Effects of Spectral Composition and Illuminance on Walking Performance and Prefrontal Cortex Activity in Younger and Older Adults: A Multimodal Study of Pedestrian Lighting

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Abstract

Lighting affects not only visual performance but also cognitive engagement and mobility, particularly in older adults navigating complex pedestrian environments. However, evidence linking lighting spectrum and intensity to real-world walking behaviour and the underlying cognitive mechanisms remains limited. This study examined how illuminance (5 vs. 500 lux), spectrally distinct lighting conditions (2700 K vs. 6000 K), and environmental complexity (obstacle presence) influence walking performance, prefrontal cortical activity, and subjective experience in younger and older adults under mesopic lighting conditions.

Thirty-eight participants completed structured walking tasks in a full-scale pedestrian laboratory under systematically varied lighting conditions. Walking duration was used as a functional indicator of mobility performance. Functional near-infrared spectroscopy (fNIRS) was employed to index prefrontal cortical activation as a marker of cognitive engagement during walking, and participants provided repeated subjective ratings of visual comfort and perceived physical and mental effort following each condition.

Results showed that dim and warmer lighting reliably slowed walking, whereas blue-enriched lighting and higher illuminance supported faster walking across environments. Older adults walked more slowly overall but derived greater benefit from blue-enriched lighting in visually and cognitively demanding settings, particularly under dim conditions. Neurophysiological findings revealed selective modulation of prefrontal engagement by lighting and environmental complexity, consistent with changes in attentional support rather than global increases in cognitive load. Subjective ratings indicated higher perceived effort under dim lighting, without reductions in comfort under blue-enriched light.

These findings inform evidence-based pedestrian lighting design by showing that blue-enriched light can support safe, comfortable mobility in ageing populations environments.

Keywords

Pedestrian lighting, Mesopic vision, Light spectrum, Walking performance, Ageing, Inclusive lighting design, Functional near-infrared spectroscopy (fNIRS)

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1.Introduction:

Safe and efficient mobility is critical for independence and quality of life, particularly in ageing populations. With age, walking becomes less automatic and more cognitively demanding, especially under visually challenging conditions. Lighting plays a key role in supporting visual perception and cognitive engagement during mobility, yet much existing research is based on bright, idealised environments that do not reflect everyday settings such as dim streets or public spaces. Insufficient or poor-quality lighting can impair gait and balance in older adults, increasing fall risk (1), whereas well-designed lighting supports confident and independent navigation.

While the effects of light intensity and spectral composition—particularly blue light—have been widely studied in driving and target-detection contexts, far less is known about their influence on pedestrian walking behaviour. In real-world environments, pedestrian lighting often falls within the mesopic range, where both rods and cones contribute to vision, altering contrast sensitivity and visual acuity. These effects are more pronounced in older adults due to age-related retinal changes, increasing the visual and cognitive demands of walking.

Correlated colour temperature (CCT) can be a determinant of visual performance under mesopic conditions, even though it does not fully characterise spectral composition. Higher CCT, blue-enriched lighting (e.g. 6000 K) enhances perceived brightness and contrast relative to lower CCT, yellow lighting (e.g. 2700 K), potentially supporting safer navigation in low-light environments (2). Beyond visual benefits, blue light also modulates cognitive function via melanopsin-containing retinal ganglion cells, increasing activation in brain regions associated with alertness and executive control (3).

However, how these visual and neural effects translate to real-world walking performance across age groups remains unclear. This study addresses this gap by examining the effects of light intensity, CCT, and environmental complexity on walking behaviour, prefrontal cortical activity, and subjective experience in younger and older adults, with the aim of informing evidence-based pedestrian lighting design.

1.1. Visual Detection Under Low-Light Conditions

1.1.1. *Peripheral and Object Detection*

A consistent finding in mesopic (twilight-level) lighting research is that light sources with higher short-wavelength (blue) content improve human target detection performance compared to “warm” or red-rich lights at the same low illuminance. In simulated night-driving experiments (background luminance 0.1–3 cd/m^2,roughly mesopic range), observers missed significantly fewer targets under *blue-rich* illumination than under yellowish or reddish light(2). These performance-based

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experiments by Bullough & Rea and others underpin the modern mesopic photometry models that give more weight to blue light for visual effectiveness at night(4). Similarly, Freiding *et al.* found that under dim background levels (0.01, 0.1, 1 cd/m^2) the *contrast threshold* needed to detect a peripheral coloured target was lowest for blue targets, meaning blue objects were more easily detectable than red or green ones in low light(5). This trend is expected because as luminance decreases into the mesopic range, vision increasingly relies on rod photoreceptors which are most sensitive to shorter wavelengths (peak ≈507 nm)(5). In short, under steady dim illumination, blue-enriched lighting tends to expand visual sensitivity and improve detection of targets or hazards in the periphery, whereas red/orange-light environments yield poorer visual alertness in those conditions(2). Notably, the advantage of blue-rich light diminishes at higher (photopic) light levels and studies report little to no difference in detection performance between different spectra(6) (rods are mostly saturated by that point).

1.1.2. *Central Vision and Recognition:*

Low-luminance benefits of blue light are not limited to peripheral vision. Laboratory studies have also reported improvements in central visual tasks, such as reading and object recognition, under blue-biased lighting when tasks are constrained by dim conditions. For example, Szálmáś et al. found faster reaction times for recognising road signs under headlamp spectra with higher S/P ratios (i.e. greater blue content), attributing this effect to rod–cone interactions whereby rods augment the luminance channel at mesopic levels (7). When brightness is perceptually equated across spectra, however, these reaction-time differences are reduced, indicating that part of blue light's advantage arises from increased perceived luminance under dim conditions (the Purkinje shift effect).

Across steady-state low-light scenarios—from obstacle recognition on dark roads to reading in dim interiors—blue-enriched illumination generally supports better visibility, higher contrast sensitivity, and faster detection than blue-depleted lighting of equal photopic illuminance (8, 9). These findings underpin consensus recommendations, such as the CIE 191:2010 mesopic photometry standard (10), which advocate considering spectral output in addition to illuminance for outdoor lighting design, given that short-wavelength-rich light can substantially increase visual efficiency at mesopic levels (11).

Field studies provide converging evidence. At equivalent photopic illuminance, pedestrian recognition distances and peripheral target detection are greater under whiter, blue-rich lamps than under yellow sodium lighting in the 1–3 lux range (12). Similarly, drivers were more likely to detect small roadway targets under bluish-white metal-halide lamps than under yellow sodium lamps at a background luminance of 0.5 cd/m² (13). Overall, under low-light conditions without significant glare, the evidence consistently indicates superior visual acuity, contrast, and response speed under blue-enriched lighting compared with long-wavelength-rich alternatives (14).

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1.1.3. Human Factors: Age and Individual Differences

Visual performance under blue-rich lighting varies with age and visual health. Older adults, due to age-related yellowing of the ocular lens or early cataracts, receive less short-wavelength light at the retina, which can reduce or even reverse the blue-light advantage observed in younger observers. For example, a Virginia Tech study comparing pedestrian detection under 3500 K “warm” LED, 6000 K “cool/blue-rich” LED, and fluorescent street lighting found that older drivers (55+ years) exhibited shorter recognition distances for pedestrians wearing blue clothing under 6000 K lighting than under lower-CCT conditions, whereas younger drivers showed the opposite pattern (15). This age-related divergence was attributed to increased short-wavelength filtering by older lenses, diminishing the effective spectral advantage of blue-rich light.

Beyond optical filtering, older adults also tend to exhibit reduced rod function and contrast sensitivity under mesopic conditions, further attenuating the benefits of blue-enriched illumination. This does not imply that blue light is detrimental to older vision; rather, it suggests that older individuals may derive smaller relative gains from blue-rich lighting and remain more dependent on overall brightness and contrast. For visually impaired populations, such as those with early age-related macular degeneration, mesopic vision is generally poorer, and although direct evidence on spectral effects is limited, reduced retinal sensitivity is likely to similarly blunt spectral advantages.

Glare and comfort factors

Blue-rich headlights and LEDs tend to produce more discomfort glare at night (partially because short waves scatter in the eye and cause more “dazzle”). Some individuals (especially those with early cataract or larger dark-adapted pupils) may find blue-heavy light sources *uncomfortable*, even if objectively those lights improve detection distances(16). This has led to interest in eyewear or coatings that selectively cut blue light at night to reduce glare. While such filters can increase subjective comfort by toning down the harsh blue spikes from LED headlights, they also slightly reduce the mesopic efficacy of the light reaching the eye. The trade-off is between comfort and absolute visual sensitivity. As an example, modern “night driving” glasses with mild blue attenuation claim to reduce glare; tests of their impact on actual detection performance generally show *minimal change* – they neither greatly help nor hurt detection in controlled conditions(17). Thus, for populations with sensitivity to glare, a non-blue-rich (more yellow) light may subjectively feel better even if pure detection distance might be a bit shorter. In design terms, one approach is to use bluish light for peripheral vision tasks (to maximize detection) but limit direct blue glare in drivers’ line of sight.

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1.2. Blue Light Exposure, Brain Activity, and Cognitive Performance

1.2.1. Neural Mechanisms

Blue light (~460–480 nm) strongly influences brain function via melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs), which project to arousal and cognitive centres. The fMRI shows that even 50 s of blue light (473 nm) increases activation in the thalamus, hippocampus, and locus coeruleus compared with violet (430 nm) or green (527 nm) light (3). These subcortical effects propagate to the prefrontal cortex (PFC), explaining blue light's alerting and cognitive effects.

Using functional near-infrared spectroscopy (fNIRS), Scholkmann et al. demonstrated that all colours activate the visual cortex, but only blue light increases PFC oxygenation, confirming a colour-specific frontal response(18). EEG evidence(19) further shows that blue light suppresses alpha (8–12 Hz) and enhances beta activity—signatures of heightened alertness(19). Together, imaging and electrophysiology indicate that blue light uniquely engages both visual and non-visual pathways to enhance cortical arousal.

1.2.2. Cognitive Enhancement in Young Adults

Blue light consistently improves attention and executive control in young adults. In fMRI studies, 30 min of blue-light exposure increased dorsolateral PFC activation and improved reaction time in working-memory tasks compared with amber light (20). Killgore et al. (21) found similar enhancements during an executive-function task, with participants achieving equal accuracy under blue light but with lower metabolic effort, suggesting greater neural efficiency.

At rest, Killgore et al. (22)showed that blue light strengthened functional connectivity between the left dorsolateral prefrontal cortex (DLPFC) and 30 cortical/subcortical regions, including the hippocampus and temporal-occipital cortex, correlating with better vigilance performance.

Behavioural data also confirm wavelength-specific gains. In a crossover study, narrow-band blue (460 nm) exposure shortened simple reaction time and improved dynamic balance, while red (630 nm) did not (23). A verbal-fluency fNIRS study likewise found stronger cerebral oxygenation under blue versus red light (18). Moreover, blue-light benefits can persist: Kim et al. (24) reported improved post-exposure auditory-memory accuracy without increased sleepiness, implying a delayed cognitive facilitation.

1.2.3. Age-Related Differences

Age markedly moderates blue-light responsiveness. Using fMRI, Daneault et al. (25)found that older adults (≈61 y) exhibited reduced blue-light activation in the pulvinar, PFC, amygdala, and occipital cortex compared with younger adults (≈23 y). Although some visual-thalamic activity persisted, the overall neural response and

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performance gain were smaller, indicating diminished non-visual sensitivity with aging.

To test whether this decline was optical or neural, Daneault et al. (26) compared seniors with natural versus clear intra-ocular lenses. Despite restored retinal transmission, both groups showed similarly weak cortical responses, suggesting that age-related neural adaptation—rather than lens yellowing—underlies the reduced effect. Thus, while the older brain remains light-responsive, its capacity for blue-light-induced cognitive enhancement appears constrained, likely due to attenuated ipRGC or cortical responsiveness.

1.2.4. Comparisons with Other Light Colours

Across modalities, blue light outperforms red, green, and amber in activating cognitive networks. In fNIRS studies show that only blue produces robust PFC hemodynamic responses (18). In contrast, red or green primarily affect visual cortex and cardiorespiratory parameters without frontal engagement. The fMRI evidence confirms this spectral specificity: blue evokes widespread activation in thalamic and frontal circuits, while longer wavelengths do not (3).

