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Lighting Effects on Older Adults' Visual and Nonvisual Performance: A Systematic Review

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ABSTRACT

Lighting plays an important role in daily life: It helps people perform daily activities independently and safely, and also benefits their health. This study assesses the research evidence of lighting's impacts on older adults in four domains: (a) performance of activities of daily living and instrumental activities of daily living; (b) circadian rhythm; (c) fall prevention and postural stability; and (d) sleep quality. A comprehensive review of lighting studies on older adults' visual and nonvisual performance was conducted using a modified PRISMA systematic review process. For the first domain, some older adults had difficulty in using the toilet, preparing meals, and doing laundry under lower illuminance. For the second domain, brighter and bluish lighting improved older adults' circadian rhythm. For the third domain, low-intensity LED lighting affixed on door frames can help older adults maintain postural stability and prevent falling during nighttime movement. Finally, some studies concluded that receiving outdoor daylight during exercise was beneficial to older adults' sleep quality. This study provides several methodological, theoretical, and collaborative suggestions for developing a more conclusive evidence base for lighting standards and strategies for older adults.

KEYWORDS

Visual and nonvisual task; circadian rhythm; falls; sleep

Background and objectives

The aging population is rapidly increasing. According to U.S. Census Bureau projections in 2012, the population age 65 years and older will be 83.7 million in 2050, accounting for more than 20% of the total population by 2050; the number of people age 85 years and older will reach 18 million, making up 4.5% of the U.S. population in 2050 (Ortman, Velkoff, & Hogan, 2014). Older adults with declining physical conditions are less able to participate in social and physical activities due to physical environmental barriers, with inadequate lighting being one of the barriers (Clarke & Nieuwenhuijsen,

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2009). As lighting is a ubiquitous element of the physical environment, the Illuminating Engineering Society (IES) (ANSI/IES & RP-28–16,[1] 2016) recognizes its key role in occupants' health and safety by noting that a supportive visual environment with appropriate lighting should be considered as a preventive measure to reduce fall risks and sleep disorders.

However, to date, no review study has specifically examined lighting's impacts on the health and safety of older adults and their living environments. Existing literature reviews have analyzed bright light therapy on older adults with dementia and the general population (Shikder, Mourshed, & Price, 2012; van Maanen, Meijer, van der Heijden, & Oort, 2016; White, Ancoli-Israel, & Wilson, 2013), and the effect of daylight and night lighting on health of the general population (Aries, Aarts, & van Hoof, 2013; Beute & Kort, 2014; Cho et al., 2015). It has been 5 years since Shikder and colleagues' (2012) review on visual and psychophysiological performance[2] in older adults with dementia. Given the rapidly growing aging population and the need for housing appropriate for their needs and physical conditions, the purpose of this study is to systemically analyze the existing research of lighting's effect on generally healthy older adults' visual and nonvisual performance.

Physiological changes in the visual system with increasing age lead to impaired spatial contrast sensitivity, prolonged dark adaptation, and decreased visual processing speed (Oweley, 2016). The prevalence of blindness and vision impairment increases rapidly with age, particularly among people older than 75 years (Prevent Blindness America, 2002). With aging eyes, many older adults confront new challenges of their environment: They cannot see clearly under low illumination or at night; poor vision can lead to fall accidents among older adults; and they need longer time to adapt to dark environments, such as transitioning from bright outside to inside, compared to younger generations (Oweley, 2016). ANSI/IES RP-28–16 (2016) indicates that good lighting for younger adults may not be appropriate for older adults: "They often need unusually large amounts of light to optimize visual performance or, paradoxically, focused task lighting because normal amounts of light are debilitating to them" (p. 4).

Also, lighting plays an important role in sleep quality. Older adults' sleep quality diminishes due to sleep/wake cycle and hemostasis changes (Dijk, Duffy, & Czeisler, 2000) and decline of melatonin secretion (Cooke & Ancoli-Israel, 2011). Appropriate sunlight exposure can regulate secretion of melatonin, which is associated with mediation of circadian rhythms and improvement of sleep quality among older adults (Lin & Liao, 2016). Circadian rhythm refers to the body's biological "clock," a cycle directed by the hypothalamus, that tells our bodies when to sleep, rise, and eat, and regulates many physiological processes. This cycle is affected by environmental cues, such as sunlight and temperature. Recent research documents adverse health effects resulting from disrupted circadian rhythms (National Institute of Health, 2016). Thirty minutes per day of sun exposure is recommended for improving older adults' sleep quality (Duzgun & Durmaz Akyol, 2017; Lin & Liao, 2016). However, according to one study, older adults in nursing homes only spent 10.5 minutes a day with lighting levels higher than 1000 lux; the limited time exposure to daylight decreased older adults' sleep quality (Shochat, Martin, Marler, & Ancoli-Israel, 2000).

Unfortunately, in many places such as nursing homes, the built environment lacks appropriate lighting parameters and design for older adults (Noell-Waggoner, 2006). For example, research documents insufficient daylight exposure and limited access to outdoors in long-term care facilities (ANSI/IES RP-28–16, 2016), and low illuminance levels in the indoor environments (Lewis & Torrington, 2013). This systematic review was conducted, in part, to identify the research evidence to date that would best guide future practices for designing and lighting living spaces for generally healthy older adults' visual and non-visual performance.

Research design and methods

Shikder and colleagues' (2012) review of the relationship between older adults with dementia and lighting provides a valuable research framework for analyzing lighting's effect on older adults' visual performance and non-visual performance. The visual performance included task performance, navigation and wayfinding, and safety; nonvisual-related performance included depression, circadian sleep–wake cycle disorder, and restless behavior among patients with dementia. This review complements Shikder and colleagues' review by adding research targeting healthy older adults, which was not the focus of their review. In addition, with new studies on lighting and older adults being published after 2012, this review includes the current body of knowledge on lighting's effect on older adults' visual and nonvisual performance.

Searching protocol

This study adopted two strategies to identify potential research studies. The first strategy identified relevant peer-reviewed journal articles that were listed in Web of Science. Four sets of search terms are shown in Figure 1. Among them, terms in two sets (lighting condition, population) were used to search articles' titles; terms in the other two sets (built environment, visual, and nonvisual) were used to search articles' topics. In addition, the

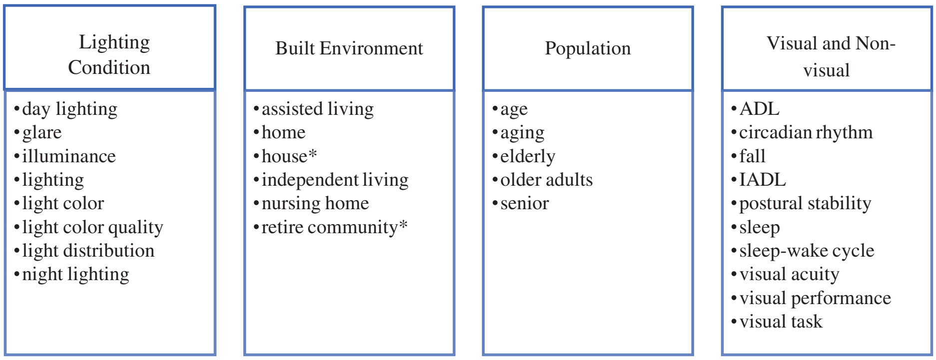

Figure 1. Four Sets of Searching Terms on Web of Science.

following criteria were established to identify and select articles: (a) published in a peer-reviewed journal; (b) published after 1990[3]; and (c) published in the English language. Using this search strategy, 60 journal articles were identified.

