Optimal lighting levels for stair safety: influence of lightbulb type and brightness on confidence, dynamic balance and stepping characteristics

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Highlights

- Young and older adults exhibited more cautious stair descent in compact fluorescent lamp bulb light
- Riskier stepping patterns were shown in young and older adults during stair descent in compact fluorescent lamp bulb light
- High powered (100W) LED bulbs may offer a safer alternative to compact fluorescent lamp bulbs for use over stairwells

Abstract

Introduction: Poor lighting has been associated with stair falls in young and older adults. However, current guidelines for illuminating stairs seem arbitrary, differ widely between sources, and are often difficult to interpret.

Aims: Here we examined the influence of real-world bulb illumination properties on stair descent safety in young and older adults, with a view to generating preliminary evidence for appropriate lightbulb use/stair illumination.
Methods: Stair tread illumination (lux) was measured in a standard UK home (2.23m ceiling) from a low (50W; 630 lm) and a high (103W, 1450 lm) power compact fluorescent lamp (CFL) bulb from the time they were turned on until they reached full brightness. This enabled modelling of their illumination characteristics during warm up. Illumination was also measured from a low (40W, 470 lm) and a high (100W, 1521 lm) power LED bulb at first turn-on. Computer-controlled custom lighting then replicated these profiles, in addition to a Bright control (350 lux), on an instrumented staircase descended (3×trials per light condition) by 12 young (25.3±4.4 years; 5 males), 12 higher ability older (HAOA: 69.6±4.7 years; 5 males) and 13 lower ability older (LAOA: 72.4±4.2; 3 males) healthy adults. Older adults were allocated to ability groups based on physiological and cognitive function. Stair specific confidence was assessed prior to the first descent in each new lighting condition, and whole-body 3D kinematics (Vicon) quantified margins of stability and foot clearances with respect to the step edges. Mixed ANOVAs examined these measures for within-subject effects of lighting (×5), between-subject effects of age (×3) and interactions between lighting and age.
Results: Use of CFL bulbs led to lower self-reported confidence in older adults (20.37%, p=.01), and increased margins of stability (12.47%, p=.015) and foot clearances with respect to the step edges (10.36%, p=.003). Importantly, using CFL bulbs increased foot clearance variability with respect to the bottom step (32.74%, p=.046), which is where a high proportion of falls occur.
Conclusion: Stair tread illumination from CFL bulbs at first turn on leads to less safe stair negotiation. We suggest high powered LED bulbs may offer a safer alternative.

Keywords: Ageing; Falls risk; Illumination; Margin of stability; Stair ambulation

Declarations of interest: none

1 Introduction

Stair falls are a leading cause of injury and mortality in older adults, and poor lighting has been associated with an increased risk of falls on stairs (Jacobs, 2016). However, evidence linking illumination to fall risk during stair descent, when considering specific type and brightness of lightbulbs commonly found in home environments, is limited. For example, energy saving bulbs, such as compact fluorescent lamp (CFL) bulbs, can take minutes to reach full brightness, which may leave stairwells poorly lit initially. Light emitting diode (LED) bulbs, on the other hand, reach full brightness instantaneously, and may offer a safer alternative for use over stairwells. Yet, how CFL and LED bulbs impact on stair safety has not previously been examined. This was the focus of the present study.

Descending stairs is challenging to stability. Indeed, an injurious fall is three times more likely during stair descent than during ascent (Startzell et al., 2000). During transfer between steps, the body's centre of mass (CoM) is shifted outside of the base of support and lowered to the next step. This causes the upper body to accelerate forwards and downwards, and its momentum must be controlled at step-contact through adequate hip, knee and ankle moments (McFadyen and Winter, 1988; Novak and Brouwer, 2011). Controlling foot trajectory with respect to step-edges is also an important part of stair descent (Cohen, 2000). Catching a heel or toe on a step edge can introduce a sudden change to the planned movement, and depending on the severity, may require rapid repositioning of the limb to prevent a fall.

Older adults exhibit riskier movement patterns than young adults during stair descent, which may be indicative of a reduced ability to control balance. For example, they have shown smaller anteroposterior (AP) margins of stability than younger adults (Bosse et al., 2012), which is measured as the distance between the extrapolated CoM and the forward boundary of the base of support. A smaller margin of stability leaves less time to decelerate the CoM prior to initiating the next step, and could increase the chances of falling during a misstep. In addition, older adults have previously exhibited smaller (Hamel et al., 2005) and more variable foot clearances over step-edges when compared to young adults (Zietz et al., 2011), which could increase the risk of tripping. Given the reduced ability to recover from trips on flat ground (Pavol et al., 2001), older adults may also be at a greater risk of falling following a trip on stairs. Furthermore, injurious falls are more likely to occur in older adults (Jacobs, 2016).