Comparisons with amber light further illustrate blue's superiority in cognitive performance. Blue but not amber enhances functional connectivity within attentional and memory networks (22) and improves later memory recall (27).

Real-world experiments in classrooms and workplaces echo laboratory data: daylight or cool white (blue-enriched) lighting produces smaller pupil diameters, shorter fixation times, and more localized PFC activation than warm artificial light, signifying lower visual strain and higher neural efficiency(28). These findings support human-centric lighting designs using moderate-intensity blue-enriched spectra to promote alertness and cognitive clarity.

Neuroimaging and electrophysiological evidence converge on the conclusion that blue light acutely enhances cortical arousal, attention, and executive processing through, possibly melanopsin-mediated activation of subcortical arousal centres and prefrontal networks. In young adults, it improves reaction time, working-memory accuracy, and network connectivity, whereas in older adults these benefits are blunted. Compared with other wavelengths, blue light uniquely recruits the PFC and related circuits, underpinning its role as the most effective spectral component for sustaining alert cognition.

1.3. Walking as a Visually and Cognitively Mediated Process

Safe locomotion in real environments depends on the integration of sensory input with higher-order cognitive control. Even during apparently simple level walking, people continually engage attention, planning, and decision-making to adapt their gait to changes in surface, gradients, obstacles, other road users, and lighting conditions(29). Vision is central to this process: it supports route planning, obstacle

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detection, foot placement, and postural stability, and allows walkers to anticipate hazards rather than respond only at the last moment(30, 31). These functions are especially critical in visually challenging environments, such as at night, in low contrast conditions, or where glare and deep shadows reduce visibility.

1.3.1. Cortical Contributions to Everyday Walking

Over the last decade, mobile neuroimaging has shown that walking engages not only spinal and subcortical locomotor circuits but also cortical networks. In particular, functional near-infrared spectroscopy (fNIRS) and related methods have demonstrated consistent involvement of the prefrontal cortex (PFC) during walking, even when no explicit secondary task is imposed(32). The PFC is associated with attention, executive control and planning, and its activation during walking is interpreted as reflecting the cognitive effort required to maintain safe gait in a continuously changing environment.

Evidence from naturalistic studies reinforces this view. Using mobile fNIRS in a real street environment, Burgess et al. (33) showed that rostral PFC (BA 10) is active while people walk and manage everyday goals, such as remembering to carry out intended actions at specific locations. Although that study included a prospective memory component, the key implication for the built environment is that walking in a real street inherently recruits frontal brain systems linked to monitoring, planning and self-initiated behaviour (33). Even when individuals are not performing a formal “dual task”, the act of navigating urban space, processing signage, monitoring traffic, evaluating crossings and lighting conditions, places cognitive demands on the walker.

Systematic reviews of fNIRS work indicate that prefrontal activation increases as walking becomes more demanding, for example when speed increases, when surfaces are uneven, or when additional cognitive requirements are imposed(32, 34). From an environmental design perspective, this suggests that features which increase visual or postural uncertainty (e.g. poor visibility, patchy lighting, or cluttered pavements) are likely to increase the cognitive load associated with walking, even in the absence of any added “task”.

1.3.2. Ageing, Vision and Gait in Everyday Environments

Ageing introduces additional complexity into this visually and cognitively mediated process. Older adults commonly exhibit slower gait, greater variability, and an increased risk of falls, particularly in unfamiliar or poorly lit environments. Epidemiological studies identify multiple visual risk factors for falls, including reduced visual acuity, impaired contrast sensitivity, constricted visual fields, and cataract (35). Experimental work further shows that loss of the lower visual field—critical for obstacle detection and foot placement—leads to slower, more cautious walking across irregular surfaces (36).

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Laboratory studies confirm that even modest visual degradation alters gait. Under reduced lighting, older adults typically adopt shorter steps, slower walking speeds, and increased gait variability (37, 38), consistent with age-related ocular changes such as lens yellowing, smaller pupils, and reduced retinal sensitivity, which diminish retinal illuminance and contrast, particularly under low light or glare (39). Consequently, older pedestrians must allocate greater attentional resources to surface interpretation and hazard detection, leaving fewer cognitive resources available for navigation.

Neuroimaging findings support this interpretation of increased cognitive effort. fNIRS studies show greater prefrontal cortex (PFC) activation in older than younger adults during ordinary walking, reflecting a shift from automatic to more consciously controlled gait (32). However, this compensatory recruitment is limited, with reduced flexibility in prefrontal modulation as walking demands increase (34, 40). From a built-environment perspective, this suggests that older walkers have reduced cognitive reserve to cope with additional challenges posed by poor lighting or visually complex streetscapes. Adequate lighting that supports clear perception of kerbs, steps, surface changes, and obstacles can therefore reduce visual and cognitive burden, whereas suboptimal lighting may increase effort, slow walking, and elevate fall risk.

The primary aim of this study was to examine how lighting spectrum, illuminance, and environmental complexity influence walking behaviour in pedestrian environments, using walking duration as a functional indicator of mobility performance. Functional near-infrared spectroscopy (fNIRS) was employed as a complementary method to probe the cognitive mechanisms underlying these behavioural effects, with prefrontal cortical activation indexing changes in cognitive engagement and attentional demand during walking.

Illuminance, correlated colour temperature (CCT), and environmental complexity were systematically manipulated, with age group treated as a between-subject factor. The study addressed three related questions: (1) how illuminance, spectral composition, and obstacle presence affect walking duration; (2) how these factors modulate prefrontal cortical activity during walking; and (3) whether these effects differ between younger and older adults. Behavioural, neurophysiological (fNIRS), and subjective measures were analysed to characterise the combined behavioural and cognitive consequences of lighting in pedestrian environments.

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2. Method:

2.1. Design

The experiment adopted a 2 × 2 × 2 × 2 mixed factorial design, with four independent variables: Illuminance (bright: 500 lux vs. dim: 5 lux), Correlated Colour Temperature (CCT) (blue: 6000 K vs. yellow: 2700 K), Obstacle Presence (present vs. absent), and Age Group (younger vs. older adults). Illuminance, CCT, and obstacle presence were manipulated within subjects, while age group was treated as a between-subjects factor.

This design allowed for the examination of main effects and interactions among environmental lighting conditions, environmental complexity, and participant age on cognitive load as indicated by prefrontal cortical activation measured using fNIRS and on walking speed, which served as a behavioural indicator of cognitive–motor interference.

Each participant completed eight walking trials, representing all combinations of the within-subject factors. Walking speed and fNIRS signals were recorded concurrently during each trial to capture neurobehavioral responses to variations in the experimental environment.

2.2. Participants

Fifty-three participants were recruited via university mailing lists, local community postings, and snowball sampling. Total participants comprised of 21 younger adults (5 female; aged 18 - 37 years; *M* = 25.2, *SD* = 6.74), 17 older adults (11 female; aged 62 – 80 years; *M* = 71.8, *SD* = 4.91), and 15 autistic adults (Data from autistic adults are not included in the analyses reported in this paper). Descriptive statistics for participant demographics are presented in Table 1. The present paper focuses only on the younger and older adult groups (*n* = 38) to investigate the effect of ageing.

Table 1. Participant Demographic Characteristics by Age Group (Young vs. Older Adults).

Characteristic		**Young Adults (n = 21)**	**Older Adults (n = 17)**	**Total (N = 38)**
Age	Age (years)	M = 25.2 (SD = 6.74), Range = 18–37	M = 71.8 (SD = 4.91), Range = 62–80	-
Sex	Female, n (%)	5 (23.8%)	11 (64.7%)	16 (42.1%)
	Male, n (%)	16 (76.2%)	6 (35.3%)	22 (57.9%)
Education	Primary School	0 (0%)	2 (11.8%)	2 (5.3%)
	GCSEs / A-levels	10 (47.6%)	6 (35.3%)	16 (42.1%)
	Undergraduate/ Postgraduate	10 (47.6%)	8 (47.1%)	18 (47.4%)

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	Doctoral Degree	1 (4.8%)	0 (0%)	1 (2.6%)
	Other	0 (0%)	1 (5.9%)	1 (2.6%)

Note. Values are presented as counts and percentages unless otherwise specified. Age is reported as Mean (SD) and range.

All participants completed a screening questionnaire to determine eligibility and provided written informed consent prior to participation. Inclusion criteria required participants to have normal or corrected-to-normal vision, no known neurological disorders affecting navigation abilities, and the ability to walk independently for at least 20 minutes. Participants with a history of cataract surgery were excluded from the study. Ethical approval for the study was obtained from the UCL Research Ethics Committee (ID: 5975/003).

2.3. Apparatus and Materials

The experiment was conducted at the UCL PEARL facility, a full-scale immersive street laboratory designed to simulate real-world pedestrian environments under controlled experimental conditions. The environment was configured to resemble urban walking paths with adjustable ambient lighting and reconfigurable physical obstacles.

2.3.1. Lighting Setup

UCL PEARL is fit with ETC RAYN Rosa lighting fixtures with a custom chip which offers a wide range of available wavebands, each of which can be controlled individually and high output ideal for laboratory research. Four lighting condition were used to study the effect of intensity and spectral component of the light. The lower light level used in this study corresponds to the recommended illuminance for the P4 class of pedestrian lighting, as specified in EN 13201-2:2015 (41). The higher light level corresponded to a typical office lighting condition(42). Two correlated colour temperatures (CCTs) were employed: one representing a warmer LED light with a lower scotopic/photopic (S/P) and melanopic/photopic (M/P) ratio, and another representing a cooler (blue-enriched) LED light with higher S/P and M/P ratios. The light specification can be found in Table 2 (Figure 1-3). The illuminance on the floor was highly uniform (Figure 2), measured at the centre points of the rectangular walking area to ensure consistency across conditions. For Unified Glare Rating (UGR) calculations, a LumiDISP luminance distribution analyser was used to capture luminance maps for each of the four lighting conditions at four distinct locations. This analyser, a calibrated digital SLR camera equipped with a fisheye lens, provides pixel-level estimates of luminance and angular size. The accompanying software computes UGR values from each luminance map (Figure 2).

The UGR expresses the psychological impact of glare from luminaires within a visual field and is computed using the formula:

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$$UGR = 8\log_{10}\left(\frac{0.25}{L_b}\sum\frac{L^2\omega}{p^2}\right)$$

where $L$is the luminance of each luminaire in the direction of the observer (cd/m²), ω is the solid angle subtended by the luminaire at the observer's eye, $p$is the Guth position index accounting for the luminaire's location within the field of view, and $L_b$is the background luminance.

The scotopic/photopic (S/P) ratio was calculated from the spectral power distribution (SPD) of each light condition. The SPD was multiplied by the CIE standard luminous efficiency functions for scotopic vision $(V'(\lambda))$and photopic vision $(V(\lambda))$to obtain the corresponding scotopic and photopic luminous fluxes. The S/P ratio was then determined as the quotient of these two integrated values:

$$S/P = \frac{K_s \int P(\lambda)V'(\lambda)d\lambda}{K_p \int P(\lambda)V(\lambda)d\lambda}$$

where $P(\lambda)$is the relative spectral power distribution, and $K_s$and $K_p$are the scotopic and photopic luminous efficacy constants, respectively.

The melanopic/photopic (M/P) ratio was derived from the spectral power distribution (SPD) of each light source following the method outlined by the CIE (CIE S 026/E:2018)(43). The SPD was weighted by the melanopic spectral sensitivity function $(V_{\text{mel}}(\lambda))$, representing the response of intrinsically photosensitive retinal ganglion cells (ipRGCs), and by the photopic luminous efficiency function $(V(\lambda))$. The M/P ratio was calculated as the ratio of the melanopic to photopic luminous flux:

$$M/P = \frac{\int P(\lambda)V_{\text{mel}}(\lambda)d\lambda}{\int P(\lambda)V(\lambda)d\lambda}$$

where $P(\lambda)$is the relative spectral power distribution of the light source.

Table 2. Specifications of the experimental light conditions, including illuminance, correlated colour temperature (CCT), scotopic/photopic (S/P) ratio, unified glare rating (UGR), and melanopic/photopic (M/P) ratio.

Condition	Average Illuminance on the floor (lux)	CCT (K)	S/P ratio	UGR	Melanopic/Photopic ratio (M/P)
Dim-Yellow	5	2700	1.46	4	0.41
Dim-Blue	5	6000	2.82	3	1.1
Bright-Yellow	500	2700	1.70	20	0.55
Bright-Blue	500	6000	2.26	19	0.84

This resulted in four distinct lighting conditions: *bright blue, bright yellow, dim blue,* and *dim yellow* (see Figure 1).