The second strategy involved identifying relevant research reported in the "gray literature." The initial attempt to search Google Scholar using the combined four sets of terms failed because the search engine has limited space to include all the search terms. As a result, an abridged version of the search terms was used on Google Scholar, and the publication time period was set between 1990 and 2018. Similarly with the Web of Science search, lighting condition and population terms were limited to title, while built environment and visual and nonvisual terms limited to topics. The search terms for the gray literature are shown in Figure 2. Consequently, 30 articles were identified through Google Scholar.

Another search for gray literature was made of two lighting journals: *Lighting Research & Technology* and *LEUKOS: The Journal of the Illuminating Engineering Society*. Since these journals focus on lighting issues, only one set of searching terms was used: age, aging, elderly, older adults, senior. The result was 14 articles from *Lighting Research & Technology*, and three articles from *LEUKOS: The Journal of the Illuminating Engineering Society*. In addition, 12 articles were identified by examining the reference lists of the articles identified in Web of Science, Google Scholar, and lighting journals searches. In sum, the two search strategies of the gray literature resulted in 119 articles.

Screening protocol

The screening process was developed from the PRISMA flow diagram (Moher, Liberati, Tetzlaff, & Altman, 2009), and it was divided into four parts: identification, screening, eligibility, and inclusion. The screening

Lighting Condition	Built Environment	Population	Visual and Non-visual
• glare • illuminance level • lighting • light color quality • light distribution	• home • house	• age • aging • elderly • older adults	• ADL • circadian rhythm • postural stability • sleep • visual

Figure 2. Four Sets of Searching Terms on Google Scholar.

process and the number of identified articles in each process are shown in Figure 3.

Four screening criteria for study selections are included for this review. The first criterion was that studies should be conducted at home, retirement communities, long-term care facilities, or nursing homes.[4] The second criterion ensured that studies with participants having severe mental health or physiological conditions (e.g., dementia, Alzheimer) are excluded. The third criterion was the study addressed topics of visual (e.g., activities of daily living) and/or nonvisual (e.g., sleep quality, postural stabilization, falls prevention) performance. The fourth criterion established that studies should address lighting factors and light quality in detail, such as light color, illumination, light distribution, glare, and the like.

After applying these screening criteria, there were 27 articles from Web of Science, one article from Google Scholar, two articles from *Lighting Research & Technology* journal, and 12 articles identified from reference, resulting in a total of 42 articles. Among these, eight were literature reviews. Since this current systematic review focuses on empirical, evidence-based studies, the literature review articles were excluded. In addition, the search process identified 12 lighting therapy articles. Because the main purpose of this study is to analyze naturalistic settings and older adults' visual and nonvisual performance, these 12 articles were excluded, as shown in Figure 3. As a result, the total number of empirical, evidence-based studies for this review was 22.

General characteristic of examined studies

Overall, research topics and measuring devices related to lighting and older adults changed over time. In the early 1990s, research was primarily concerned with older adults' sleep quality and bright light therapy, and sleep parameters were measured by electroencephalogram (EEG). Gradually, research expanded to consider naturalistic lighting on older adults' naps and nighttime sleep, and sleep parameters' measurements changed to

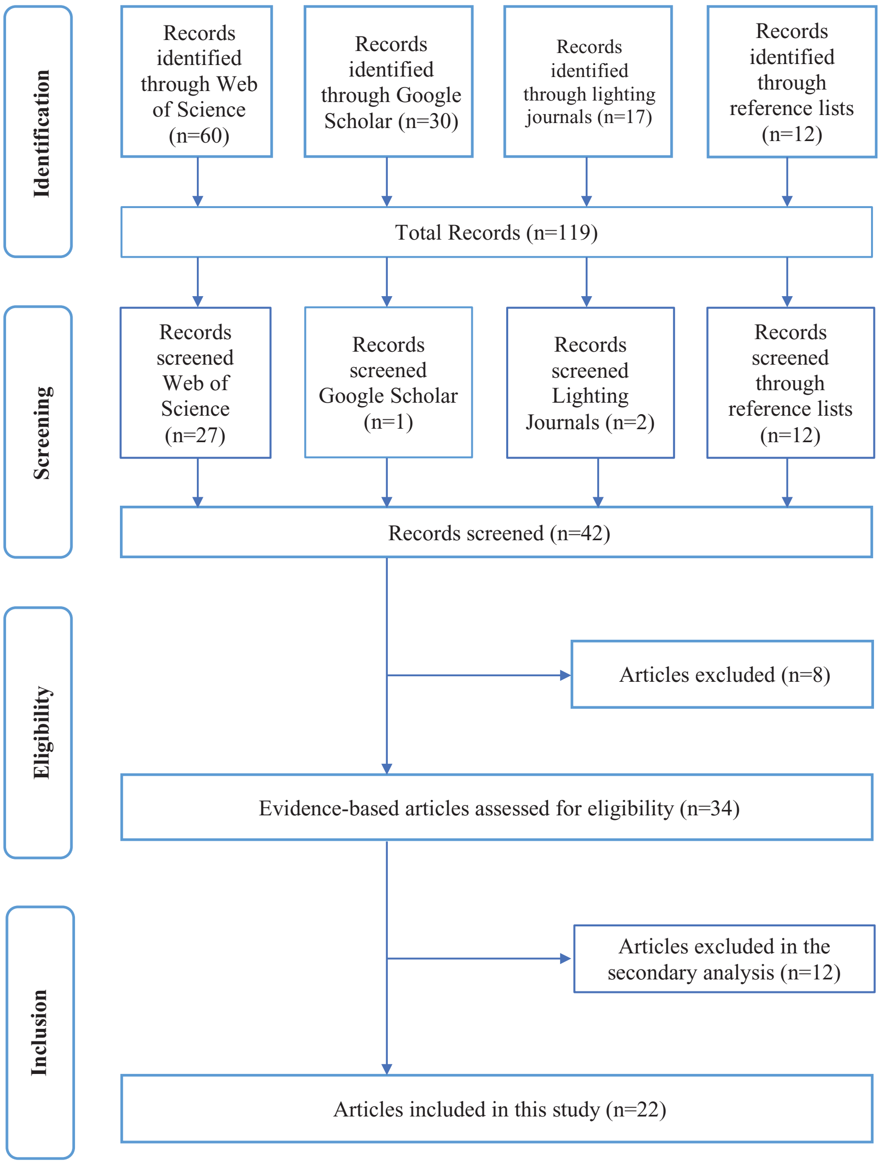

Figure 3. PRISMA Flow Diagram.

actigraphy, and melatonin concentrations. After 2000, research started to focus on older adults' living environments by interviewing older adults and identifying potential lighting design problems in their homes.

Results

ANSI/IES RP-28–16 (2016, p. 1) claims that "Loss of independence has been identified as the greatest fear of aging, so today's senior will be looking for answers to maximize their aging vision." Following ANSI/IES

RP-28-16's categorization of key lighting issues to advance independence and autonomy among older adults and the importance of lighting's effect on visual and nonvisual performance, this review classified the identified 22 studies into four categories: (a) performance of activities of daily living (ADLs)/instrumental activities of daily living (IADLs); (b) circadian rhythm; (c) fall prevention and postural stability; and (d) sleep quality.

Performance of ADLs and IADLs

It is important that older adults can perform ADLs and IADLs independently if they want to pursue a high-quality life and live independently. ADLs include bathing, dressing, going to the toilet, transferring, continence, and feeding (Katz, Ford, Moskowitz, Jackson, & Jaffe, 1963); IADLs include ability to use telephone, shopping, food preparation, housekeeping, laundry, transportation, responsibility for one's own medications, and ability to handle finances (Lawton & Brody, 1969). Three studies examined the relationship between indoor lighting and performance of ADLs and IADLs (see Table 1).

