quality of the data recorded at the plain of the eye (i.e. lapel sensor) represents more accurately light incident on the eye. The actiware software also indicated that the devices were on the participant and excluded the data that was invalid.

At this time, there are few alternatives to the actiwatch, which are commercially available and it still remain the device of choice in the most recent studies (Sander *et al.*, 2015). The actiwatch is also a good representation of the future of healthcare sensors. It demonstrates it is possible to integrate multiple sensors measuring a range of variables in a single device. Future developers of sleep monitoring equipment may wish to investigate the integration of sound or temperature sensors, thus building a more accurate picture of current environmental conditions.

Although this research demonstrated successfully administering an in-situ visual assessment there were limitations in the equipment sourced for measuring vision. The in-situ measure meant that the room test conditions were difficult to control, e.g. lighting provisions were not consistent across study settings, the distance from the test board was difficult to maintain etc. Future research could employ simple tactics such as using a test boards mounted at a fixed angle and/or internally illuminated to maintain a uniform brightness across the test board. This would ensure consistent viewing conditions and constant illumination. Advanced studies may wish to take an ophthalmological approach and record intraocular pressure (i.e. fluid pressure in the eye), biomicroscopic evaluations (i.e. a magnified view of the eyes structure providing and anatomical diagnosis of various eye diseases) and measuring the light transmittance properties of the lens (Broendsted *et al.*, 2011; Sander *et al.*, 2015). An assessment at this detail, however, requires an experienced ophthalmologist and as yet has only been conducted in healthy older people (Sander *et al.*, 2015). Nevertheless, this thesis advanced lighting research by demonstrating it is possible to measure vision in a real life setting, and returned interesting results.

This research used the sleep/wake cycle as a circadian marker, but lacked a biological marker such as melatonin assay, salivary cortisol or tympanic temperature (core body temperature). These tests are a biological indication of a person's circadian rhythms. However, they require added involvement from participants, such as blood or saliva samples. These would be a considerable request for older people, who may be experiencing cognitive decline and cause confusion about their health and medical state. A possible alternative in future studies with older people would be tympanic temperature, taken with a thermometer in the ear (van Hoof *et al.*, 2009). Taking such measurements requires the expertise of qualified nursing staff and may also be time consuming and labour intensive methodology.

7.6 Future research agenda

This thesis contends that blue light exposure and illuminance levels were associated with sleep quality. It postulated that other physiological, health, lifestyle factors and a range of environmental qualities could be predictor variables of sleep. Future research should consider a combination of these factors and the mechanisms in which they operate in regulating sleep. This would require very careful study design to isolate potential predictor variables and their relationship with sleep. In Box 7.3 are a series of future research recommendations.

Box 7.3 Future research recommendations

1) **Further empirical research is required to continue exploring the complex relationships** between physiological factors, irregularities in melatonin secretion across the day, circadian rhythmicity, visual health and light as the modulators of sleep. Already discussed at length, it is now vital to incorporate a visual assessment as there is still much that is unknown about the non-visual performance of the eye. Currently, there is limited information available to compare lighting studies with vision measured in a fieldwork setting. To better understand the eye and the role of the ipRGC and other pathways in sleep more work is needed.

2) **Future research agendas should examine physical activity**. This thesis demonstrated that daytime activity may also be playing a role in sleep quality of older people. With much media interest and a reported financially strained NHS (Campbell, 2014) researching simple and effective solutions to health problems are important for a sustainable future. There is need to better understand what role routine and simple sleep hygiene play in regulating sleep, as these are likely to be easily implemented.

3) **Research in autism should explore the role of routine, lifestyle and sleep hygiene**. There are many unanswered questions about the use of dietary supplements such as melatonin. This research postulated that light exposure should be investigated as a non-pharmaceutical alternative to modulate sleep.