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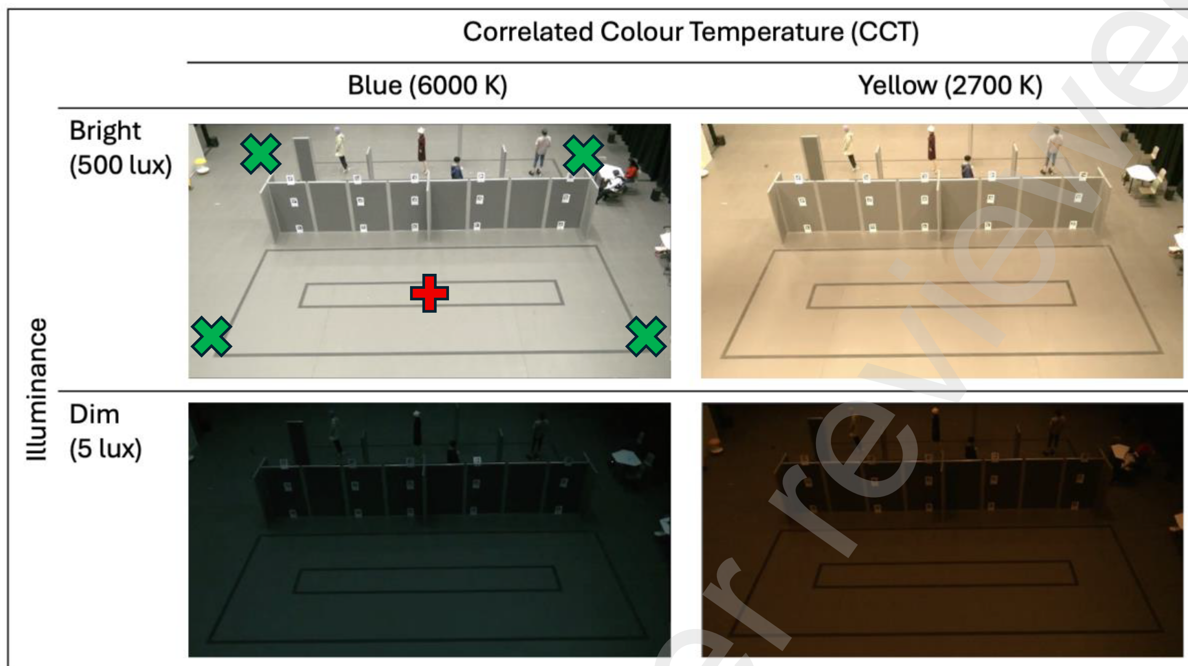
Figure 1. *Experimental Lighting Conditions Across Illuminance and CCT Combinations.*



Note. The figure displays the four lighting conditions used in the experiment: Bright Blue (500 lx, 6000 K), Bright Yellow (500 lx, 2700 K), Dim Blue (5 lx, 6000 K), and Dim Yellow (5 lx, 2700 K). Red cross shows the location where the illuminance was measured. Green crosses show the location that UGR were calculated.

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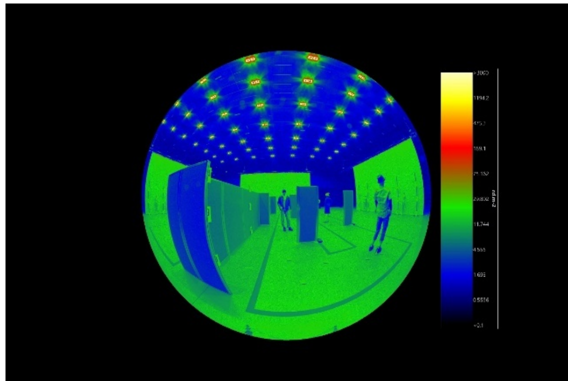
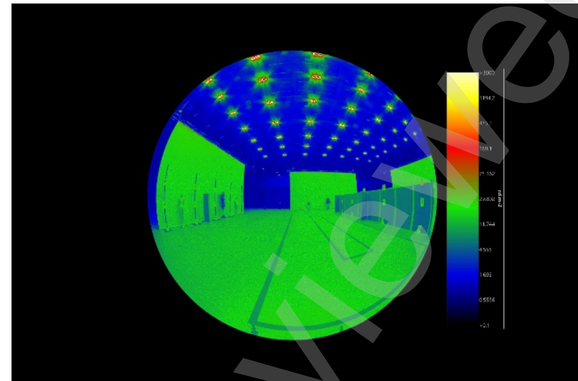
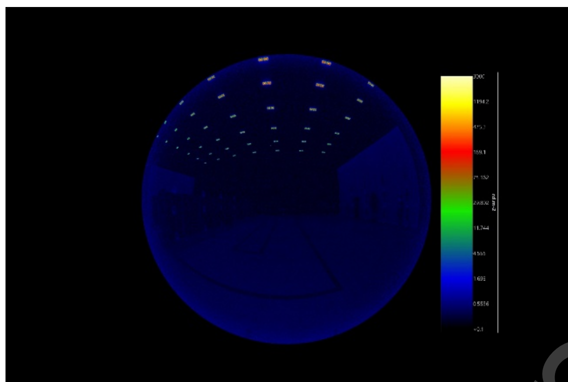
Figure 2. Example luminance map illustrating the spatial light distribution within the experimental environment.



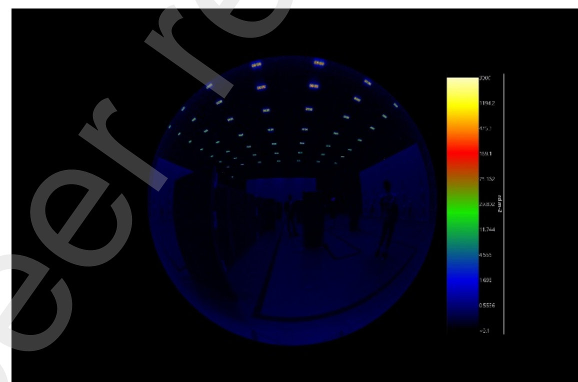
b. Luminance Map of 500 lux, 6000K, Obstacle



a. Luminance Map of 500 lux, 2700K, No Obstacle



c. Luminance Map of 5 Lux, 6000K, No Obstacle



c. Luminance Map of 5 lux, 2700K, Obstacle condition

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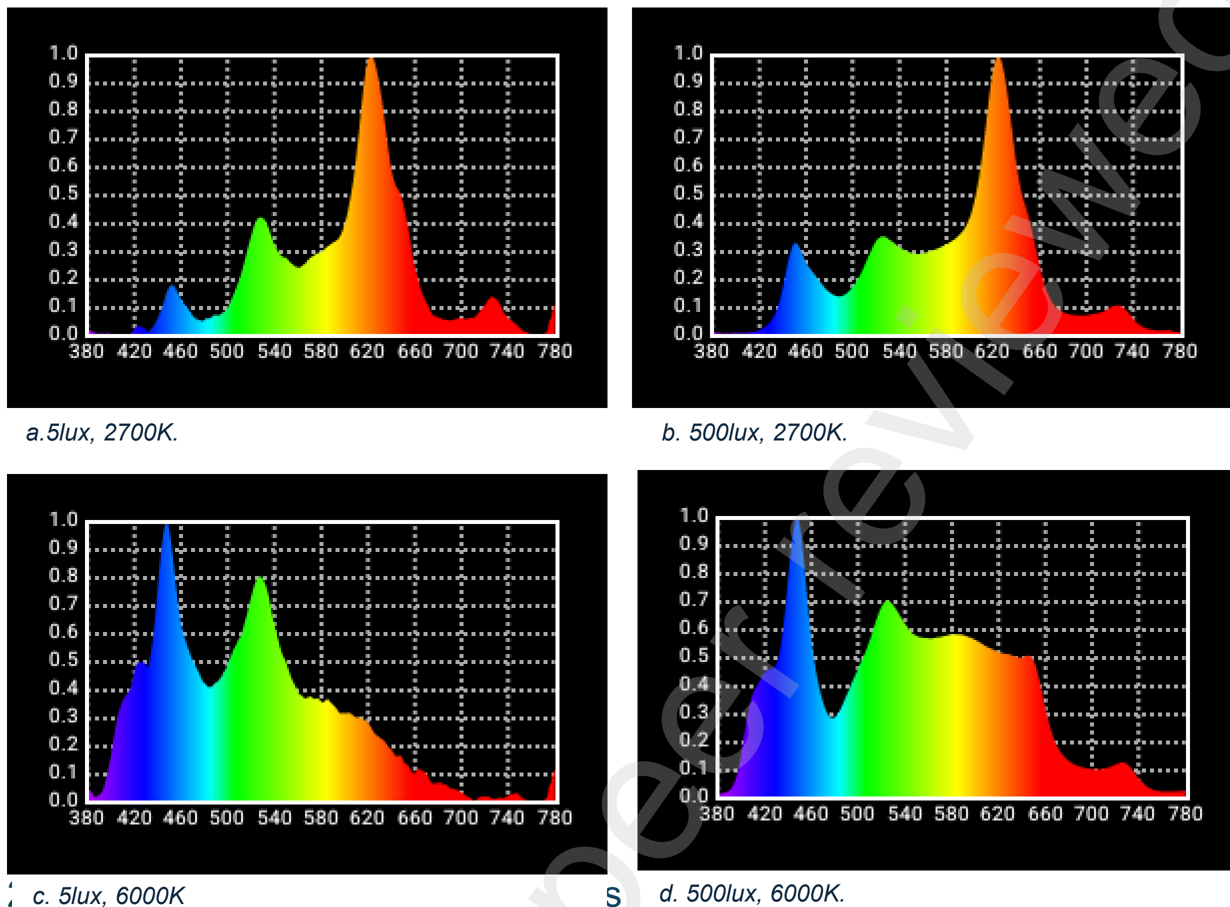
Figure 3. Spectral Power Distribution (SPD) of the four conditions.



a.5lux, 2700K.

b. 500lux, 2700K.

c. 5lux, 6000K

d. 500lux, 6000K.

Participants walked along a rectangular route measuring 11 m × 4 m, with a 1.5 m wide walking lane clearly marked using floor tape. Two environmental configurations were implemented. In the obstacle-present condition, the walking path included freestanding mannequins, upright boards, and small floor-level obstacles (they were 10x10x0.5 cm objects with Weber luminance contrast ≈ 0.069 under 5 lux condition and Weber contrast ≈ 0.363 under 500 lux). These obstacles introduced narrow passages and required directional changes, simulating the spatial complexity of cluttered urban environments. In the obstacle-absent condition, all obstructions were removed, allowing participants to navigate the same path with minimal interference.

Figure 4 presents a schematic illustration of the two environmental configurations, highlighting the arrangement of obstacles and the consistent path dimensions. Figure 5 shows two real-life photographs of the experimental setup during data collection, providing context for the physical space and layout used.