Lee, Jeong, and Hirate (2009) examined 309 older adults' lighting environment in various residential communities. One ADL, going to the toilet, was the focus of this study, particularly for older adults who awakened at night and went to bathroom two to three times. Residents evaluated illuminance levels of bathrooms, expressed concerns about lighting condition when they went to bathroom at night, and showed their lighting preferences towards sleep-inducing lighting, such as dim light and warm color light. Descriptive statistical tests revealed no discernible pattern among the older adults. No measurements of illuminance levels were provided in the study.

Barstow, Bennett, and Vogtle (2011) interviewed 22 older adults with vision loss about lighting impacts on their ADLs and IADLs. Older adults expressed how inappropriate lighting impacted their ADLs and IADLs, such as preparing meals, getting mail, and doing laundry. Older adults also mentioned glare issues and their compensation strategies (i.e., avoid being out in bright sunlight, and use window coverings to prevent glare at home). While the interview results were useful in identifying inappropriate lighting designs in older adults' homes, a larger sample and specific illuminance level measurements are needed to enrich the understanding of range and appropriate lighting environments for older adults.

Eilertsen, Horgen, Kvikstad, and Falkenberg (2016) measured indoor illuminance levels by calibrated illuminance meter at 114 homes in Norway. The homes included apartments, detached houses, and semidetached houses. Older adults were asked to rate their ADLs and IADLs performance under the illuminance level, to self-rate lighting quality (i.e., illuminance

Table 1. Performance of ADLs/IADLs.

Author	N	Mean age (years)	House type	ADLs and IADLs	Visual issues	Subjective lighting aspects/measurement	Objective lighting measurement	Statistical analysis
Barstow et al., 2011	22	71	A retirement community	Preparing meals; getting mail; laundry; setting appliances dials and knobs	Macular degeneration, diabetic retinopathy, glaucoma	Interview: task lighting/ outdoor lighting on steps and in garages for safety; contrast; glare	N/A	N/A
Eilertsen et al., 2016	114	75	Apartment, detached house, semidetached house	Dressing; bathing, mobility; telephone; food preparation, housekeeping, laundry, taking medicine, reading	Normal visual with a Snellen visual acuity score that exceeds 0.7	Visual Analogue Scale (VAS); illuminance level, lighting direction, glare	Light levels were measured in the kitchen, living room, bathroom, bedroom, stairway, and hallway	One sample t-test; Wilcoxon signed-rank test; Mann–Whitney test; Kruskal–Wallis test; Pearson's correlation
Lee et al., 2009	309	60–90	Complex housing, retirement communities, senior housing, single-family housing	Go to toilet	N/A	Bright/dim; lighting color; lighting at bedtime, midnight; bathroom lighting; sleep inducing lighting	N/A	Descriptive statistics

levels, glare issues), and to self-report their visual problems. Results showed that all rooms measured had illuminance levels significantly below the recommended lighting level of IES for older adults. Significant difference was found in the lighting levels at home between older adults with high and low income levels: Older adults with high income had a higher illuminance level compared to those with low income. Surprisingly, older adults still expressed satisfaction toward performing ADLs and IADLs although the ambient illuminance level was lower than standard. The authors further speculated that older adults may not be aware that low illuminance levels can influence their vision, ADLs, and IADLs.

Together, these three studies, with their sample sizes, encompass a diversity of older adults with different housing types and visual abilities, thereby enriching the scope of lighting environment data: Eilertsen and colleagues (2016) used Pearson's correlations to analyze lighting level and older adults' ability to read and write. However, two studies show a lack of in-depth statistical analyses. Lee and colleagues (2009) only provided general descriptive statistical results for each question; no inferential statistics or descriptive statistics examining the relationship between detailed lighting parameters and older adults' visual performance were conducted. Barstow and colleagues (2011) only provided excerpts from the interview transcripts, with no further analyses, such as total identified lighting issues at the interviewee's home, or frequencies of concerned lighting issues among older adults. Objective measurements of illuminance levels are typically lacking: Only Eilertsen and colleagues (2016) used both objective and subjective measurements to evaluate illuminance levels. In addition, other aspects beyond illuminance levels (e.g., contrast) may affect daily living activities, but were not examined in these studies.

Circadian rhythm

Four articles addressed effects of lighting on older adults' circadian system (see Table 2).

The study by Figueiro and colleagues (2008b) examined effects of a 24-hour lighting scheme on older adults' sleep quality. This study selected four bedrooms in a long-term care facility. Before installation, all the lamps were incandescent. Newly installed lamps set the living room with illuminance level ranging from 200 to 475 lux at cornea and with cooler color temperature (6500 K) during daytime. Color temperature is the color appearance (warm or cool) of a light source measured in degrees Kelvin (K) (ANSI/IES RP-28–16, 2016). The newly added lighting system with timers turned on lights approximately from 6:45 to 18:00, and then turned off lights at 18:00 (only low-illuminance-level incandescent lamps allowed).

Table 2. Circadian rhythm.

Author	*N*	Mean age (years)	Illuminance level	Correlated color temperature	Subjective sleep measurement	Objective sleep measurement	Study duration	Statistical method
Figueiro et al., 2008b	4	80–98	200 lux to 475 lux during 6:45 to 18:00	6500 K	PSQI	Actigraphs	2 weeks collecting baseline; 4 weeks: new lighting 2 weeks: baseline	Student *t*-test
Friedman et al., 2009; Zeitzer, et al., 2011	51	63.6	Controlled dim morning light (65 lux), dim evening (65 lux), bright morning (4000 lux), bright evening (4000 lux).	N/A	Daily sleep log	Actigraphy, polysomnography recordings	12 weeks	Paired Student *t*-test; Kruskal–Wallis; Mann–Whitney *U*-test; Cohen's *d* for effect size
Sander et al., 2015	29	69.7	240 lux to 280 lux from 8 a.m. to 1 p.m. on 5100 K and 2800 K; 140 lux and 2800 K between 1 p.m. and 6 p.m.; 100 lux and 2800 K between 6 p.m. and bedtime	5100 K; 2800 K; CRI: above 80	PSQI; sleep diary; Morningness–Eveningness questionnaire	Saliva melatonin, pupilometer, Actiwatch	Total 7 weeks: 3 weeks with 5100 K; 1 week pause; 3 weeks with 2800 K	Paired *t*-test; chi-squared test

This purpose of the lighting system is to give cooler color temperature and higher illuminance level during daytime and warmer color temperature and lower illuminance level at night. In the study, 10 female participants were recruited. However, only four completed the study, with age ranging from 80 to 98 years. The Pittsburg Sleep Quality Index (PSQI) questionnaire evaluated older adults' sleep quality subjectively, and actigraphs measured rest/activity rhythms objectively. Dependent variables, subjective and objective sleep quality, were collected twice: once before the installation of a new light system and once after installation. The *t*-test results showed (a) no statistically significant difference between the PSQI before and after the lighting intervention; (b) although sleep efficiency did not reach statistical significance, descriptive statistics showed sleep efficiency increased after the lighting intervention. Given the very small sample size of four individuals, caution needs to be given to the results. Nonetheless, the study does lend support to researchers and designers exploring and further validating new lighting systems for sleep quality.

Friedman and colleagues (2009) manipulated illuminance levels and examined their effects on sleep quality among older adults with insomnia. Twenty-one older adults with an average age of 63.6 years participated in the experiment, involving exposure to two controlled illuminance levels (65 or 4000 lux) at two times (morning or evening) for 45 minutes per day and lasting 12 weeks. Otherwise, the pattern of older adults' daily light exposure did not change. Objective measurements (actigraphy and polysomnography) and subjective measurements (sleep log and questionnaires) were used to assess sleep quality. The study also verified older adults' consistent adherence to lighting treatment by checking their wrist-worn lighting meters. However, the findings indicated no significant difference between the scheduled morning or evening bright light (4000 lux), and morning or evening dim light (65 lux). Although some changes were identified in subjective measurements of sleep, the researchers suggested that changes in the subjective measurements were possibly due to sleep hygiene instructions or participation effects.