4) **Explore architectural and design elements in relation to the physiological human response**. There is already growing interest in applying neuroscience findings to design (Edelstein, 2006; Eberhard, 2009). The application of scientific findings, which reveal how the brain might process the built and natural environments, could progress the way in which we design to a new level. What seem like outwardly disparate disciplines can be brought together, generating pertinent questions in relation to the practise of architecture, engineering, psychology, interior and exterior lighting design.

5) **Health monitoring and sensor technology**. This research used a novel body sensor to monitor sleep/wake and activity in two populations with sensory issues. The researcher did not report participant resistance to the technology, but feedback from the ASD group suggested that aesthetics of the product might help towards participant engagement. Future research should continue to investigate methods of integrating sensor technology, which either excites a participant's interest or is unobtrusive and becomes undetectable. This could consist of integration into clothing fabrics or design customisation by participant. Research designs and methods that reduced burden upon participants could help towards extended research periods and provide robust quantitative measures of variables.

7.7 Closing comments

Together the studies in this thesis support an association between sleep and light exposure as well as reinforcing the role of good light exposure in regulating circadian rhythms and daytime activity levels. The research suggested associations between sleep and physical activity, morning blue light exposure and sleep as well as cognitive function and visual function in older people. The cross-sectional study identified the variations in seasonal light exposure showing this to be very low in the winter, and yet found no significant differences in the sleep patterns of older people. This finding alone establishes grounds to explore the impact of poor lighting in winter in relation to the health and wellbeing of older people. Moreover, this study indicated that lighting may be relatively low independent of the time of year, raising further questions about the adequacy of current lighting provisions for older people.

The thesis brought to attention a novel and largely under explored area in relation to adolescents living with ASD. The pilot study demonstrated the successful administration of a protocol in adolescents with ASD, whilst suggesting interesting associations between light and delayed sleep onset. Although there is little imperial evidence to compare findings and the sample size was small the study had strength in the innovative use of visual aids for recruitment, conveying a study protocol and a sympathetic approach to working with young people with complex sensory issues.

The key message arising from this research is that morning light is fundamental to circadian entrainment and whilst advocating higher illuminance levels indoors and effectively using the daylight it also recommends artificial lighting should complement this. The thesis also aims to advocate that a diurnal light pattern should be adhered to in order to maintain regular circadian rhythms and ensure a habitual sleep/wake cycle.

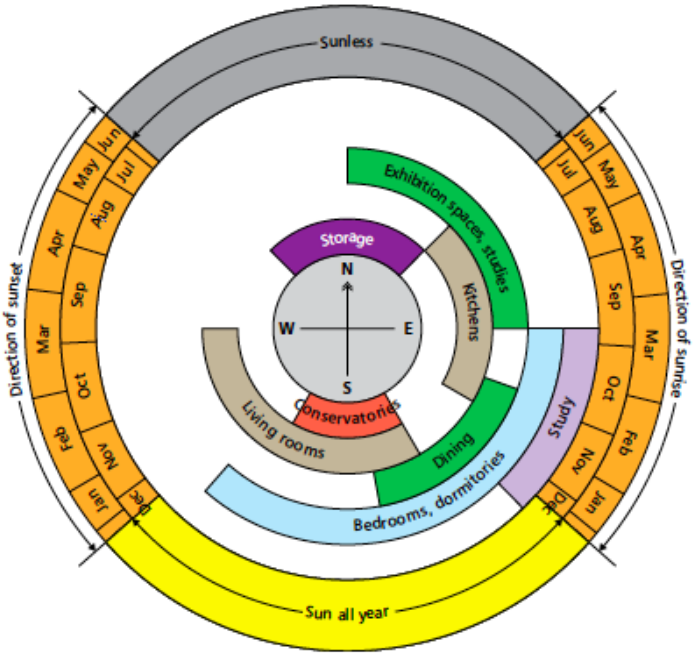
Future studies should continue to explore light in a growing older population and groups with sensory issues, with the aim to better understand the blue spectral irradiance of light sources beneficial to circadian entrainment. For change to occur the design community must champion the benefits of light and to have a better understanding that

access to daylight at the correct time of day is fundamental to those with a range of sensory issues and pre-exiting sleep disruption conditions.