Figure 4. *Schematic illustration of walking path configurations.*

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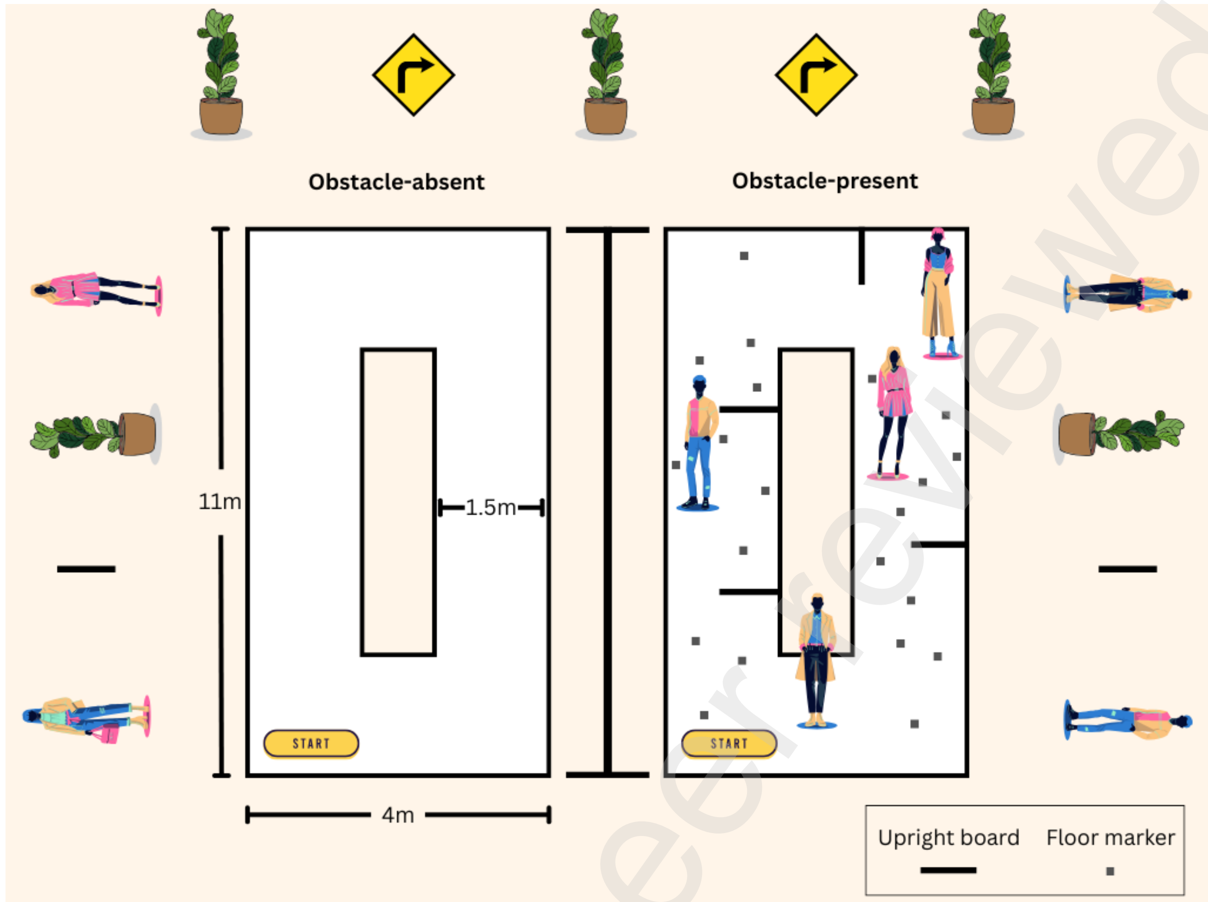
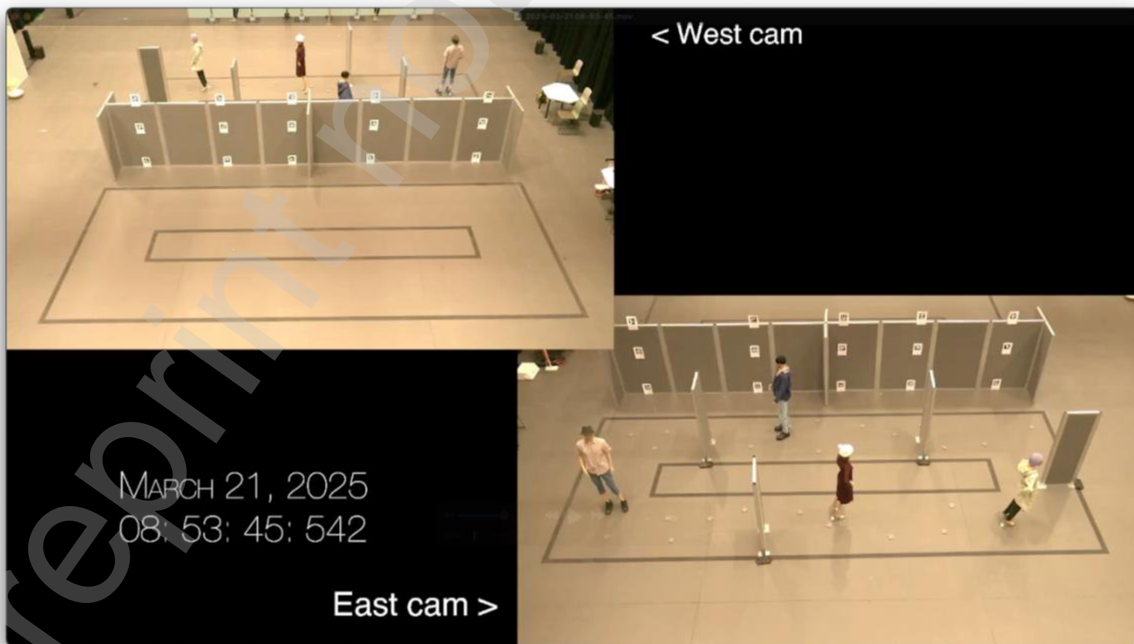


Figure 5. *Real-world setup of the experimental environment at UCL PEARL.*



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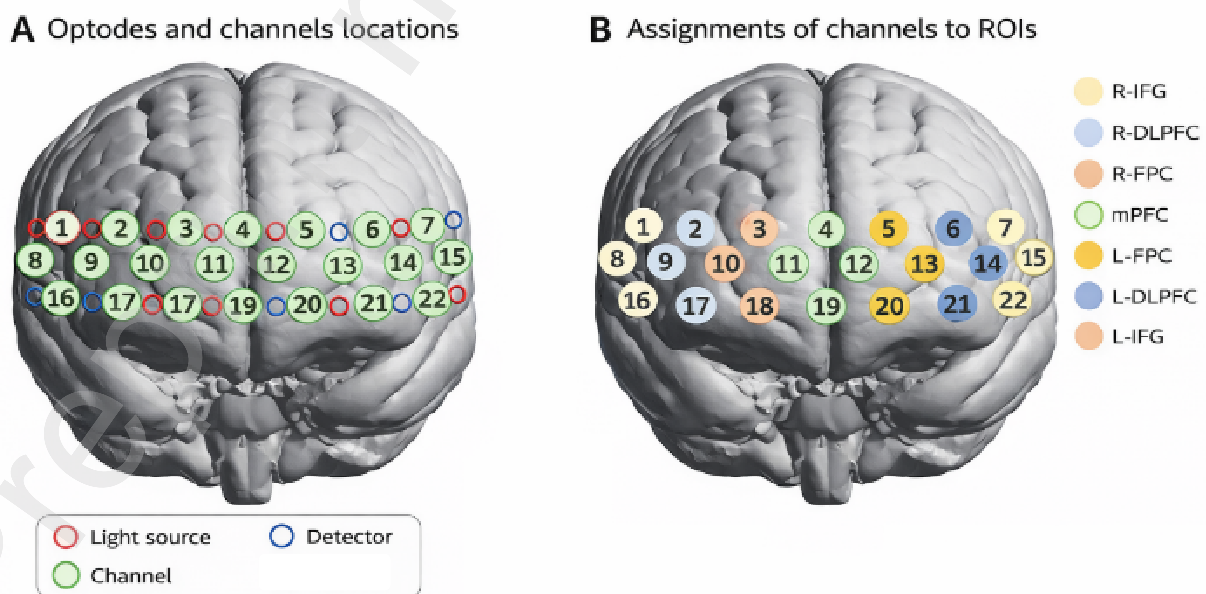
2.3.3. fNIRS Signal acquisition and regions of interest (ROIs)

Cortical haemodynamic activity was recorded using a portable Shimadzu LIGHTNIRS fNIRS device with KNIRS software. Data acquisition involved 16 optical fibres (8 sources and 8 detectors), forming a total of 22 channels across the prefrontal cortex. The system sampled data at 13.33 Hz using three near-infrared wavelengths (780, 805, and 830 nm) to estimate changes in oxygenated (HbO) and deoxygenated (HbR) haemoglobin concentrations. Optode placement was guided by the international 10–20 EEG system, with Channel 19 positioned over Fpz (10% of the nasion-inion distance) to ensure consistent cap alignment across participants. This configuration provided coverage of bilateral inferior frontal gyrus (IFG), dorsolateral prefrontal cortex (DLPFC), frontopolar cortex (FPC), and medial prefrontal cortex (mPFC). Based on this coverage, seven regions of interest (ROIs) were defined a priori using a lab-established parcellation scheme from a previous study employing the same fNIRS setup (44). These included the right inferior frontal gyrus (R-IFG), right dorsolateral prefrontal cortex (R-DLPFC), right lateral frontopolar cortex (R-FPC), medial frontopolar cortex (mPFC), left lateral frontopolar cortex (L-FPC), left dorsolateral prefrontal cortex (L-DLPFC), and left inferior frontal gyrus (L-IFG). Each ROI was created by averaging beta values across a fixed combination of channels previously mapped to these anatomical regions. The specific channel-to-ROI assignments are illustrated in Figure 6. This approach was informed by established evidence linking these frontal regions to executive functions, attentional control, and context-sensitive decision-making. Signal quality across channels was subsequently evaluated through visual inspection and spectral analysis, with preprocessing steps described in the next section.

Figure 6. *Optodes layout and region of interest (ROI) assignments across the prefrontal cortex.*



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2.3.4. fNIRS Signal Processing and Analysis

Neurophysiological analyses were conducted to characterise the cognitive correlates of walking under different lighting conditions and to support interpretation of the behavioural findings. Given the exploratory and mechanistic role of fNIRS in this study, emphasis is placed on robust main effects that survive correction for multiple comparisons, rather than on exhaustive regional activation patterns.

2.3.4.1. Data Pre-Processing

Prior to statistical modelling, the fNIRS data were pre-processed using the Homer2 software package in MATLAB, following the quality check procedure outlined by Pinti et al. (2019)(45). Raw intensity signals were visually inspected to detect and exclude channels with poor signal quality. Specifically, channels were excluded if the power spectral density (PSD) did not show a distinct heartbeat peak around 1.2 Hz, if multiple flat horizontal lines were present (suggesting saturation), or if the intensity time series exhibited prominent motion artefacts or appeared flat, indicating signal loss. The number of participants contributing valid data to each channel and region of interest (ROI) is reported in Appendix 2.

First-level statistical analysis was conducted using a channel-wise general linear model (GLM) to estimate fNIRS activation signals, down sampled to 1 Hz, using the SPM for fNIRS toolbox in MATLAB. For each participant, a design matrix was constructed to model the timing of both the auditory attention tasks, the six experimental walking trial conditions resulting from the factorial combination of Illuminance (bright vs. dim), Colour Temperature (blue vs. yellow), Pavement Condition (obstacle vs no obstacle) and transitions. These events were modelled as block regressors and convolved with the canonical haemodynamic response function (HRF). The GLM was fitted separately for each channel, and beta values representing task-related haemodynamic changes were estimated for each condition. The details of the data fNIRS data processing could be found in the paper by Pinti et. al (45). Following the Pinti et al procedure, beta values representing task-related haemodynamic changes were estimated for each condition.

2.3.5. Behavioural Measures

Walking duration for each trial was recorded using a custom-built experiment on Gorilla.sc, a browser-based behavioural research platform. The experiment interface allowed the experimenter to manually log the start and end of each walking trial in real time using an iPad. Time stamps were exported for analysis and walking duration was then computed for each trial and averaged across repetitions within each condition.

2.3.6. Adaptation Time

A key methodological consideration when using functional near-infrared spectroscopy (fNIRS) is the limited duration for which participants can comfortably wear the optode cap. Consequently, the total experimental session was restricted to

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under 40 minutes, which also constrained the time available for light adaptation. To facilitate adequate adaptation to dim illumination, all sessions began with the lower light-level conditions. Participants were initially exposed to the 5 lux environment and were allowed to adapt during the briefing and fNIRS cap fitting, which lasted approximately 15 minutes. The first two sequences of lighting conditions were conducted under 5 lux, followed by two sequences under 500 lux. Between each condition, an adaptation interval of approximately six minutes was provided to allow participants' eyes to adjust to the new light level. During this six-minute interval, participants completed a brief auditory task; data from this task are not reported in the present paper.

2.3.7. Post-Trial Questionnaire

To capture participants' subjective experiences during each lighting condition, a brief questionnaire was administered immediately following each walking trial. The questionnaire consisted of three items assessing (1) how comfortable the lighting felt, (2) how physically challenging the task was, and (3) how mentally challenging the task was. All items were presented on a 7-point Likert scale, with higher scores indicating greater intensity of the perception (e.g., greater comfort, greater challenge). These ratings were collected to assess real-time subjective impressions of each lighting environment, potentially linked to cognitive-motor load.