Zeitzer, Friedman, and Yesavage (2011) continued to analyze the data of the study conducted by Friedman and colleagues (2009), with the main purpose being to analyze ambulatory daytime light exposure's influence on phase delays and advances under the settings of bright light on morning and evening. Researchers concluded that greater light exposure during daytime hours may diminish the effectiveness of evening bright light on changing circadian phase. The impact of daylight exposure level on bright lighting treatment remained uncertain.

Sander, Markvart, Kessel, Argyraki, and Johnsen (2015) investigated the impact of blue-enriched and blue-suppressed light on 29 older adults' sleep quality. Older adults were randomly assigned to two groups: One group was exposure to blue-enriched environment for 3 weeks, the lighting intervention paused for 1 week, then exposed to a blue-suppressed environment. The other group was exposed to blue-suppressed environment for 3 weeks, paused for 1 week, and then to a blue-enriched environment for 3 weeks. The blue-enriched light correlated color temperature (CCT) was 5100K and illuminance level was 280 lux; the blue-suppressed light CCT was 2800K and the illuminance level 240 lux. Correlated color temperature (CCT) is defined as "the absolute temperature of a blackbody radiator whose chromaticity most nearly resembles that of the light source and blackbody chromaticity and is measured in units of Kelvin" (ANSI/IES RP-28–16, 2016, p. 102). Lighting intervention, the blue-enriched or blue-suppressed lighting, was conducted between 8:00 and 13:00. Then the illuminance level was controlled at the same level: 140 lux between 13:00 and 18:00, 100 lux between 18:00 and bedtime. Multiple outcome measurements were adopted: saliva melatonin, chromatic pupilometer, sleep diary, self-evaluated sleep quality, PSQI, and Morningness–Eveningness questionnaire. However, overall, no significant difference was found in sleep phase and circadian rhythm between the blue-enriched and blue-suppressed light conditions. A possible explanation can be the feasibility of lighting color temperature intervention at home: It was unacceptable to the older adults at home to set color temperature as high as a lab-controlled situation (17,000K). The researchers explained that high color temperature can possibly be an effective stimulator for circadian rhythm.

Overall, these studies were conducted either at participants' homes or at nursing homes, and participants were able to maintain their regular daily activities. Since there were no strict outdoor activity restrictions and with the unavoidability of daylight passing through the window, the outdoor daylight might affect the lighting intervention effect itself, as mentioned in the studies (Sander et al., 2015; Zeitzer et al., 2011). Also, older adults' health conditions and ages vary across studies. In addition, studies varied in terms of measured exposure time of certain illuminance level thresholds. As Friedman and colleagues (2009) suggest, changing the length of lighting intervention and lighting intervention time of a day may differently affect sleep quality of aging population. No consensus was reached across studies on how different lighting and measurement parameters impacted older adults' circadian rhythm, notably of illuminance levels, the color of light, intervention time during a day, and intervention/experiment durations change.

Fall prevention and postural stability

Four studies investigated lighting and older adults' postural stability (see Table 3).

Table 3. Fall prevention and postural stability.

Author	*N*	Mean age (years)	Groups of participants	Lighting conditions	Objective measurements	Statistical methods
Brooke-Wavell et al., 2002	33	69.7	Healthy	Normal lighting (186 lux); moderate lighting (10 lux); dim lighting (1 lux); eyes closed; repeating pattern of regularly arranged dots projected onto a wall	Body sway	Unpaired *t*-test; ANOVA
Chari et al., 2016	7500	N/A	N/A	Lighting will be installed around the exterior door frame, above the washbasin, and behind the toilet	N/A	N/A
Figueiro et al., 2011	24	82	Low falls risk vs high falls risk	Ambient illuminance with 650 lux at cornea; night lights with 0.015 lux at cornea; 0.015 lux and laser lines outlining the pathway 0.015 lux	Gait Step length	ANOVA
Figueiro et al., 2008a	12	Over 65	N/A	Door framed with LED lights with illuminance level 10 lux, 3 lux, 1 lux, and 0.3 lux; conventional lighting with 0.3 lux	Sway velocity	Post hoc Student *t*-test; ANOVA

Brooke-Wavell, Perrett, Howarth, and Haslam (2002) examined visual environment and postural stability in a lab-controlled environment. Participants were 33 healthy women with average age 69.7 years. The environment[5] produced five lighting conditions: (a) normal lighting with 186 lux; (b) moderate lighting with 10 lux; (c) dim lighting with 1 lux; (d) older adults closed their eyes; and (e) repeated dot patterns projected onto a wall with optic flow. Participants were assigned to the five lighting conditions randomly and were asked to stand in an electronic force platform with a data logger recording their center of gravity and lateral and anteroposterior sway. Sway velocity was calculated based on these recordings. Researchers concluded that participants had significantly poorer postural stability when they closed their eyes and under a dim lighting environment.

Figueiro and colleagues (2008a) examined the effects of new lighting systems with low illuminance levels on older adults' postural stabilization and fall prevention. Figueiro and colleagues (2008a) examined whether a novel lighting system—LED (light-emitting diode) lights affixed to the door frame—could assist older adults in controlling postural orientation and maintaining postural stability. Twelve older adults were asked to perform a Sit to Stand test (STS) in front of the door, which could be tilted left, tilted right, and positioned correctly. The objective measurements of sway velocity indicated that the novel lighting system had a positive impact on older adults' postural orientation and stability. Later, older adults expressed their preference for the new lighting system that produced 1 lux with infrared sensors to the incandescent lamps when they go to the bathroom at night.

In the second study, Figueiro, Plitnick, Rea, and Gras (2011) conducted experiments with 24 older adults to exam the effects of lighting cues—specifically adding a laser line demarcating a pathway in low illuminance ambient environment—on falling. The researchers measured participants' gait and step length using GAITRite Mat (an objective measurement that had been validated in other studies) in three ambient lighting conditions: (a) ceiling-mounted fixtures providing 650 lux; (b) night light providing 0.015 lux; and (c) night light and laser lines along a pathway providing 0.015 lux. Older adults were divided into two groups based on their previous frequency of falls: One group was high risk of fall with average age 82 years, and the other group was low risk with average age 75 years. Researchers found that the high fall risk group had a significant increase in velocity and a significant reduction in step length variability under the third lighting condition compared to the low fall risk group. Although average age differed in the two groups, the study suggested older adults can reduce falls if lighting cues of adequate contrast are added to the low illuminance ambient environment.

Together, these studies using inferential statistical methods, independent *t*-test, and analysis of variance (ANOVA) indicated that low illuminance level had a negative impact on older adults' postural stability. However, the studies were conducted under controlled environmental conditions, and participants were healthy older adults without visual problems. As suggested by Figueiro and colleagues (2011), older adults usually have some visual problems and it is common for them to encounter low illuminance levels at night. Consequently, samples with diverse visual capabilities in real settings are needed to validate the innovative lighting system. A pilot study conducted by Chari and colleagues (2016) described using a night light system designed by Figueiro in health care settings with a large sample size (approximately 7500 patients). The lighting will be installed around the exterior door frame, above the washbasin, and behind the toilet. Results are not yet available.

Sleep quality

Daylight and night light both play roles in sleep quality among older adults. This section describes and summarizes 11 studies that explored lighting and sleep in naturalistic settings of older adults (see Table 4).