In conclusion, this research provides valuable insights into the lighting conditions for older people living in care homes and suggested ways to improve this and future environments. The thesis identifies the need for lighting designers and architects to adopt a human-centred approach to lighting provision and facilitate deigns that enable this, whilst proposing ground for new research directions.

Appendix A: Original CIBSE room orientation and sun-path diagram

Figure 2.3 Sunlight availability by orientation at latitude 53 °N



Appendix B: Pittsburgh Sleep Quality Index (PSQI)

Instructions:
The following questions relate to your usual sleep habits during the past month *only*. Your answers should indicate the most accurate reply for the *majority* of days and nights in the past month. Please answer all the questions.

1) During the past month, when have you usually gone to bed at night?

Usual bed time

2) During the past month, how long (in minutes) has it usually take you to fall asleep each night?

Number of minutes

3) During the past month, when have you usually got up in the morning?

Usual getting up time

4) During the past month, how many hours of actual sleep did you get at night? (This may be different from the number of hours spent in bed.)

Hours of sleep per night

For each of the remaining questions, check the one best response. Please answer all questions.

5) During the past month, how often have you had trouble sleeping because you…..

a) Cannot get to sleep within 30 minutes
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

b) Wake up in the middle of the night or early morning
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

c) Have to get up to use the bathroom
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

d) Cannot breathe comfortably
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

e) Cough or snore loudly
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

f) Feel too cold
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

g) Feel too hot
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

h) Had bad dreams
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

i) Have pain
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

j) Other reason(s), please describe
_____
_____
_____

How often during the past month have you had trouble sleeping because of this?

Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

6) During the past month, how would you rate your sleep quality overall?

Very good_____

Fairly good_____

Fairly bad_____

Very bad_____

7) During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep?
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

8) During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

9) During the past month, how much of a problem has it been for you to show enthusiasm to get things done?

No problem at all_____

Only a very slight problem_____

Somewhat of a problem_____

A very big problem_____

10) Do you have a bed partner or roommate?

No bed partner or roommate?_____

Partner/roommate in other room_____

Partner in same room, but not same bed_____

Partner in same bed_____

If you have a roommate or bed partner, ask him/her how often in the past month you have had)…

a) Loud snoring
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

b) Long pauses between breaths while asleep
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

c) Legs twitching or jerking while you sleep
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

d) Episodes of disorientation or confusion during sleep?
Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week _____

e) Other restlessness while you sleep; please describe
_____
_____
_____

Not during the past month _____
Less than once a week _____
Once or twice a week _____
Three or more times a week_____

Appendix C: Mini Mental State Examination (MMSE)

I. **ORIENTATION** (Ask the
following questions; correct = ❑) **Record Each Answer:** (Maximum Score = 10)
What is today's date? Date (eg, May 21) 1 ☐
What is today's year? Year 1 ☐
What is the month? Month 1 ☐
What day is today? Day (eg, Monday) 1 ☐
Can you also tell me what season it
is? Season 1 ☐
Can you also tell me the name of
this hospital/clinic? Hospital/Clinic 1 ☐
What floor are we on? Floor 1 ☐
What city are we in? City 1 ☐
What county are we in? County 1 ☐
What state are we in? State 1 ☐
II. IMMEDIATE RECALL (correct = ❑) (Maximum Score = 3)
Ball 1 ☐
Flag 1 ☐
Tree 1 ☐
Ask the subject if you may test
his/her memory. Say "ball, "flag,"
"tree" clearly and slowly, about on
second for each. Then ask the
subject to repeat them. Check the
box at right for each correct
response. The first repetition
determines the score. If he/she does
not repeat all three correctly, keep
saying them up to six tries until
he/she can repeat them
NUMBER OF TRIALS: _____
III. **ATTENTION AND**
CALCULATION
A. Counting Backwards Test (Record each response, correct = ☐
) (Maximum Score = 5)
93 1 ☐
86 1 ☐
79 1 ☐
72 1 ☐
Ask the subject to begin with 100
and count backwards by 7. Record
each response. Check one box at
right for each correct response. Any
response 7 or less than the previous
response is a correct response. The
score is the number of correct
subtractions. For example, 93, 86,
80, 72, 65 is a score of 4; 93, 86,
78 70, 62, is 2; 92, 87, 78, 70, 65 is
0.
65 1 ☐
B. Spelling Backwards Test
D 1 ☐