2.4. Experimental Protocol

The study took place at the UCL Person-Environment-Activity Research Laboratory (PEARL), a large-scale indoor facility designed to emulate real-world pedestrian environments under controlled conditions.

Following briefing, participants were fitted with a portable fNIRS headband, with optode placement aligned to the international 10–20 EEG system and Channel 19 aligned to the Fpz location to ensure consistent positioning across participants. Signal quality was monitored in real time using the manufacturer's software to ensure adequate light intensity and stability.

Each participant completed eight walking trials covering all combinations of illuminance (bright vs. dim), CCT (blue vs. yellow), and obstacle presence (present vs. absent). Trial order was counterbalanced (with dim condition first) and randomised. To improve efficiency, most sessions were run in pairs, with one participant completing an obstacle-present path while the other completed an obstacle-absent path, both under the same lighting condition.

Participants were instructed to walk four laps around each setting, encompassing both the obstacle and non-obstacle courses. They were asked to walk at their normal, self-selected pace, avoiding both rushing and walking slower than usual.

Walking duration and cortical haemodynamics were recorded continuously during each trial. After both paths for a given lighting condition, participants completed a

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post-trial questionnaire on perceived comfort, physical challenge, and mental challenge. Between lighting conditions, participants performed an auditory attention task to accommodate lighting transitions (see Figure 7).

Figure 7. *Overview of the experimental procedure comprising four lighting condition blocks.*

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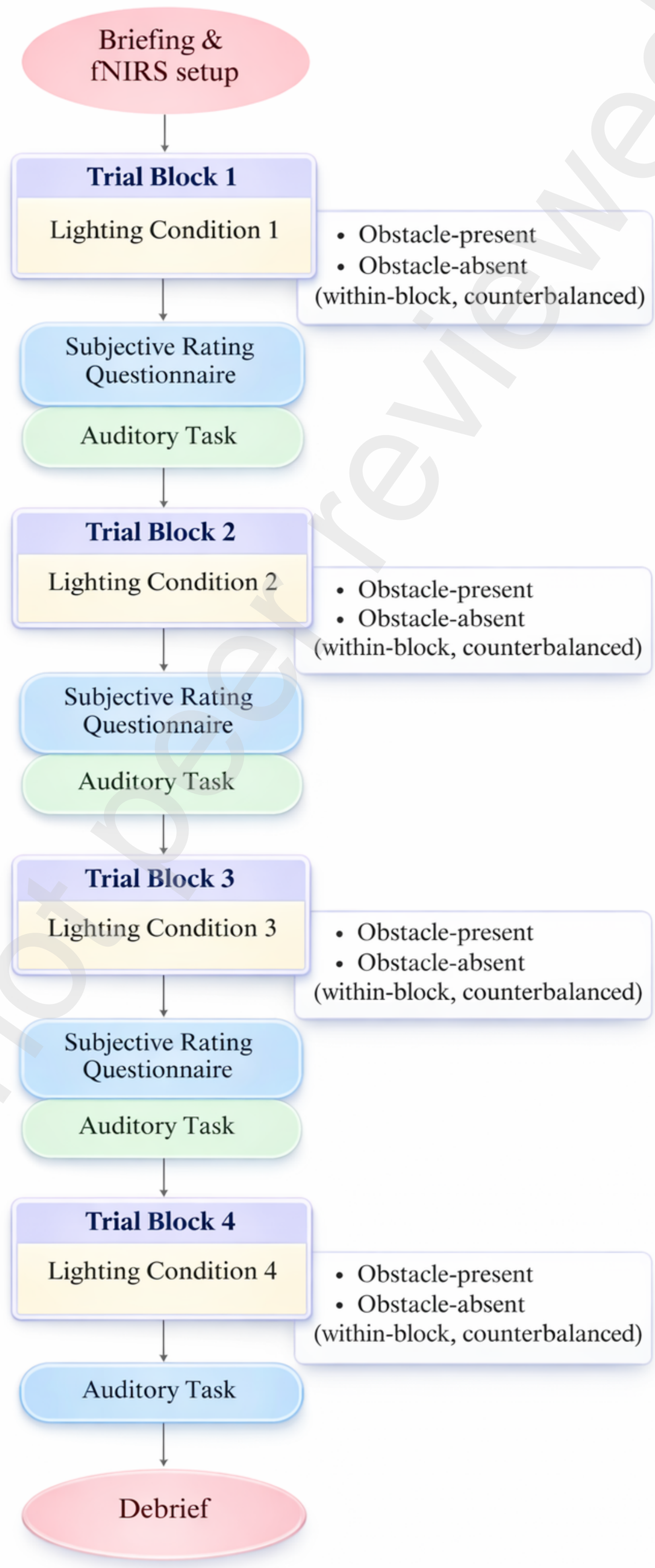
Lighting Conditions (counterbalanced)

- Bright Yellow
- Bright Blue
- Dim Yellow
- Dim Blue



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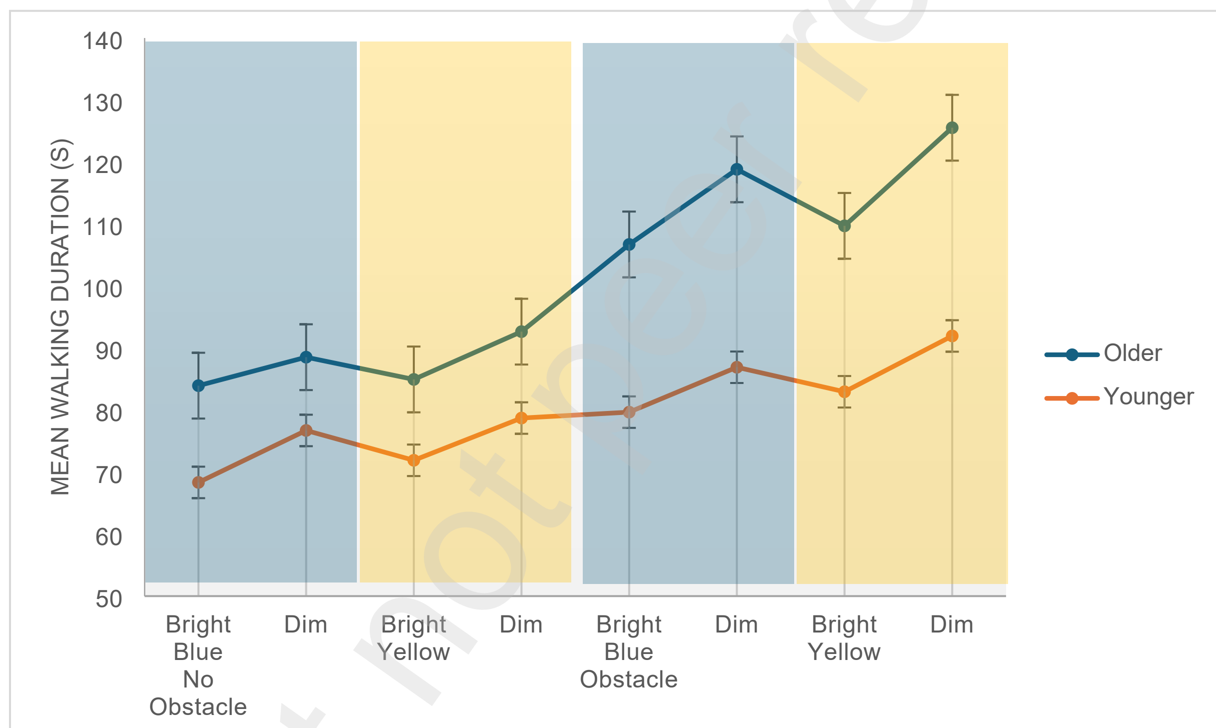
The full experimental session lasted approximately 30 to 40 minutes, including briefing, equipment setup, walking trials, inter-trial tasks, and debriefing.

3. Results:

3.1. Behavioural Measures: Walking duration

Figure 8 and Appendix 1 present the results for walking duration across the different experimental conditions.

Figure 8. Mean walking duration as a function of Age Group, Intensity, Correlated Colour Temperature (CCT), and Pavement Condition.



3.1.1. Main Effects

Walking duration (s) across the 8 lighting conditions was first analysed with a linear mixed-effects model (LMM) including CCT (yellow, blue), INTENSITY (dim, bright) and PAVEMENT (obstacle, no obstacle) as within-subject fixed factors and Group (younger, older) as a between-subject factor, with Participant as a random intercept.

The LMM showed robust main effects of all three lighting factors and Group on walking duration (Table 3):

PAVEMENT: Participants walked substantially more slowly when an obstacle was present than when walking on a flat pavement, $F(1, 99.51) = 154.71$, $p < .001$. The parameter estimate indicated that obstacle trials were on average ≈12.2 s longer than no-obstacle trials ($t = -12.44$, 95% CI [−14.18, −10.28] when coded as no-

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obstacle relative to obstacle; negative sign reflects shorter duration in the no-obstacle condition).

INTENSITY: Walking was slower under dim than bright illumination, $F(1, 110.07) = 76.15$, $p < .001$. Bright light reduced walking duration by ≈7.3 s on average compared with dim ($t = -8.73$, 95% CI [−8.94, −5.63] for bright vs dim).

CCT: Participants also walked more slowly under yellow than blue light, $F(1, 112.22) = 17.64$, $p < .001$. Blue light shortened duration by ≈3.6 s relative to yellow ($t = -4.20$, 95% CI [−5.26, −1.89] for blue vs yellow).

Group: Across conditions, older adults were significantly slower than younger adults, $F(1, 36.60) = 9.22$, $p = .004$. The group parameter estimate suggested that older adults took ≈14.7 s longer than younger adults on average ($t = -3.04$, 95% CI [−24.53, −4.89] for younger vs older).

Table 3. LMM fixed effects on walking duration (s)

Effect	$F(df_1, df_2)$	p	Direction (slower condition)
Pavement	154.71 (1, 99.51)	< 0.001	Obstacle > No-obstacle
Intensity	76.15 (1, 110.07)	< 0.001	Dim > Bright
CCT	17.64 (1, 112.22)	< 0.001	Yellow > Blue
Group	9.22 (1, 36.60)	0.004	Older > Younger

3.1.2 Repeated-measures ANOVA (complete-case check)

To verify the robustness of the linear mixed-model (LMM) findings, a repeated-measures ANOVA was conducted on data from participants who completed all eight experimental conditions (N = 36; 20 younger, 16 older). The design included three within-subject factors—Correlated Colour Temperature (CCT) (blue vs. yellow), Intensity (bright vs. dim), and Pavement Condition (obstacle vs. no obstacle)—and one between-subject factor, Age Group (younger vs. older adults; Table 4). This analysis largely confirmed the main effects observed in the LMM and allowed for detailed examination of interaction effects.

Significant main effects were found for intensity, pavement condition, and CCT. Walking duration was significantly shorter under bright light ($F(1, 34) = 54.64$, $p < .001$, partial $\eta^2 = .62$; M = 85.8 s) than under dim light (M = 94.6 s), indicating an improvement of approximately 8.8 s. Participants also took longer to complete the obstacle course ($F(1, 34) = 49.02$, $p < .001$, partial $\eta^2 = .59$; M = 99.8 s) compared with the no-obstacle condition (M = 80.5 s), reflecting a mean increase of 19.3 s. Additionally, walking duration was shorter under blue light ($F(1, 34) = 18.17$, $p < .001$, partial $\eta^2 = .35$; M = 88.3 s) than under yellow light (M = 92.1 s), a difference of approximately 3.8 s.

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A significant between-subjects effect of Age Group was also observed, with older adults walking more slowly overall ($F(1, 34) = 16.55$, $p < .001$, partial $\eta^2 = .33$; M = 101.7 s) compared with younger adults (M = 78.7 s), mirroring the pattern found in the LMM.