Hood, Bruck, and Kennedy (2004) explored the relationship of three factors, daily light exposure, daytime activity, and sleep quality, among 33 healthy older subjects. Sensors were used to record five parameters of subjects' activities: activity, movement, immobility, extended immobility, and fragmentation index. Light meters were used to measure ambient light exposure, with three thresholds of light levels being 500, 3000, and 10,000 lux. PSQI was used to measure older adults' subjective sleep quality, and nocturnal immobility was used to measure sleep quality objectively. They concluded that daily activity was beneficial to sleep quality, and older adults had substantive sleep quality improvement given exposure to ambient light with illuminance over 3000 lux.

Two studies (Alessi et al., 2005; Martin et al., 2006) investigated 492 older adults who lived in four nursing homes in Los Angeles; the purpose was to find factors related to abnormal circadian rhythm, daytime sleepiness, and nighttime sleep disturbance. Both studies found that those older adults whose lifestyles included staying in their rooms for approximately one-third of the day or who were seldom engaged in outdoor activities had daytime sleepiness and nighttime sleep disruption. Martin and colleagues (2006) also concluded that older adults receiving little bright light had excessive daytime sleepiness and nighttime sleep disruption.

Three observational studies conducted by Obayashi and colleagues (2012, 2014a, 2014b) examined the relationship between light exposure and

Table 4. Sleep quality.

Author	N	Mean age (years)	Sleep parameters	Lighting condition	Lighting measurement	Sleep objective measurement	Sleep subjective measurement
Alessi et al., 2005; Martin et al., 2006	492	87.8	Nighttime total sleep; percentage of nighttime sleep; nighttime number of awakenings; mean of nighttime awakening length; daytime sleep	Mean daytime light exposure; minutes of light exposure; minutes of light exposure exceeds 1000 lux per day; mean number of light changes exceeds 25 lux per night	Hand-held lighting meters	Actigraph	Behavioral observations: daytime sleep; social and physical activities and social conversation
Dzierzewski et al., 2014	79	63.6	Sleep onset latency; wake time after sleep onset;	Natural bright light outdoor	N/A	N/A	Sleep quality rating (1 to 5, 5 excellent, 1 *worst*)
Hood et al., 2004	33	74.2	Activity; movement; immobility; extended immobility; fragmentation index	Total minutes above 500 lux; total minutes between 3000 lux and 10,000 lux	Light meter worn on jacket, and data recorded by Mini Mitter 2000 Data Logger	Actigraph	Diary sleep efficiency; PSQI
Karami et al., 2016	19	80	Subjective sleepiness	Exposed daylight from 9 to 10 a.m. and from 4 to 5 p.m.: light intensity was more than 50,000 lux in the horizontal surface; 20,000 lux in the vertical surface	N/A	Blood sample: melatonin levels	Karolinska Sleepiness Scale (KSS)
Nioi et al., 2017	16	72–99	Sleep onset latency, sleep efficiency, wake after sleep onset, total sleep time	Total minutes above 1000 lux; mean illuminance level in summer and winter	Light-sensitive photodiodes mounted on the Actiwatch	Actiwatch	PSQI
Obayashi et al., 2012	192	69.9	Duration of in-bed period; during of	Daylight, night light	Light meter Actiwatch2 for evening light;	Urinary sample: melatonin	N/A

(*continued*)

Table 4. Continued.

Author	*N*	Mean age (years)	Sleep parameters	Lighting condition	Lighting measurement	Sleep objective measurement	Sleep subjective measurement
			out-bed period; bed-time; wake time		portable light meter for night light		
Obayashi et al., 2014a	192	69.9	Sleep on latency	Evening light, nighttime light	Light meter Actiwatch2 for evening light; portable light meter for night light	Actigraph	PSQI
Obayashi et al., 2014b	857	72.2	Sleep-onset latency, wake-after-sleep onset, total sleep time, sleep-mid time	Bedroom lighting	Light meter	Actigraph; urinary sample: melatonin	PSQI
Ichimori et al., 2015	44	82.8	Rest–activity cycle	Indoor light: living room, pillow; out-door light	Illuminance logger	Activity meter	PSQI; 3-day lifestyle questionnaire
Tsuzuki et al., 2015	8	64	Time in bed; sleep latency; sleep period time; wake after sleep onset; sleep efficiency index	Illuminance above 2500 lux; above 1000 lux; average illuminance during daytime, sleeping period, average 30 minutes before morning awake	Actiwatch-L	Actigraph	Questionnaires

circadian rhythm among aging population under daily life settings. Obayashi and colleagues (2012) attempted to find associations between melatonin and daylight by measuring daylight and night light exposure. Daylight—referred to lighting exposure out-of-bed period—had two metrics: average of illuminance level during out-of-bed time, and total minutes of light at least 1000 lux. Night light[6]—referred to light exposure during in-bed period—had three metrics: average illuminance level in-bed time, total minutes of light of at least 10 lux, and total minutes of light of at least 100 lux. Researchers concluded there was a positive relationship between daylight exposure and urinary melatonin excretion in the older adults at home. That is, increased daylight exposure was beneficial to older adults' sleep quality.

Two years later, Obayashi and colleagues (2014a) examined the effect of night light exposure on 857 participants' sleep quality under home setting. Participants' average age was 72.2 years. The older adults were divided into quartiles according to illuminance level exposure at night. The interquartile range of illuminance level at night was between 0.1 and 3.4 lux, and the median illuminance level was 0.8 lux. Older adults' sleep quality was evaluated by using an actigraph, urinary tests (melatonin metabolite), and PSQI. Researchers found that older adults' sleep quality decreased when the illuminance level at night increased.

Also, Obayashi, Saeki, and Kurumatani (2014b) addressed the relationship between evening light exposure and sleep-onset latency among 192 subjects with a mean age of 69.9 years. Researchers measured each participant's evening light exposure by a wrist-worn lighting meter; during the out-of-bed time, that is, 4 hours before in-bed time, the median evening light exposure was 27.3 lux. During the 2 hours after in-bed time, the median nighttime light was 0.1 lux. Sleep onset latency was measured by a previously validated Actiwatch. Researchers concluded that exposure to evening light in residential settings prolonged subsequent sleep-onset latency in the older adults.

Dzierzewski and colleagues (2014) examined the relationship between older adults' exercise behaviors and sleep. One purpose of the study was to explore whether exercising outdoors or indoors benefited sleep quality, since exercising outside tended to get increased exposure to bright daylight. Older adults were asked to rate the frequencies they were engaging in 20-minute bouts of mild, moderate, and vigorous activities. Participants were asked to estimate the time they spent on sleep latency and wake time after sleep onset. However, researchers did not find that exposure to bright daylight had an effect on older adults' relationship between exercise and sleep.

Tsuzuki, Mori, Sakoi, and Kurokawa (2015) aimed to see the effect of seasonal change of thermal environment and illuminance levels on sleep quality in older adults by using actigraphy for five consecutive days on four different seasons. There were eight healthy male participants with an average age of 64 years. Sleep parameters included time in bed, sleep latency, sleep period time, wake after sleep onset, and sleep efficiency index. Environmental parameters included amount and duration of illuminance, temperature, and humidity levels. This was the first study combining environmental variables in examining their impact on sleep quality. Researchers concluded that increased lighting level during 4 hours before sleeping weakened sleep quality as measured by bedtime delayed, wake-up time the next morning becoming earlier, and wake-up after sleep onset prolonged. In addition, increased temperature and humidity during sleep impaired sleep quality by increasing the wake time after sleep onset. However, there was a positive relationship between exposure to increased illuminance level during daytime and sleeping time.

Ichimori, Tsukasaki, and Koyama (2015) measured indoor and outdoor illuminance, and investigated light exposure and sleep quality among frail older adults. The indoor illuminance logger was placed in either living rooms or bedrooms, depending upon the places where participants spent time most. The outdoor illuminance level was measured by a light meter installed on the roof of a research facility. Median illuminance level during activity time was 538 lux, and median illuminance level in bed was 3 lux. Participants' sleep quality was measured by PSQI. However, there was no significant relationship between illuminance level and sleep quality. Possible explanations for nonsignificant findings may be that participants were frail older adults, and the study only used subjective measurements of sleep quality since using objective measurement by EEG would take time to explain the technique to older adults who lived at home and the researchers considered the EEG measurement was a burden to the older adults.