L 1 □
Ask the subject to spell the word "WORLD" backwards. Record each response. Use the instructions to determine which are correct responses, and check one box at right fore each correct response.
R 1 □
C. Final Score O 1 □
Compare the scores of the Counting W 1 □
Backwards and Spelling Backwards tests. Write the greater of the two socres in the box labeled FINAL SCORE at right, and use it in deriving the **TOTAL SCORE**.
FINAL SCORE_____ (Max of 5 or Greater of the two Scores)
IV. **RECALL** (correct = □) (Maximum Score = 3)
Ball 1 □
Flag 1 □
Ask the subject to recall the three words you previously asked him/her to remember. Check the Box at right for each correct response. Tree 1 □
V. Language (correct = □) (Maximum Score = 9)
Naming Watch 1 □
Show the subject a wrist watch and ask him/her what it is. Repeat for a pencil.
Pencil 1 □
Repetition
Ask the subject to repeat "No, ifs, ands, or buts." Repetition 1 □
Three -Stage Command
Takes paper in hand 1 □
Folds paper in half 1 □
Establish the subject's dominant hand. Give the subject a sheet of blank paper and say, "Take the paper in your right/left hand, fold it in half and put it on the floor." Puts paper on floor 1 □
Reading
Hold up the card that reads, "Close Closes eyes 1 □
your eyes." So the subject can see it clearly. Ask him/her to read it and do what it says. Check the box at right only if he/she actually closes his/her eyes.
Writing
Give the subject a sheet of blank paper and ask him/her to write a sentence. It is to be written sponataneously. If the sentence contains a subject and a verb, and is sensible, check the box at right.

Correct grammar and punctuation
are not necessary.
Writes sentence 1 □

Copying

Show the subject the drawing of the intersecting pentagons. Ask him/her to draw the pentagons (about one inch each side) on the paper provided. If ten angles are present and two intersect, check the box at right. Ignore tremor and rotation.

Copies pentagons 1 □

DERIVING THE TOTAL SCORE

Add the number of correct responses. The maximum is 30.

TOTAL SCORE

_____

23-30 = Normal / 19-23 = Borderline / <19 = Impaired Up to Grade 8 Level

Appendix D: Warwick Edinburgh Mental Wellbeing Scale (WEMWBS)

The Warwick-Edinburgh Mental Well-being Scale (WEMWBS)

Below are some statements about feelings and thoughts.

Please tick the box that best describes your experience of each over the last 2 weeks

STATEMENTS	None of the time	Rarely	Some of the time	Often	All of the time
I've been feeling optimistic about the future	1	2	3	4	5
I've been feeling useful	1	2	3	4	5
I've been feeling relaxed	1	2	3	4	5
I've been feeling interested in other people	1	2	3	4	5
I've had energy to spare	1	2	3	4	5
I've been dealing with problems well	1	2	3	4	5
I've been thinking clearly	1	2	3	4	5
I've been feeling good about myself	1	2	3	4	5
I've been feeling close to other people	1	2	3	4	5
I've been feeling confident	1	2	3	4	5
I've been able to make up my own mind about things	1	2	3	4	5
I've been feeling loved	1	2	3	4	5
I've been interested in new things	1	2	3	4	5
I've been feeling cheerful	1	2	3	4	5

Warwick-Edinburgh Mental Well-Being Scale (WEMWBS)

Appendix E: Personal questionnaire

Daily routine questionnaire

Please complete and return

Name ……

Date ……..

Part 1 YOURSELF (Please tick or complete the response where indicated)

1- Gender

Male ☐

Female ☐

2 – Date of birth……..