Several interactions did reach or approached significance. A significant Pavement × Age Group interaction ($F(1, 34) = 8.27$, $p = .007$, partial $\eta^2 = .20$) indicated that the obstacle condition imposed a greater cost for older adults (e.g., under dim light: younger ≈ 88.1 s vs. older ≈ 122.4 s; difference ≈ 34 s) compared with younger adults (≈ 12–19 s difference), suggesting that surface irregularities disproportionately affected older walkers. The Intensity × Pavement interaction was also significant ($F(1, 34) = 5.44$, $p = .026$, partial $\eta^2 = .14$), revealing that bright lighting reduced walking duration more on obstacle trials (≈ 14.2 s reduction) than on no-obstacle trials (≈ 6.7 s reduction), particularly among older adults. Finally, a trend-level Intensity × Pavement × Age Group interaction ($F(1, 34) = 4.06$, $p = .052$, partial $\eta^2 = .11$) suggested that the combined benefit of bright illumination and a smooth walking surface may have been somewhat stronger in older adults, although this effect did not reach conventional significance.

Although several interaction effects did not reach significance, they provide valuable context for interpreting the data. The Intensity × Age Group interaction was not significant ($F(1, 34) = 1.76$, $p = .19$, partial $\eta^2 = .05$), indicating that both age groups benefited similarly from brighter lighting. Likewise, the CCT × Age Group interaction was non-significant ($F(1, 34) = 0.01$, $p = .90$, partial $\eta^2 \approx 0$), suggesting comparable effects of blue versus yellow light across age groups. The four-way CCT × Intensity × Pavement × Age Group interaction also failed to reach significance ($F(1, 34) = 0.04$, $p = .84$, partial $\eta^2 = .001$), confirming that overall response patterns were consistent between younger and older adults across conditions.

Table 4. Repeated-measures ANOVA on walking duration (s), complete cases (N = 36)

Effect	F(1, 34)	p	partial η²
INTENSITY	54.64	< 0.001	0.62
PAVEMENT	49.02	< 0.001	0.59
CCT	18.17	< 0.001	0.35
INTENSITY × Group	1.76	0.19	0.05
PAVEMENT × Group	8.27	0.007	0.20
CCT × Group	0.01	0.90	0.00
INTENSITY × PAVEMENT	5.44	0.026	0.14
INTENSITY × PAVEMENT × Group	4.06	0.052	0.11
Group × Pavement × CCT x Intensity	0.040	0.843	0.001
Group (between-subjects)	16.55	< 0.001	0.33

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3.1.3 Simple effects

Bonferroni-corrected pairwise comparisons of INTENSITY within each combination of Group, PAVEMENT and CCT showed that dim light almost always produced longer walking durations than bright light. For younger adults, dim illumination significantly slowed walking in all conditions (all ps $\leq .008$; dim – bright ≈ 6–8 s). For older adults, dim light also reliably increased walking duration in most conditions, with particularly large effects when an obstacle was present (e.g. +16.25 s under yellow and +12.13 s under blue, both ps < .001) and on no-obstacle pavement under yellow light (+8.00 s, $p = .001$).

The only condition in which the dim–bright difference did not reach significance was older adults walking on the no-obstacle pavement under blue light (dim − bright = 5.31 s, 95% CI [−1.20, 11.83], p = .107). Although the omnibus 4-way interaction was not significant, the pattern of simple effects was consistent with smaller dim-light slowing in this favourable combination; however, this difference was not statistically reliable, and the confidence interval includes both no effect and meaningful slowing.

3.2. fNIRS Data Analysis

Statistical analysis – primary linear mixed-effects models.

fNIRS beta values were analysed using linear mixed-effects models (LMMs), fitted separately for each ROI. Because the dependent variable (HbO β-values) had very small numerical values, it was rescaled by multiplying by 10^6 to improve numerical stability in the mixed-effects model. This linear rescaling does not affect statistical significance or interpretation. The models included CCT (yellow, blue), INTENSITY (dim, bright) and PAVEMENT (obstacle, no obstacle) as within-subject fixed factors and Group (younger, older) as a between-subject factor. Participant was included as a random intercept to account for repeated measurements within individuals. This approach allows unequal numbers of observations per participant and uses all available data under a missing-at-random assumption. Where appropriate, p-values for a priori families of tests (e.g., main effects of lighting factors across ROIs) were adjusted using the false discovery rate (FDR). A summary of results are shown on Figure 9.

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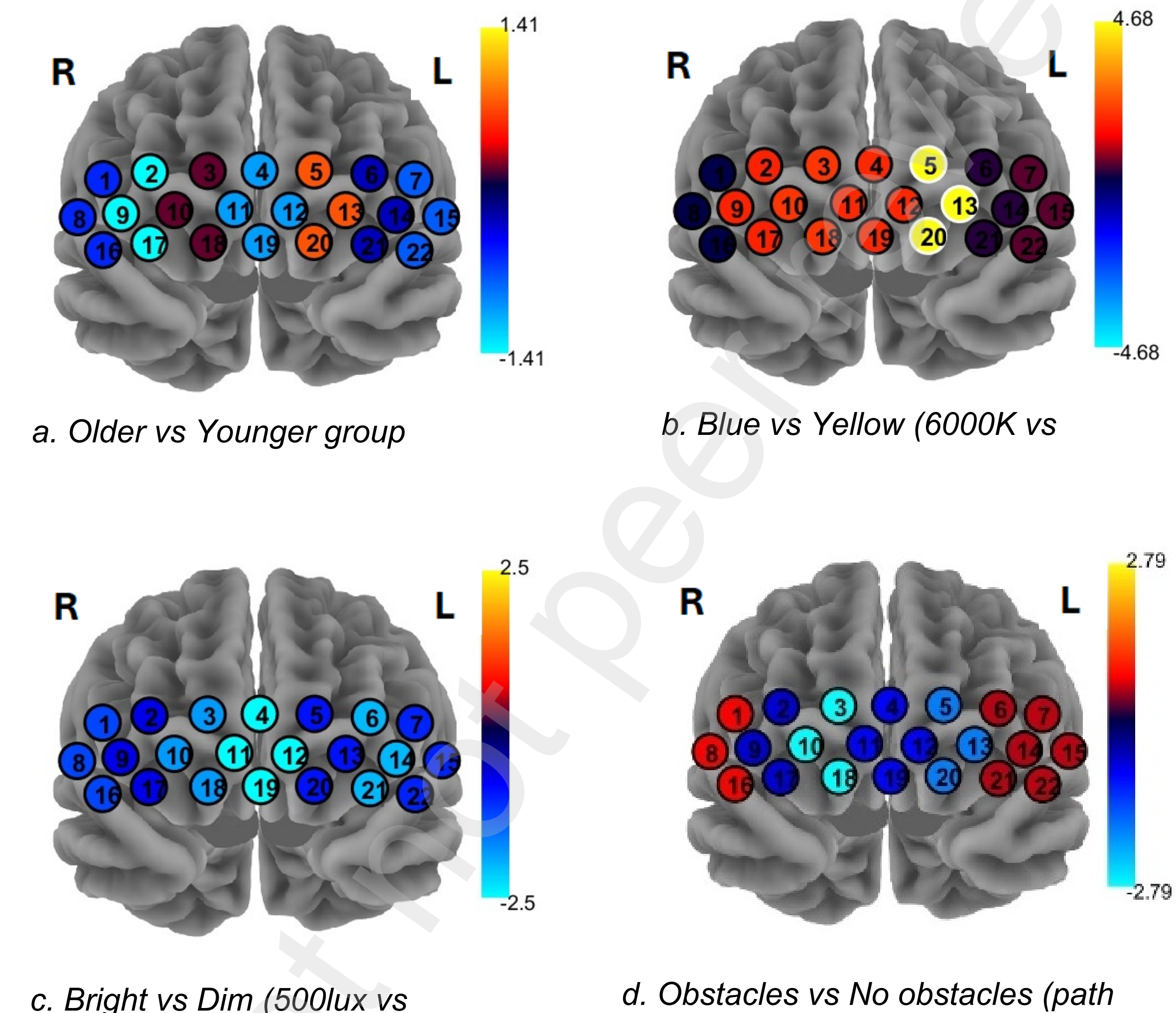
Figure 9. Spatial distribution of *t*-values from linear mixed-effects models (LMMs) across prefrontal ROIs for the following contrasts: (a)Older vs Younger group, (b)Blue vs Yellow light (6000 K vs 2700 K), (c)Dim vs Bright intensity (5 lux vs 500 lux), and (d)Obstacles vs No-obstacles (path condition). Significant ROIs (FDR-corrected $p < 0.05$) are indicated by white circles, . Colour bars represent *t*-values and higher values indicate greater prefrontal engagement. Reference levels were: CCT = yellow, intensity = dim, pavement = obstacle, and group = older.



3.2.3 fNIRS Results

Following false discovery rate (FDR) correction across ROIs, one main effect remained significant (q<.05) and two effects showed FDR-adjusted trends (p_{FDR} <.10). A main effect of Pavement Condition (no-obstacle vs obstacle) was observed in the right frontopolar cortex (R-FPC; p_{FDR} =0.063). In the medial prefrontal cortex (mPFC), Intensity (bright vs dim) showed an FDR-adjusted trend (p_{FDR} =0.098). A robust main effect of correlated colour temperature (CCT; blue vs yellow) emerged in the left frontopolar cortex (L-FPC; p_{FDR} =0.004). No other main effects or interactions survived FDR correction. Key contrasts are summarised in Table 5; full ROI outputs are provided in Appendix 3.

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Table 5. Summary of LMM main effects (lighting / pavement) that survived FDR correction (p_{FDR} < 0.10). Estimates are fixed-effect coefficients (difference between the non-reference and reference level), with associated t-statistics and p-values.

ROI	Factor	Estimate	df	t value	p_{uncorr}	p_{FDR}
R-FPC	Pavement	-0.061	30.65	-2.79	0.009	0.063
mPFC	Intensity	-0.084	106.39	-2.50	0.013	0.098
L-FPC	CCT	0.126	62.14	4.68	1.6065e-05	0.004

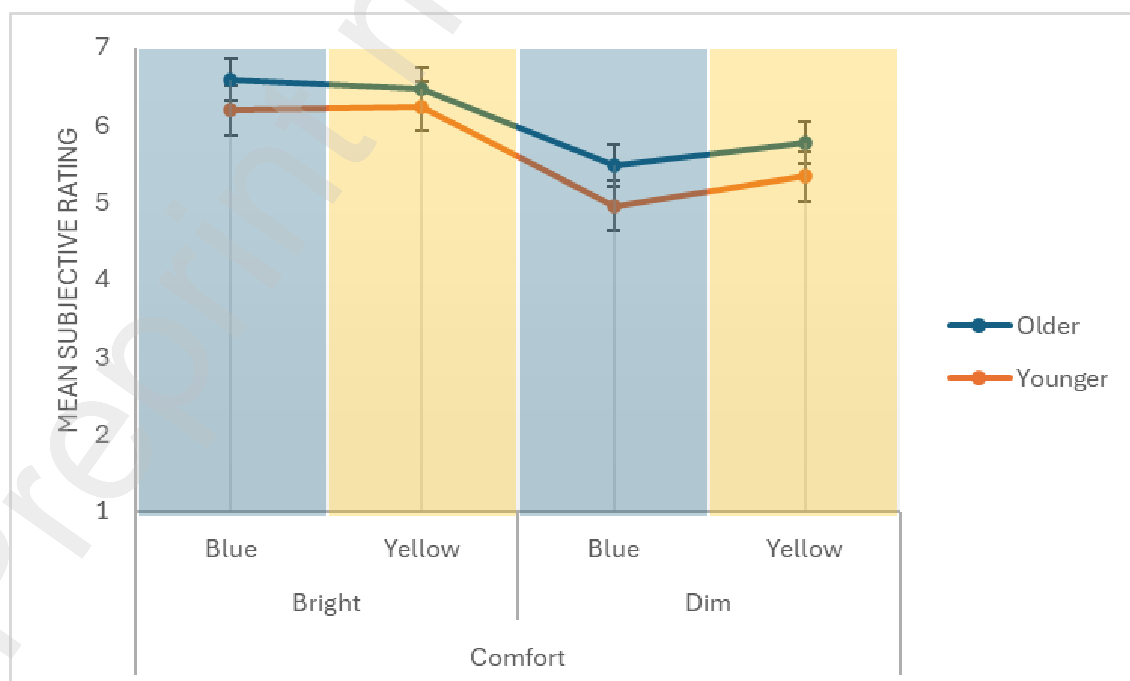
Note: Reference levels: CCT = yellow, INTENSITY = dim, PAVEMENT = obstacle, Group = older. Positive estimates indicate higher β for Blue vs Yellow (CCT), Bright vs Dim (Intensity), and No-obstacle vs Obstacle (Pavement), relative to the stated reference levels.