Poor lighting has been linked to increased incidences of falls on stairs. Reducing stair tread illumination from around 86 lux to 22 lux increased step accident rates from 11% to 22% (Carson et al.

1978; p.52-53, cited in Thorpe, 2005). This may be related to inability to delineate edges of steps/treads or visual cues such as step nosings or edge highlighters. Experimentally restricting light levels has also been shown to affect factors related to falls risk during stair descent. At low illumination levels, young adults increase their foot clearances with respect to step edges, whereas older adults do not (Hamel et al., 2005). Older adults thus have a smaller and more variable 'margin for error', which may increase the chances of a trip in poor light. In addition, both young and older adults exhibit slower descent speeds in poor light (Zietz et al., 2011), which may seem an intuitive adaptation when visual information is compromised. It is thus clear that adequate vision is an important component of stair descent with regard to foot step-edge clearances, and reduced visual function in older adults (e.g. acuity and contrast sensitivity) may play a role in older adults' risky stepping behaviour in lower light, particularly considering older adults look at the steps for longer when compared to young adults in normal light (Zietz and Hollands, 2009).

Previous studies of stair lighting and its influences on stair descent have some caveats. The increased foot step-edge clearance variability was shown with luminance transmission goggles instead of ambient light (Hamel et al., 2005), which may not be ecologically valid. The studies showing slower stair descent in poor light were limited to comparing very dark with very bright illumination (e.g. 1 lux compared 220 lux; Zietz et al. 2011), and may thus not be representative of light produced by real-world bulbs, or only included older adults with vision problems (Shaheen et al., 2018). Furthermore, both of these studies focused on the middle phase of stair descent, where descent speed reaches a 'steady-state' and lower limb trajectories seem only to be fine-tuned. However, more falls occur when walking on the top or bottom three steps (Templer, 1992) corresponding to the transitions onto and off stairs. Different strategies are required to safely make these transitions (Alcock et al., 2015), such as greater neuromuscular recruitment in the supporting limb, which has been suggested to lead to poor body sway regulation in older adults (Lee and Chou, 2007), and increases in executive demands are known in these transition phases (Miyasike-daSilva and McIlroy, 2012). Whilst it is known that foot clearances can become more variable in poor light during the transition phases in older adults (Hamel et al., 2005), the influence of ambient lighting on dynamic balance and stepping in these regions has not been examined. Another factor overlooked in lighting studies is confidence and anxiety. Anxiety has previously been shown to be associated with riskier stepping patterns during obstacle negotiation tasks (Young and Hollands, 2012), and increased confidence was observed in conditions when subjects were able to preview the obstacles prior to stepping (Curzon-Jones and Hollands, 2018). If illumination levels can influence confidence and anxiety during stair descent, it may in turn be associated with altered balance and stepping patterns. Finally, current guidelines for illuminating stairs range between 100 lux (Ireland Department of the Environment, 2010) and 300 lux (AARP, n.d.), and are typically only given in measures of illumination, which may be difficult to interpret for the average user. Therefore, there is a need to generate preliminary evidence for appropriate lightbulb use over stairwells.

The aims of the present investigation were: 1) to examine the influence of real-world bulb illumination levels on confidence and anxiety, dynamic balance, and stepping characteristics during each phase (entry, steady-state, and exit) of stair descent; 2) to elucidate if and how older adults are adversely influenced by low illumination levels; 3) to generate preliminary evidence for appropriate lightbulb use/illumination over public and private stairwells.

2 Methods

2.1 Participants

Twelve young (YA: 18-35 years) and 25 independent and community-dwelling older (≥65 years) healthy adults were recruited from the host institution and from local older adult groups (characteristics of participants reported in Table 1). A priori statistical power calculations (Gpower statistical software) using data from Hamel et al. (2005) indicate 14 participants per group was the required sample size (Effect size: $d = 0.985$, $\alpha = 0.05$, power = 0.8) to identify age-related differences in foot clearance with respect to step edges during stair descent in low light. Older adults cognitive function was assessed with the Trail Making Test (described in Assessments) and all fell within normative values (Tombaugh, 2004). Participants were included in the study if they could descend stairs in a step-over-step manner without walking aids (canes or crutches), and had no self-reported musculoskeletal or balance issues which might influence stair negotiation. The investigation was carried out in accordance with the host institution guidelines for research involving human participants, and all procedures, information to the participants, and consent forms, were approved by the host institution's Research Ethics Committee. All participants gave written informed consent in accordance with the Declaration of Helsinki.