3 - Which ethnic group do you belong to?

☐White Scottish

☐Other White UK

☐Any other white background (specify) _____

☐Other ethnic background (specify) _____

Part 2 HEALTH (Please tick or complete the response where indicated)

1 - In general would you say that, for a person of your age, your health is*:*

□Very good

□Good

□Neither Good nor Poor

□Poor

□Very poor

Part 2 DAILY ROUTINE (Please tick or complete the response where indicated)

1 - Where to you like to spend your time in the morning?

□Living room

□Dining room

□Bedroom

□Outside

2 - What are typical morning activities?

□Watch TV

□Talk

□Read

□Sleep

□Exercise

□Entrainment

□Other……..

3 - Where to you like to spend your time in the afternoon before?

□Living room

□Dining room

□Bedroom

□Outside

4 - What are typical afternoon activities?

□Watch TV

□Talk

□Read

□Sleep

□Exercise

□Entrainment

□Other……..

5 - How often do you spend time outside?

□Once a day

□A few times a week

□Once a week

□Never

6 – At what time of day are you generally outside (weather permitting)?

□Morning - post breakfast

□Afternoon – post lunch

□Other……..

7 – For how long are you outside?

□30mins or less

□30mins to 1 hour

□1 hours +

□All day (i.e. excursions)

□Other……..

8 - What do you like to do in the evenings before going to bed?

□Watch TV

□Read

□Listen to music/radio

□Talk with friends

This is the end of our questionnaire.

Thank you for your time.

Appendix F: ASD staff focus group and parent one-to-one questions

ASD – Focus Group Questions

About the child

1. How old is your child?
2. Are they male/female?
3. Have you ever taken part in a previous clinical trial involving either a lighting intervention or melatonin tablets?

Sleep

1. What time do they go to bed?
2. What time do they get up?
3. How often do they wake during the night and for how long?
4. How often do they sleep through the night?
5. Does disrupted sleep appear worse during the winter or summer months?
6. How does the lack of sleep impact on them and your family?

Daily routine

1. Does your child regularly spend time outside during mid-morning to early afternoon?
2. For how long and at what time does your child use a computer/ laptop/ipad /tablet /smart-phone etc.?
3. At what time of the day is your child at their best?
4. Can you identify the triggers for this? i.e. they've been playing outside/ playing with the computer / playing indoors etc.

Pilot study

1. Baseline data to see if light and sleep are linked.
2. Do you think the actiwatch will be tolerated?
3. What type of reward/incentive would be appropriate and not cause difficulties among the participants.

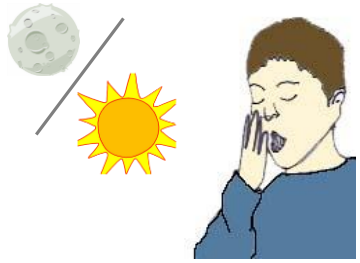
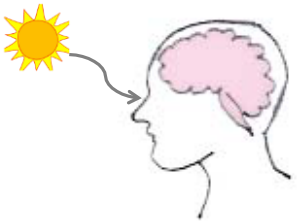
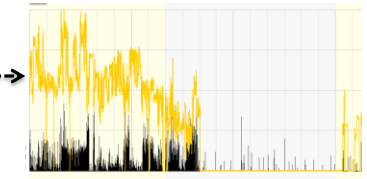
Appendix G: Visual storyboard

HERIOT WATT UNIVERSITY

Light, health, body

Exploring the associations between light exposure and sleep patterns

EPSRC Pioneering research and skills

1 – We are studying light and sleep patterns 	2 - We have an internal body clock that responds to changes in light. that helps know when to wake up and when to fall asleep. 	3 - Light can come from lots of different sources. 
4 - Light at different times of the day can have different effects on our body. 	5 - We can use an actiwatch to measure our light exposure and activity levels. 	6 - We can look at a graph of our sleep-activity and light patterns! 