For completeness, the same LMM framework was applied to all other ROIs. After FDR correction across ROIs, no main effects of CCT, INTENSITY, PAVEMENT or Group, and no interactions among these factors, survived correction in these additional regions (See Appendix 3).

3.3. Subjective Ratings of Lighting Conditions

Descriptive statistics for comfort, physical challenge, and mental challenge ratings by group, Intensity, and colour are presented in Appendix 4 and illustrated in Figure 10. Subjective ratings were analysed using a linear mixed-effects model with Group (younger vs older adults), Light Intensity (Bright vs Dim) and CCT (Blue vs Yellow) as fixed factors, a random intercept for participants, and scores as the dependent variable (see Table 6).

Figure 10. Mean rating for comfort, mental demand, and physical demand for younger and older participants under 5 Lux (dim) lighting, 500 Lux (bright), 2700K (Yellow) and 6000K(Blue) lighting condition.



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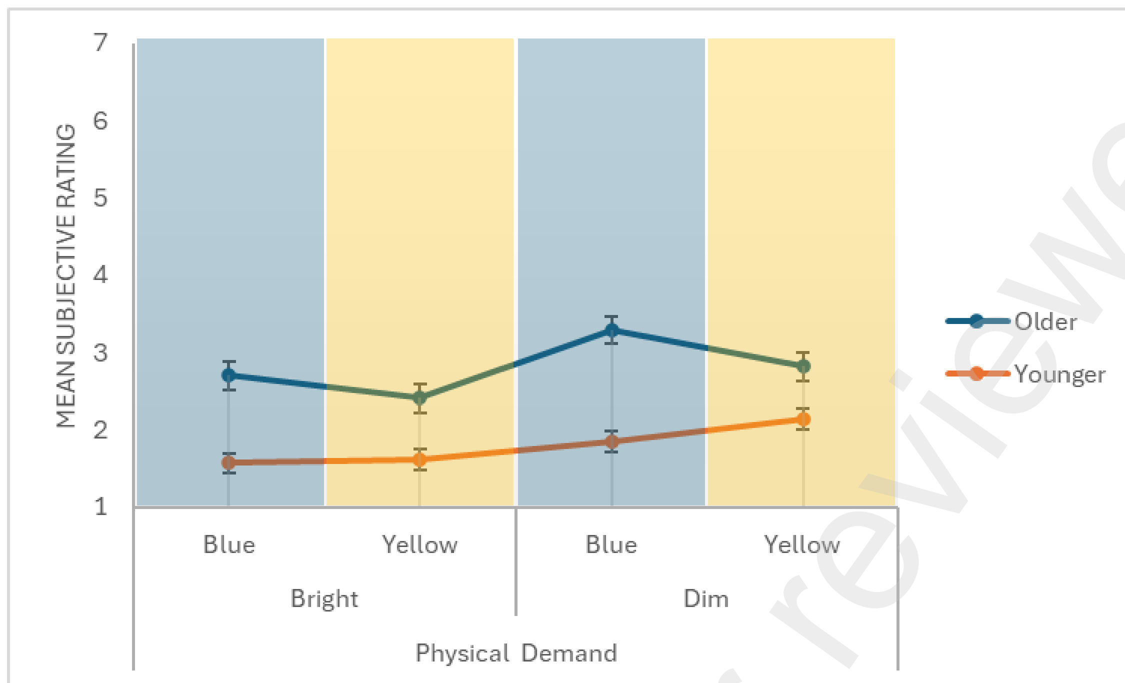

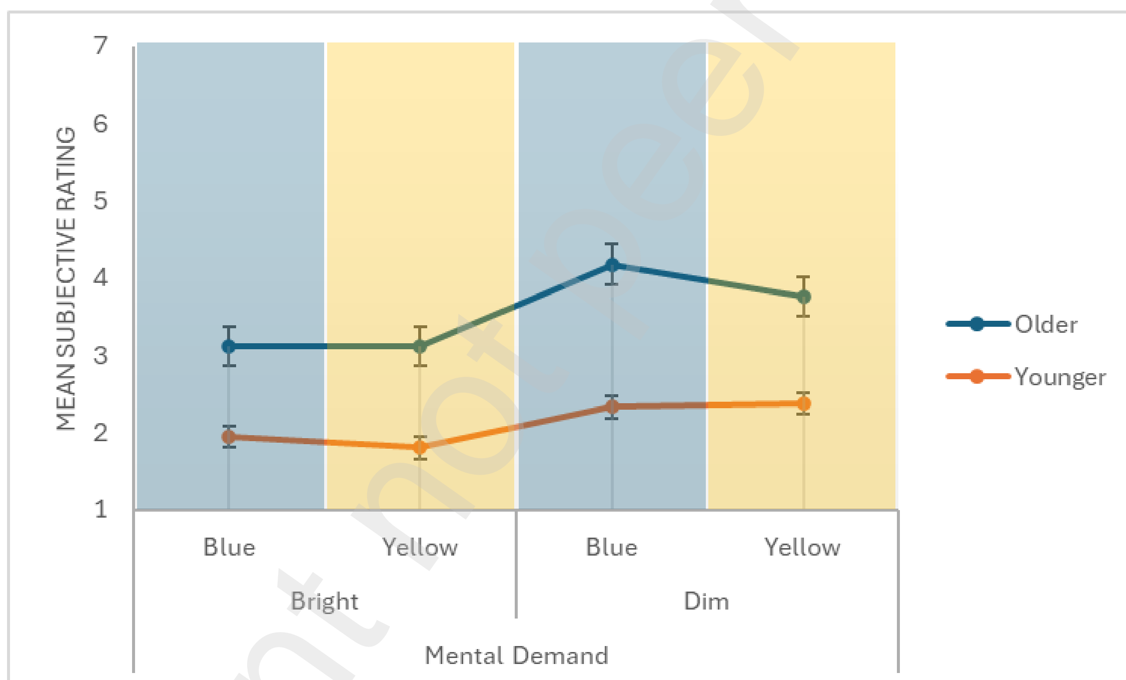

3.3.1 Comfort

Overall, participants rated the conditions as relatively comfortable. Participants rated lighting as significantly more comfortable under bright conditions compared to dim, $F(1, 86.15) = 37.40$, $p < .001$. No significant main effect of Group or Colour Temperature was observed, and no interactions reached significance.

3.3.2. Physical Challenge

Overall, the task was rated as moderately physically demanding. There were significant main effects of Group, $F(1, 36.74) = 5.51$, $p = 0.024$. Younger participants reported lower physical demand than older participants. The main effect of Intensity showed a significant effect, $F(1, 62.06) = 12.53$, $p < 0.001$. Estimated marginal

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means suggested that physical demand ratings were lower under Bright light than under Dim light. The main effect of CCT was not significant, $F(1, 28.75) = 0.003$, $p = .957$. Physical demand ratings were very similar under Blue light and Yellow light.

Repeated-Measures Pairwise Comparisons revealed that older adults found blue lighting significantly more physically challenging than yellow lighting, $p = 0.032$, while no such difference was observed for young adults ($p = 0.29$). When comparing age groups, older adults rated physical challenge significantly higher than young adults under blue lighting ($p = 0.0012$), but not under yellow lighting ($p = 0.091$). These results suggest that blue lighting increased perceived physical difficulty specifically for older adults with a mean difference of 0.38 points. No interactions reached significance.

3.3.3 Mental Challenge

Overall, the task was rated as moderately mentally demanding. Significant main effects were found for Group, $F(1, 35.82) = 6.72$, $p = 0.014$. Younger participants reported lower mental demand than older participants. Light intensity was also significant, $F(1, 83.85) = 19.58$, $p < 0.001$. Mental demand ratings were higher under Dim light than under Bright light. The main effect of CCT was not significant, $F(1, 49.66) = 0.02$, $p = 0.88$. Older adults reported greater mental challenge overall, and participants rated dim lighting as more mentally demanding than bright lighting. No interactions were statistically significant.

Table 6. Fixed-effect estimates (Estimate [SE] and p-value) from linear mixed-effects models for subjective comfort, mental demand, and physical demand ratings.

Predictor	Comfort	Mental	Physical
Intercept	5.714 (0.198), **p<.001**	3.709 (0.397), **p<.001**	2.895 (0.305), **p<.001**
Group	−0.419 (0.250), p=.102	−1.325 (0.511), **p=.014**	−0.911 (0.388), p=**.024**
Intensity	0.963 (0.158), **p<.001**	−0.575 (0.129), **p<.001**	−0.413 (0.117), **p<.001**
CCT	−0.160 (0.161), p=.325	0.016 (0.110), p=.888	0.004 (0.075), p=.957

4. Discussion

This study examined how light intensity, spectral composition, and environmental complexity interact to influence walking behaviour, prefrontal cortical activity, and subjective experience in younger and older adults. Across both age groups, reduced intensity and obstacle presence reliably slowed walking and increased cognitive demand, while blue-enriched (6000 K) lighting supported faster gait compared with yellow (2700 K) lighting, particularly under dim conditions. The fNIRS results showed that lighting and task demands modulated prefrontal activity during walking, with blue-enriched light selectively engaging frontopolar regions associated with attentional control. Importantly, although older adults walked more slowly and

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reported greater effort overall, prefrontal activation did not differ significantly between age groups.

4.1. Behavioural Results: Faster Gait Under Blue Light

Blue-enriched lighting facilitated faster and more stable walking, particularly under challenging environmental conditions. All three factors, light intensity, colour temperature, and obstacle presence, significantly influenced walking speed in both age groups, although the magnitude and pattern of effects differed by age. Younger adults exhibited the strongest effect of colour temperature when navigating obstacles: under blue 6000 K lighting, they maintained a higher walking speed through the obstacle course, whereas under yellow 2700 K lighting they slowed down more. In contrast, for older adults, the critical factor was the interaction between light colour and brightness. Blue light was especially beneficial in dim environments, where older participants walked noticeably faster (or slowed less) under blue than yellow illumination. This suggests that cooler light may have enhanced visibility or alertness, helping older adults compensate for reduced luminance.

Interestingly, when older adults were exposed to blue light in obstacle-free conditions, reducing illuminance did not significantly impair walking speed, implying that blue-enriched light can partially offset the disadvantages of low lighting. By enhancing visibility and cognitive readiness, 6000 K lighting supported more confident gait in situations that typically induce caution or hesitation. Participants moved faster without any observed safety cost (no falls occurred), indicating that high-CCT, bluish lighting (high in S/P and M/P ratios) may promote safer and more efficient mobility. These findings are consistent with prior reports that inadequate lighting slows gait in the elderly (38) and demonstrate that optimising the *spectral composition* of light, rather than increasing brightness alone, can improve walking performance.

4.2. Neural Results: Blue Light Engages Prefrontal Cognitive Resources

Functional near-infrared spectroscopy (fNIRS) revealed that blue light also modulated prefrontal activation during walking. Across both age groups, exposure to 6000 K lighting led to greater activity in prefrontal regions than 2700 K yellow lighting, reflected in increased oxygenated haemoglobin levels. The strongest colour-related effect occurred in the left frontopolar cortex, which is associated with executive control and sustained attention. This observation aligns with previous neurophysiological research showing that blue light enhances prefrontal activation through arousal pathways (18, 19), whereas warmer light does not produce the same effect.

Importantly, blue light appeared to facilitate this compensatory engagement among older adults. Under blue illumination, they maintained walking speed under dim or obstacle conditions while exhibiting robust prefrontal activation, suggesting that blue

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light enhanced cognitive arousal sufficiently to meet task demands. Taken together, these findings suggest that the ageing brain remains responsive to light, and that blue wavelengths can confer measurable cognitive benefits in older adults, in contrast to prior reports of smaller or null effects (25, 26). In this context, blue light appears to act as a form of external support, augmenting prefrontal recruitment to help older individuals sustain performance. This interpretation aligns with established neurophysiological models in which blue light activates melanopsin-containing retinal ganglion cells and downstream brainstem arousal centres, which project to the prefrontal cortex to promote alertness and executive control (3, 19).

4.3. Role of fNIRS as mechanistic support for behavioural findings

It is important to interpret the fNIRS findings in the context of the study's primary behavioural aims. The principal contribution of this work lies in demonstrating that blue-enriched lighting supports faster walking under visually and cognitively demanding conditions, particularly in older adults. The fNIRS data are intended to provide mechanistic insight into how lighting conditions modulate cognitive engagement during walking, rather than to identify widespread or maximal cortical activation patterns.