Karami, Golmohammadi, Heidaripahlavian, Poorolajal, and Heidarimoghadam (2016) examined the effect of sunlight exposure on sleep quality among 19 older adults with average age of 80 years in a nursing home. The study lasted for 6 weeks, and the intervention was to ask older adults to be exposed to sunlight twice daily: 30 minutes from 9 to 10 a.m. and 30 minutes from 4 to 5 p.m. The estimated sunlight illuminance level was 50,000 lux in the horizontal and 20,000 lux in the vertical. Blood samples were collected to examine the melatonin levels before and after intervention, and older adults were asked to subjectively rate their sleep quality by questionnaire: Karolinska Sleepiness Scale (KSS). Researchers concluded that daylight exposure can improve older adults' sleep by delaying sleep phase.

Nioi, Roe, Gow, McNair, and Aspinall (2017) examined the summer and winter daylighting exposure's effect on older adults' sleep quality with 20 participants of ages 72 to 99 years. A wrist-worn Actiwatch was able to detect activity movement and sleep. Objective sleep metrics included sleep onset latency, sleep efficiency, wake after sleep onset, and total sleep time; subjective sleep quality measurement (PSQI) was also used. Light-sensitive photodiodes mounted on the Actiwatch were used to measure the exposed illuminance level. Twenty older adults participated in the summer data collection process for 4 days, with mean morning illuminance level at 466 lux and the time of exposure over 1000 lux at 46 minutes. Sixteen older adults remained in the winter data collection for 4 days: The mean morning illuminance level was 65 lux and the time exposure over 1000 lux was 3 minutes. According to the researchers, older adults significantly increased physical activities and received longer daylight exposure over 1000 lux in the summer. However, this study did not find significant differences in sleep quality, neither in objective nor in subjective measurements. Researchers considered that small sample size and participants without severe cognitive decline might explain the nonsignificant findings in sleep quality between seasons.

In sum, eight of the 11 studies in this section suggested daylight exposure benefits older adults' sleep quality, and nighttime/evening lighting exposure has a negative impact on older adults' sleep quality. Three studies (Dzierzewski et al., 2014; Ichimori et al., 2015; and Nioi et al., 2017) did not identify the outdoor light exposure and sleep quality improvement. Although studies (Nioi et al., 2017; Tsuzuki et al., 2015) mentioned seasonal change illuminance levels' effect on the older adults' sleep, researchers reached different conclusions since the sleep and lighting parameters and participants' demographics differed. Due to complex factors involved in analyzing sleep quality and lighting exposure, the majority of studies in this section adopted logistic/linear/multivariate regression to find a suitable model to represent their findings. Notably, it was difficult to isolate daylight, physical activity, and sleep quality separately, and physical activity can be a confounding variable indirectly influencing older adults' sleep quality (Hood et al., 2004). More contextual factors and potential mediating and moderating factors need to be considered, such as different stages of older adulthood and geographical differences in terms of amount of sunlight (Dzierzewski et al., 2014). While the small number of research studies does not allow for reaching consensus, the findings are provocative and warrant more studies to examine the relationship of natural daylight exposure, and sleep and exercise.

Discussion and implications

This section highlights lighting's effect on older adults' health and performance, and discusses future research directions.

Highlights of research findings

The previous section not only described individual studies but also summarized and assessed the research within each thematic domain. While the review reveals a number of patterns among the studies, the research in this area is not formative or substantial enough to reach definitive conclusions due to the small number of studies in certain research domains, the diversity of sample characteristics, and various measurements involved in the studies. Nonetheless, emerging patterns deserve increased research attention and suggest practical application to designing and modifying residential settings for older adults. It appears that aging eyes adapt poorly to extremely bright light or dim light; thus, appropriate illuminance levels are needed to support older adults' ADLs and IADLs performance (Ishihara, Ishihara, Nagamachi, Osaki, & Hiramatsu, 2004). Although some studies mention that generally poor lighting condition can contribute to older adults' fall accidents at home, no detailed lighting parameters (i.e., lighting illuminance levels, lighting color, types of lamps) or strategies are discussed. The lab-controlled studies included in this literature review provide detailed lighting strategies for helping older adults navigate safely at home. For example, visual cues by outlining a pathway at night from bed to bathroom can ensure safety by increasing postural stability and preventing falling. Increased daylight exposure also can benefit older adults' sleep quality at night. In addition, with the development of tunable LED lamps, more innovative LED interventions are expected to maintain older adults' safe navigations at night and improve circadian rhythms.

These overall findings are derived from a systematic review process, conducted and reviewed by three researchers, although the review process was not carried out independently. In addition, assessments for risk of bias within and across studies, based on the research integrity or validity of each study, were not untaken here. Nonetheless, the process was systematic (i.e., operated under an established protocol), thoroughly documented, and followed an interactive critique process among the researchers, lending itself to transparency. Further, since this systematic review only includes evidence-based studies (i.e., no research reports that had not gone through a journal-based peer review process), other potential relationships between lighting and health may be absent in the overall findings. For example, one research report not included in this review concludes that tunable LED lamps are not only beneficial to older adults' safe navigation but also helpful in maintaining circadian rhythms (Davis, Wilkerson, Samla, & Bisbee, 2016). Clearly while this review identifies a number of important relationships between lighting and older adults' performance based on the peer-reviewed research to date, it also suggests directions for future research.

Future directions

Strengthen experimental methods and measurements

Based on the research to date in this field, caution must be heeded in extrapolating solid research conclusions, in part because of limitations in research approaches (e.g., nonexperimental studies) and measurements (e.g., lack of consistency in providing actual metrics of illuminance level point or contrast levels), as noted previously. Further, there are no consistent lighting and sleep measurements among the identified studies. For example, although some studies gave rationales for why certain lighting thresholds play a role in older adults' sleep quality, the lighting thresholds in the studies varied considerably, from 1000 to 2500 lux.

Yet the research to date suggests potentially important links and effects between lighting and older adults' health and performance. In developing a stronger evidence base, future research needs to strengthen and include those research approaches and metrics that can identify, examine, and substantiate effective lighting thresholds for improving sleep quality. For example, various sleep measurements are identified in the review: Some studies preferred to use questionnaires since objective measures could burden participants. Others (e.g., Ichimori et al., 2015) thought objective measures such as EEG increased strain on research participants and were inapplicable in their homes. Further, others (e.g., Hood et al., 2004) expressed technical difficulties in adopting polysomnography in natural settings. Future research pursuits need to assess and compare these various measurement techniques in establishing valid and reliable metrics, perhaps leading to adoption of multifaceted subjective and objective sleep measurements.

Lastly, while some studies demonstrate valid, well-crafted and thoroughly described statistical analyses, others lack important statistical analysis steps and descriptions. Few studies mentioned conducting power analysis to ensure reaching statistically significant conclusions, except one study by Alessi and colleagues (2005). In the future, power analysis should be undertaken to establish sufficient sample sizes before collecting and analyzing data.

Incorporating mediating/moderating and contextual factors

Although many studies explored the relationship between daylight exposure and sleep quality, no consensus was reached. In part, this reflects the lack of a theoretical model that drives this research arena. Such theoretical models would demand inclusion of contextual, mediating and moderating factors, such as physical activity, different age groups of older adults, and the like. Some confounders that may impact older adults' sleep include sleep hygiene, noises, sunlight, and physical activity levels during waking periods. If a climate with abundant sunlight can encourage older adults to go outside, research studies and models could incorporate whether the amount of daylight exposure or outdoor exercise is a key contributing factor to older adults' sleep quality in such regions. In addition, future studies need to include other related physical environment factors, such as noise, that may interact or coincide with lighting and affect sleep quality.