United Nations Educational, Scientific and Cultural Organization · International Year of Light 2015

Appendix H: Spearman's rho blue light and illuminance correlations

Correlations for summer	Morn illuminance	Morn blue light	Evening illuminance	Evening blue light	Daytime illuminance	Daytime blue light
Morn illuminance	1					
Morn blue light	.98**	1				
Evening illuminance	.27	.27	1			
Evening blue light	.27	.27	.93**	1		
Daytime illuminance	-.22	-.23	-.09	-.11	1	
Daytime blue light	-.26	-.28	-.08	-.12	.98**	1

Correlations for winter	Morn illuminance	Morn blue light	Evening illuminance	Evening blue light	Daytime illuminance	Daytime blue light
Morn illuminance	1					
Morn blue light	.85**	1				
Evening illuminance	-.04	-.25	1			
Evening blue light	-.27	-.21	.40	1		
Daytime illuminance	-.29	-.40	.58*	.14	1	
Daytime blue light	-.61*	-.50*	.05	.37	.52*	1

Appendix I: Participant information sheet

Participant Information sheet for proposed environmental light and sleep study

For the attention of potential research participants: Please find outlined below a proposed PhD study looking at the existing light levels and sleep quality. We would also like to visit your facility to hold an information meeting to explain the study; demonstrate equipment and answer any questions you may have.

Who are we? I'm Mandy Nioi, a PhD research student, working with Dr Jenny Roe and Prof Peter Aspinall at the School of the Built Environment, Dr Alan Gow, School of Life Sciences, Heriot Watt University, David McNair, Cadogans Expert Engineers and Prof Bal Dhillon, Professor of clinical ophthalmology at the University of Edinburgh. I have a research grant from the Engineering and Physical Sciences Research council (EPSRC) to explore blue light exposure across the life span and study the inherent health and wellbeing effects.

What are we doing? The aim of the project is to explore the most effective time and duration of blue light exposure to help promote good sleep, health and wellbeing. Blue light is the bright light strongest between mid-morning and mid-afternoon, which helps us synchronise our body clock.

Why we would like to measure sleep and the existing light levels? The intention of the study is to understand better sleep profiles, rest-activity patterns, cognitive functioning and existing environmental light levels.

What is involved if you choose to take part in the study? Those that choose to participate will then be asked to wear, continuously for 4 days, a wrist mounted watch that monitors sleep, rest-activity patterns and light exposure levels. The watch is small, non-invasive and waterproof. In order to get an accurate account of these variables it must be worn continuously 24hours and only removed during long periods of bathing or showering.

What will happen to the information collected? With your permission, we'd like to use the data collected, to be evaluated as part of the final PhD thesis and help inform us in designing a further study. All personal details will be omitted and anonymised.
What do I have to do next? If you are interested in taking part please complete the consent form below, this can be return to me or left for collection. I will contact you before the study is to begin to arrange a suitable time to provide the equipment to you. Of course, you may withdraw your permission at any time during the project.

Amanda Nioi – PhD Researcher
Heriot Watt University, School of the Built Environment
Edinburgh
EH14 4AS
Mobile: 0754 888 6592
Email: an197@hw.ac.uk

Appendix J: Participant/parent consent form

CONTRIBUTOR CONSENT

I confirm that I have read and understand the information sheet and that I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily by the researcher.

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

I understand that my name will not be used in any written evaluations of the project.

I agree to take part in the project by signing below.

_____ _____ _____

Participant name Signature Date

Please return this form to:

Amanda Nioi – PhD Researcher
Heriot Watt University
School of the Built Environment
Riccarton Campus
Edinburgh
EH14 4AS

Mobile: 0754 888 6592
Email: an197@hw.ac.uk
THANK YOU

Amanda Nioi and Dr Jenny Roe

Appendix K: ASD post-study participant questionnaire

Post-study feedback questions Falkland house School.

1. What did you like most about the study?
2. What did you like least about the study?
3. Did you find the watch difficult to wear?
4. If you could change the watch what would you do?
5. Would you take part in a follow up study?

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