Consistent with this role, significant effects following correction for multiple comparisons were spatially specific and confined to frontopolar and medial prefrontal regions. These areas are strongly implicated in attentional control, monitoring, and goal-directed behaviour during locomotion (32), and their selective modulation by lighting and environmental complexity is consistent with the behavioural interpretation that blue-enriched light may facilitate more efficient cognitive support for walking (3).

The absence of broad or age-differentiated prefrontal activation should not be interpreted as a lack of neural relevance. Rather, it suggests that under favourable lighting conditions, walking can be supported without excessive recruitment of executive resources. This interpretation aligns with the behavioural finding that participants (particularly older adults) maintained or increased walking speed under blue-enriched light without corresponding increases in subjective discomfort. However, the present sample was relatively small, and subtle group differences or additional regional effects may emerge in a larger, better-powered cohort.

4.4. Subjective Experience: Comfort and Effort Under Different Lights

Overall, both blue (6000 K) and yellow (2700 K) lighting were rated as comfortable and tolerable, with no major comfort differences between colour temperatures in either age group. However, older adults reported walking under blue 6000 K as more physically demanding than under yellow 2700 K, a pattern not seen in younger adults. This suggests blue light increased activation and pace in older adults without reducing comfort.

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Older participants also reported higher mental demand than younger participants across conditions, consistent with greater cognitive effort during walking, but blue light did not significantly change perceived mental demand.

Lighting intensity showed the clearest effects: dim light (5 lux) was less comfortable and more demanding than bright light (500 lux), especially for older adults. This aligns with evidence that older adults need higher illuminance for similar comfort and performance (46). Subjective ratings confirm the 5-lux obstacle condition was the most demanding, matching where objective benefits of blue light were strongest.

In sum, blue-enriched light did not reduce comfort but did increase perceived physical effort in older adults, and performance gains occurred without clear conscious awareness—supporting the need to combine subjective ratings with objective behavioural and neural measures.

4.5. Age-Dependent Responses to Blue Light

Age shaped how participants used lighting during walking, especially in visually/cognitively demanding conditions. One factor is optical ageing: lens yellowing reduces blue-light transmission, lowering contrast sensitivity in older adults (15). Despite this, our findings indicate that blue-enriched light was most beneficial for older participants in dim conditions, suggesting that higher short-wavelength content may help support effective contrast. Older adults may need substantially higher luminance, up to five times, to achieve comparable clarity (46). Together, this highlights that spectrum can matter, but sufficient overall brightness remains essential for safe mobility.

Non-visual (alerting) responses also appear to weaken with age. Neuroimaging shows blue light still activates arousal- and cognition-related regions in older adults, but with smaller responses than in younger adults (25). In this study, overall prefrontal activity did not significantly differ by age across lighting conditions; however, within older adults, blue-enriched light was linked to better walking performance and task-related modulation of prefrontal activity under challenging conditions, without exceeding levels seen in younger adults. Coupled with older adults' higher perceived effort, this suggests compensation via greater cognitive involvement rather than increased neural efficiency.

Strategy differences likely contributed. Younger adults tend to rely on more automatic gait control, whereas older adults use a more attention-focused strategy in complex or dim environments (47). Blue light may support this compensatory control by increasing alertness and facilitating prefrontal engagement. Consistent with overload accounts (47), the pattern here suggests demands stayed within manageable limits, allowing effective resource allocation.

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4.6. Mechanistic Interpretation: CCT, Mesopic Luminance, and Non-Visual Pathways

Although correlated colour temperature (CCT) was used to operationalise the lighting conditions in this study, the observed effects are unlikely to be driven by CCT per se. Rather, CCT served as a pragmatic descriptor to distinguish spectrally contrasting conditions within a multidisciplinary experimental framework. At the mesopic light levels employed here, visual sensitivity depends strongly on spectral composition, and higher-CCT lighting typically results in increased mesopic luminance for a given photopic illuminance. Accordingly, the behavioural effects observed under blue-enriched lighting—particularly faster walking under dim and obstacle-rich conditions—are more plausibly attributable to increased mesopic luminance than to CCT itself.

In parallel, the modulation observed in prefrontal fNIRS signals likely reflects contributions from non-visual photoreception. Blue-enriched spectra preferentially stimulate melanopsin-containing intrinsically photosensitive retinal ganglion cells, which project to subcortical arousal systems and cortical networks involved in attention and executive control. The absence of widespread or age-differentiated cortical effects may therefore reflect behavioural compensation, whereby participants adjusted walking speed to maintain task performance, attenuating neural contrasts. Together, the findings indicate that lighting influences mobility through combined visual and cognitive pathways, and that spectral composition can support task-relevant neural engagement and walking performance without inducing age-related differences in cortical activation. Importantly, the mechanisms underlying these effects are unlikely to be explained by CCT alone and instead reflect interactions between spectral composition, mesopic luminance, and non-visual photoreception.

4.7. Design implications

For design, the results emphasise prioritising adequate brightness, while noting that blue-enriched spectra can provide additional support for older pedestrians. Because older adults are more glare-sensitive and prefer uniform, diffused illumination (46), blue-enriched lighting should be applied carefully. In this study, comfort was not reduced under blue light, suggesting that well-distributed, glare-controlled blue-enriched illumination can enhance safety without adverse effects.

5. Conclusion

Together, the behavioural, neural, and subjective findings demonstrate that lighting design can meaningfully influence mobility and cognitive engagement in everyday environments. Blue-enriched, high-CCT lighting enhanced gait performance and prefrontal activation, particularly in older adults, without compromising comfort, suggesting that appropriate spectral tuning can improve both safety and cognitive alertness during walking. These results highlight the importance of considering not

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only illuminance but also spectral composition in architectural and urban lighting. For ageing populations, integrating blue-enriched yet glare-controlled lighting solutions in walkways, residential corridors, and public circulation areas may help sustain mobility, confidence, and cognitive functioning in low-light or visually complex settings.

Together, these findings demonstrate that blue-enriched lighting improves functional walking performance, with neurophysiological measures providing convergent evidence that such lighting conditions support mobility by modulating cognitive engagement rather than increasing cognitive load.

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Appendices

Appendix 1. *Descriptive Statistics of Walking Duration Across Experimental Conditions*

Condition	Group	Mean (Std.)
Dim-Yellow-Obstacles	Younger	90.100 (16.419)
	Older	125.875 (33.512)
	Total	106.000 (30.866)
Dim-Blue-Obstacles	Younger	86.150 (16.063)
	Older	118.937 (30.778)
	Total	100.722 (28.620)
Dim-Yellow-No Obstacles	Younger	77.800 (15.900)
	Older	93.562 (18.063)
	Total	84.806 (18.443)
Dim-Blue-No Obstacles	Younger	75.150 (14.478)
	Older	89.250 (18.260)
	Total	81.417 (17.526)
Bright-Yellow-Obstacles	Younger	82.300 (21.0616)
	Older	109.625 (26.323)
	Total	94.444 (26.970)
Bright-Blue-Obstacles	Younger	78.900 (16.254)
	Older	106.812 (23.282)
	Total	91.306 (23.950)
Bright-Yellow-No Obstacles	Younger	71.900 (15.100)
	Older	85.562 (13.226)
	Total	77.972 (15.689)
Bright-Blue-No Obstacles	Younger	67.100 (17.806)
	Older	83.937 (13.178)
	Total	74.583 (17.847)

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Appendix 2. *Number of Participants Contributing Valid fNIRS Data per Channel and Region of Interest (ROI)*

Region of Interest (ROI)	Channels	Participants per Channel	Participants per ROI
Right Inferior Frontal Gyrus (R-IFG)	1, 8, 16	35, 35, 35	35
Right Dorsolateral PFC (R-DLPFC)	2, 9, 17	22, 20, 35	35
Right Frontopolar Cortex (R-FPC)	3, 10, 18	21, 19, 23	26
Medial PFC (mPFC)	4, 11, 12, 19	19, 16, 13, 20	19
Left Frontopolar Cortex (L-FPC)	5, 13, 20	22, 19, 24	25
Left Dorsolateral PFC (L-DLPFC)	6, 14, 21	23, 35, 18	35
Left Inferior Frontal Gyrus (L-IFG)	7, 15, 22	23, 35, 20	35

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Appendix 3. *Fixed-Effect Estimates (μβ) from Linear Mixed-Effects Models Across Prefrontal Regions of Interest. Reference levels: CCT = yellow, INTENSITY = dim, PAVEMENT = obstacle, Group = older. Positive estimates indicate higher β for blue, bright, no-obstacle or younger relative to their respective reference.*

	R-IFG					R-DLPFC					R-FPC				
Parameters	Est	SE	CI		p_{adj}	Est	SE	CI		p_{adj}	Est	SE	CI		p_{adj}
Intercept	0.02	0.22	-0.44	0.48	0.942	-0.02	0.10	-0.22	0.18	0.928	0.04	0.13	-0.22	0.31	0.739
CCT	0.01	0.04	-0.07	0.08	0.878	0.05	0.03	0.00	0.11	0.114	0.05	0.03	0.00	0.11	0.114*
Intensity	-0.06	0.05	-0.15	0.04	0.396	-0.02	0.04	-0.10	0.05	0.512	-0.06	0.03	-0.12	0.01	0.175
Pavement	0.03	0.04	-0.04	0.11	0.525	-0.02	0.03	-0.07	0.04	0.525	-0.06	0.02	-0.11	-0.02	**0.063***
Group	-0.19	0.33	-0.86	0.49	0.804	-0.19	0.14	-0.47	0.09	0.804	0.03	0.17	-0.32	0.39	0.804

	L-FPC					L-DLPFC					L-IFG				
Parameters	Est	SE	CI		p_{adj}	Est	SE	CI		p_{adj}	Est	SE	CI		p_{adj}
Intercept	-0.06	0.16	-0.39	0.27	0.725	0.07	0.09	-0.10	0.25	0.804	0.14	0.20	-0.28	0.55	0.552
CCT	0.13	0.03	0.07	0.18	**0.004***	0.01	0.03	-0.05	0.07	0.848	0.02	0.04	-0.05	0.10	0.773
Intensity	-0.03	0.04	-0.11	0.04	0.453	-0.07	0.04	-0.15	0.00	0.161*	-0.05	0.05	-0.16	0.05	0.552
Pavement	-0.05	0.03	-0.11	0.01	0.263	0.02	0.03	-0.04	0.08	0.525	0.02	0.04	-0.05	0.10	0.525
Group	0.16	0.21	-0.27	0.59	0.804	-0.03	0.12	-0.27	0.21	0.804	-0.21	0.27	-0.76	0.34	0.804

	mPFC				
Parameters	Est	SE	CI		p_{adj}
Intercept	-0.06	0.10	-0.26	0.15	0.562
CCT	0.06	0.03	0.00	0.13	0.114
Intensity	-0.08	0.03	-0.15	-0.02	**0.098***
Pavement	-0.02	0.03	-0.08	0.03	0.525
Group	-0.13	0.13	-0.39	0.13	0.804

Note: p-values marked with an asterisk indicate that the uncorrected $p < 0.05$.

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Appendix 4. *Descriptive Statistics for Subjective Ratings across Lighting Conditions and Age Groups*

Measure	Group	Intensity	CCT:Blue	CCT:Yellow
Comfort	Old	Bright	6.59 (1.23)	6.47 (1.50)
		Dim	5.47 (1.28)	5.76 (0.90)
	Young	Bright	6.19 (1.17)	6.24 (0.89)
		Dim	4.95 (1.53)	5.33 (1.06)
Mental	Old	Bright	3.12 (2.00)	3.12 (2.15)
		Dim	4.18 (1.88)	3.76 (1.75)
	Young	Bright	1.95 (1.32)	1.81 (1.44)
		Dim	2.33 (1.15)	2.38 (1.32)
Physical	Old	Bright	2.71 (1.76)	2.41 (1.46)
		Dim	3.29 (1.57)	2.82 (1.67)
	Young	Bright	1.57 (0.93)	1.62 (1.16)
		Dim	1.86 (0.79)	2.14 (1.35)

Note. Values represent mean subjective ratings on a scale from 1 to 7, with standard
deviations in parentheses.

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