Collaborative multidisciplinary research

A multidisciplinary team of lighting designers, clinicians, and medical researchers might advance future research in a more comprehensive manner by generating a comprehensive theoretical model and research design of lighting impact on older adults' visual and nonvisual performance. Those studies with clinical and medical staff (Barstow et al., 2011; Figueiro et al., 2011; Friedman et al., 2009; Sander et al., 2015) provided a valuable professional examination of visual acuity and diagnosis of older adults' visual impairment, and objective physiological measurements—factors often lacking in studies conducted without clinical and health collaborators. Given the complexity in the field of lighting and aging eyes, changing demographics among older adults, and limited research providing mature conclusions in lighting effect on older adults' visual and nonvisual performance, it would be promising to conduct multidisciplinary research to supplement the body of knowledge in this field.

Developing new evidence-based lighting standards

During the review process, although two studies do not fall into the four analyses categories mentioned in the preceding, Lasagno, Issolio, Pattini, and Colombo (2014) and Lewis and Torrington (2013) provide insightful suggestions to the future lighting standards development based on their studies' results: Lighting design should address the transitional areas between exterior and interior (such as corridors and halls), increase illuminance levels in the kitchen and bathroom, increase daylight permeability, make lighting control accessible to the older adults, and others. Lasagno and colleagues (2014) emphasize the importance of having diversity factors to enrich the research results and help lighting standards development, such as population diversity, climate zones, building orientations, and spatial complexity. In addition, lighting standards should cover illuminance levels for nonvisual tasks instead of giving thresholds for visual tasks only (Lasagno et al., 2014). While these are viable suggestions, the depth of research in this arena still is insufficient for establishing new evidence-based lighting standards. However, with such a goal in mind, professional lighting, health care, and seniors' housing organizations might work together in developing a multidisciplinary research agenda for the field and its application to creating and renovating improved living environments for older adults.

Notes

1. The lighting standard for seniors is titled “Lighting and the Visual Environment for Seniors and the Low Vision Population.” It includes quality and quantity of lighting for vision, design guide, light source, daylight, light for seniors’ health, and lighting controls.
2. In Shikder and colleagues’ review, the psychophysiological performance included depression, circadian sleep–wake cycle disorder, and restless behavior among patients with dementia. Since this review mainly focuses on generally healthy older adults, no restless behavior is examined. For consistency throughout the review, Shikder’s review aspects are referred as visual and nonvisual performance.
3. It happened that all search results were published after 1990.
4. Since very few systematic studies on illuminance effects on older adults’ falls have been conducted in residential settings, two laboratory-based studies on this topic were included.
5. This study is performed under lab-controlled environment. The reason to include this particular lab study is that a subsequent study by Figueiro et al. (2008a) is built upon this research.
6. In the studies of Obayashi and colleagues (2012, 2014a, 2014b), the night light is measured by portable lighting meters placed 60 cm above the floor, near the bed, facing the ceiling.

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References

Alessi, C. A., Martin, J. L., Webber, A. P., Kim, E. C., Harker, J. O., & Josephson, K. R. (2005). Randomized, controlled trial of a nonpharmacological intervention to improve abnormal sleep/wake patterns in nursing home residents. *Journal of the American Geriatrics Society*, *53*(5), 803–810. doi:10.1111/j.1532-5415.2005.53251.x

ANSI/IES & RP-28-16. (2016). *Lighting and the visual envrionment for senior and the low vision population*. New York, NY: Illuminating Engineering Society of North America.

Aries, M., Aarts, M., & van Hoof, J. (2013). Daylight and health: A review of the evidence and consequences for the built environment. *Lighting Research & Technology*, *47*, 6–27. doi:10.1177_1477153513509258

Barstow, B. A., Bennett, D. K., & Vogtle, L. K. (2011). Perspectives on home safety: Do home safety assessments address the concerns of clients with vision loss? *American Journal of Occupational Therapy*, *65*(6), 635–642. doi:10.5014/ajot.2011.001909

Beute, F., & Kort, Y. A. W. (2014). Salutogenic effects of the environment: Review of health protective effects of nature and daylight. *Applied Psychology: Health and Well-Being*, *6*(1), 67–95. doi:10.1111/aphw.12019

Brooke-Wavell, K., Perrett, L. K., Howarth, P. A., & Haslam, R. A. (2002). Influence of the visual environment on the postural stability in healthy older women. *Gerontology*, *48*(5), 293–297. doi:10.1159/000065252

Chari, S. R., Smith, S., Mudge, A., Black, A. A., Figueiro, M., Ahmed, M., … Haines, T. P. (2016). Feasibility of a stepped wedge cluster RCT and concurrent observational sub-study to evaluate the effects of modified ward night lighting on inpatient fall rates and sleep quality: a protocol for a pilot trial. *Pilot Feasibility Study*, 2, 1. doi:10.1186/s40814-015-0043-x

Cho, Y., Ryu, S. H., Lee, B. R., Kim, K. H., Lee, E., & Choi, J. (2015). Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment. *Chronobiol International*, *32*(9), 1294–1310. doi:10.3109/07420528.2015.1073158

Clarke, P., & Nieuwenhuijsen, E. R. (2009). Environments for healthy ageing: A critical review. *Maturitas*, *64*(1), 14–19. doi:10.1016/j.maturitas.2009.07.011

Cooke, J. R., & Ancoli-Israel, S. (2011). Normal and abnormal sleep in the elderly. *Handbook of Clinical Neurology*, *98*, 653–665. doi:10.1016/b978-0-444-52006-7.00041-1

Davis, R. G., Wilkerson, A. M., Samla, C., & Bisbee, D. (2016). Tuning the light in senior care: Evaluating a trial LED lighting system at the ACC Care Center in Sacramento, CA. U.S. Department of Energy.

Dijk, D. J., Duffy, J. F., & Czeisler, C. A. (2000). Contribution of circadian physiology and sleep homeostasis to age-related changes in human sleep. *Chronobiol International*, *17*(3), 285–311. doi:10.1081/CBI-100101049

Duzgun, G., & Durmaz Akyol, A. (2017). Effect of natural sunlight on sleep problems and sleep quality of the elderly staying in the nursing home. *Holistic Nursing Practice*, *31*(5), 295–302. doi:10.1097/HNP.0000000000000206

Dzierzewski, J. M., Buman, M. P., Giacobbi, P. R., Jr., Roberts, B. L., Aiken-Morgan, A. T., Marsiske, M., & McCrae, C. S. (2014). Exercise and sleep in community-dwelling older adults: Evidence for a reciprocal relationship. *Journal of Sleep Research*, *23*(1), 61–68. doi:10.1111/jsr.12078

Eilertsen, G., Horgen, G., Kvikstad, T. M., & Falkenberg, H. K. (2016). Happy living in darkness! Indoor lighting in relation to activities of daily living, visual and general health in 75-year-olds living at home. *Journal of Housing for the Elderly*, *30*(2), 199–213. doi:10.1080/02763893.2016.1162256

Figueiro, M., Gras, L., Qi, R., Rizzo, P., Rea, M., & Rea, M. (2008a). A novel night lighting system for postural control and stability in seniors. *Lighting Research & Technology*, *40*, 111–126. doi:10.1177_1477153507084198

Figueiro, M. G., Plitnick, B., Rea, M. S., & Gras, L. Z. (2011). Lighting and perceptual cues: Effects on gait measures of older adults at high and low risk for falls. *BMC Geriatrics*, *11*, 49. doi:10.1186/1471-2318-11-49

Figueiro, M. G., Saldo, E., Rea, M. S., Kubarek, K., Cunningham, J., & Rea, M. S. (2008b). Developing architectural lighting designs to improve sleep in older adults. *The Open Sleep Journal*, *1*(1), 40–51.

Friedman, L., Zeitzer, J. M., Kushida, C., Zhdanova, I., Noda, A., Lee, T., … Yesavage, J. A. (2009). Scheduled bright light for treatment of insomnia in older adults. *Journal of the American Geriatrics Society*, *57*(3), 441–452. doi:10.1111/j.1532-5415.2008.02164.x

Hood, B., Bruck, D., & Kennedy, G. (2004). Determinants of sleep quality in the healthy aged: The role of physical, psychological, circadian and naturalistic light variables. *Age and Ageing*, *33*(2), 159–165. doi:10.1093/ageing/afh051

Ichimori, A., Tsukasaki, K., & Koyama, E. (2015). Illuminance, subjective sleep quality, and psychosomatic health in elderly individuals requiring care: A survey of Japan's Hokuriku region in winter. *Journal of Community Health Nursing*, *32*(2), 104–114. doi:10.1080/07370016.2015.1026158

Ishihara, K., Ishihara, S., Nagamachi, M., Osaki, H., & Hiramatsu, S. (2004). Independence of older adults in performing instrumental activities of daily living (IADLs) and the relation of this performance to visual abilities. *Theoretical Issues in Ergonomics Science*, *5*(3), 198–213. doi:10.1080/1463922021000050023

Katz, S., Ford, A. B., Moskowitz, R. W., Jackson, B. A., & Jaffe, M. W. (1963). Studies of illness in the aged the index of ADL: A standardized measure of biological and psychosocial function. *JAMA*, *185*(12), 914–919. doi:10.1001/jama.1963.03060120024016

Karami, Z., Golmohammadi, R., Heidaripahlavian, A., Poorolajal, J., & Heidarimoghadam, R. (2016). Effect of daylight on melatonin and subjective general health factors in elderly people. *Iranian Journal of Public Health*, *45*(5), 636–643.

Lawton, M. P., & Brody, E. M. (1969). Assessment of older people: Self-maintaining and instrumental activities of daily living. *Gerontologist*, *9*(3 Part 1), 179–186. doi:10.1093/geront/9.3_Part_1.179

Lasagno, C., Issolio, L., Pattini, A., & Colombo, E. (2014). Transitional spaces from exterior to interior as functional vision barriers in ageing. *Lighting Research & Technology*, *46*, 706–715. doi:10.1177_1477153514528349

Lee, K., Jeong, S., & Hirate, K. (2009). An investigation into midnight lighting for the elderly—Focusing on residence type. *Journal of Asian Architecture and Building Engineering*, *8*(1), 237–241. doi:10.3130/jaabe.8.237

Lewis, A., & Torrington, J. (2013). Extra-care housing for people with sight loss: Lighting and design. *Lighting Research & Technology*, *45*, 345–361. doi:10.1177/1477153512450451

Lin, T. C., & Liao, Y. C. (2016). The impact of sunlight exposure on the health of older adults. *Hu Li Za Zhi*, *63*(4), 116–122. doi:10.6224/jn.63.4.116

Martin, J. L., Webber, A. P., Alam, T., Harker, J. O., Josephson, K. R., & Alessi, C. A. (2006). Daytime sleeping, sleep disturbance, and circadian rhythms in the nursing home. *American Journal of Geriatric Psychiatry*, *14*(2), 121–129. doi:10.1097/01.JGP.0000192483.35555.a3

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLOS Medicine*, *6*(6), e1000097. doi:10.1371/journal.pmed.1000097

National Institute of Health. (2016). What Are Circadian Rhythms? Retrieved from https://www.nichd.nih.gov/health/topics/sleep/conditioninfo/circadian-rhythms

Nioi, A., Roe, J., Gow, A., McNair, D., & Aspinall, P. (2017). Seasonal Differences in Light Exposure and the Associations With Health and Well-Being in Older Adults: An Exploratory Study. *HERD: Health Environments Research & Design Journal*, *10*(5), 64–79. doi:10.1177/1937586717697650

Noell-Waggoner, E. (2006). Lighting in nursing homes: The unmet need. Paper presented at the 2nd CIE Expert Symposium on Lighting and Health, Ottawa, Ontario, Canada.

Obayashi, K., Saeki, K., Iwamoto, J., Okamoto, N., Tomioka, K., Nezu, S., … Kurumatani, N. (2012). Positive effect of daylight exposure on nocturnal urinary melatonin excretion in the elderly: A cross-sectional analysis of the HEIJO-KYO study. *The Journal of Clinical Endocrinology and Metabolism*, *97*(11), 4166–4173. doi:10.1210/jc.2012-1873

Obayashi, K., Saeki, K., Iwamoto, J., Okamoto, N., Tomioka, K., Nezu, S., … Kurumatani, N. (2014a). Effect of exposure to evening light on sleep initiation in the elderly: A longitudinal analysis for repeated measurements in home settings. *Chronobiology International*, *31*(4), 461–467. doi:10.3109/07420528.2013.840647

Obayashi, K., Saeki, K., & Kurumatani, N. (2014b). Association between light exposure at night and insomnia in the general elderly population: The HEIJO-KYO cohort. *Chronobiology International*, *31*(9), 976–982. doi:10.3109/07420528.2014.937491

Ortman, J. M., Velkoff, V. A., & Hogan, H. (2014). An aging nation: The older population in the United States population estimates and projections, current population reports. Retrieved from Washington, DC. https://www.census.gov/prod/2014pubs/p25-1140.pdf

Oweley, C. (2016). Vision and aging. *Annual Review of Vision Science*, *2*(1), 255–271. doi:10.1146/annurev-vision-111815-114550

Prevent Blindness America, National Eye Institute. (2002). *Vision problems in the U. S.—Prevalence of adult vision impairment and age-related eye disease in America*. Schaumburg, IL: Prevent Blindness America.

Sander, B., Markvart, J., Kessel, L., Argyraki, A., & Johnsen, K. (2015). Can sleep quality and wellbeing be improved by changing the indoor lighting in the homes of healthy, elderly citizens? *Chronobiology International*, *32*(8), 1049–1060. doi:10.3109/07420528.2015.1056304

Shikder, S., Mourshed, M., & Price, A. (2012). Therapeutic lighting design for the elderly: A review. *Perspectives in Public Health*, *132*(6), 282–291. doi:10.1177/1757913911422288

Shochat, T., Martin, J., Marler, M., & Ancoli-Israel, S. (2000). Illumination levels in nursing home patients: Effects on sleep and activity rhythms. *Journal of Sleep Research*, *9*(4), 373–379.

Tsuzuki, K., Mori, I., Sakoi, T., & Kurokawa, Y. (2015). Effects of seasonal illumination and thermal environments on sleep in elderly men. *Building and Environment*, *88*, 82–88. doi:10.1016/j.buildenv.2014.10.001

van Maanen, A., Meijer, A. M., van der Heijden, K. B., & Oort, F. J. (2016). The effects of light therapy on sleep problems: A systematic review and meta-analysis. *Sleep Medicine Reviews*, *29*, 52–62. doi:10.1016/j.smrv.2015.08.009

White, M. D., Ancoli-Israel, S., & Wilson, R. R. (2013). Senior living environments: Evidence-based lighting design strategies. *HERD: Health Environments Research & Design Journal*, *7*(1), 60–78. doi:10.1177/193758671300700106

Zeitzer, J. M., Friedman, L., & Yesavage, J. A. (2011). Effectiveness of evening phototherapy for insomnia is reduced by bright daytime light exposure. *Sleep Medicine*, *12*(8), 805–807. doi:10.1016/j.sleep.2011.02.005