2.2 Assessments

Older participants were categorised into ability groups based on visual, physiological and cognitive assessments. These were: 1) visual acuity and contrast sensitivity (FrACT); 2) Trail making test parts A and B to measure executive function; 3) three isometric knee extension maximal voluntary contractions, measured with a hand-held dynamometer (Bohannon, 1990); 4) Reaction time; 5) a lower limb matching task; 6) 30 s quiet stance on a foam mat; 7) a stair specific efficacy scale in which participants scored from 1-100% how confident they felt negotiating stairs in everyday life. Tests 4-6 were measured according the protocol outlined by Lord et al. (2003); however, a Vicon system (detailed below) was used to collect kinematics. These assessments were chosen as they have all been associated with stair descent performance. For example, Tiedemann et al. (2007) showed that knee extension strength, lower limb proprioception, edge contrast sensitivity, reaction time, leaning balance, and fear of falling, were all significant and independent predictors of stair descent performance. Executive function can slow stair descent under dual task conditions (Gaillardin and Baudry, 2018), and visual function, as previously discussed, may be of particular importance in conditions of diminished light.

The older participants were ranked from first to last (1 – 25) based on their scores for each test. For example, the person with the highest visual acuity was ranked as 1st for visual acuity, whilst the person with the lowest was ranked as 25th. This resulted in eight ranking tables (one for each assessment). Each older participant's ranks across the assessments were then summed, resulting in one ranking table containing all older participants' cumulative ranks. Those in the lower 50% percentile of this table were categorised as lower ability older adults (LAOA), and those in the higher 50% percentile were categorised as higher ability older adults (HAOA; Zietz et al., 2011). The results for all tests, and participant anthropometrics, are presented in Table 1.

2.3 Staircase apparatus

Participants descended a custom-made instrumented seven-step staircase with handrails on each side. The staircase had a top and bottom landing of sufficient length to complete an entry and exit phase (see protocol). Each step had a riser height of 19.5 cm, and a going length of 23.5 cm, which is within the current UK building regulations for commercial and private properties (Gov, 2010). The bottom four steps each contained a force-platform (FP; Kistler) sampling at 1080Hz. Whilst on the staircase, participants wore a passive overhead safety harness operated by a trained belayer. See Fig 1. for layout of staircase.

Table 1. Participant anthropometrics and assessment outcomes (±SD)

	YA (*n*=12; 7×males)	HAOA (*n*=12; 5×males)	LAOA (*n*=13; 3×males)	Older adults combined (*n*=25)
Age (years)	25.5±4.1*†	69.6±4.7	72.4±4.2	71.0±4.6
Height (cm)	178.8±11.2*†	165.5±7	164.8±7.2	165.1±6.7
Mass (kg)	80.8±18.2†	77.8±14.7	63.7±10.2	70.4±14.2
Visual acuity (logMAR)	-0.12±0.09†	0.04±0.21	0.15±0.22	0.09±0.22
Contrast sensitivity (Weber)	1.93±0.14†	1.78±0.19	1.66±0.33	1.72±0.27
Executive function (s)	17.8±6.5*†	19.6±8.1§	41±22.8	30.7±20.2
Lower limb matching (SD)	2.93±0.97†	3.14±1.74§	4.71±1.49	3.96±1.78
Knee extension torque (Nm)	126.2±44.5*†	75.4±35.3	63±20.6	67±28.7
Quiet stance on foam mat (cm)	167.3±45.8	170.2±44.6	173±44.7	171.7±43.7
Reaction time (s)	0.28±0.04†	0.32±0.06	0.35±0.06	0.34±0.06
General stair confidence (%)	99.6±1.4†	92.3±9	88.2±9.4	90.2±9.3

Significant difference (p<.05) between: *Young and HAOA; †Young and LAOA; §HAOA and LAOA. Executive function: time taken to complete trail making test part B, minus that for part A. Lower limb matching: SD of 5 successive trials. Knee extension torque: highest of three trials. Quiet stance on a foam mat: total path of the CoM. Reaction time: average of 10 successive trials.

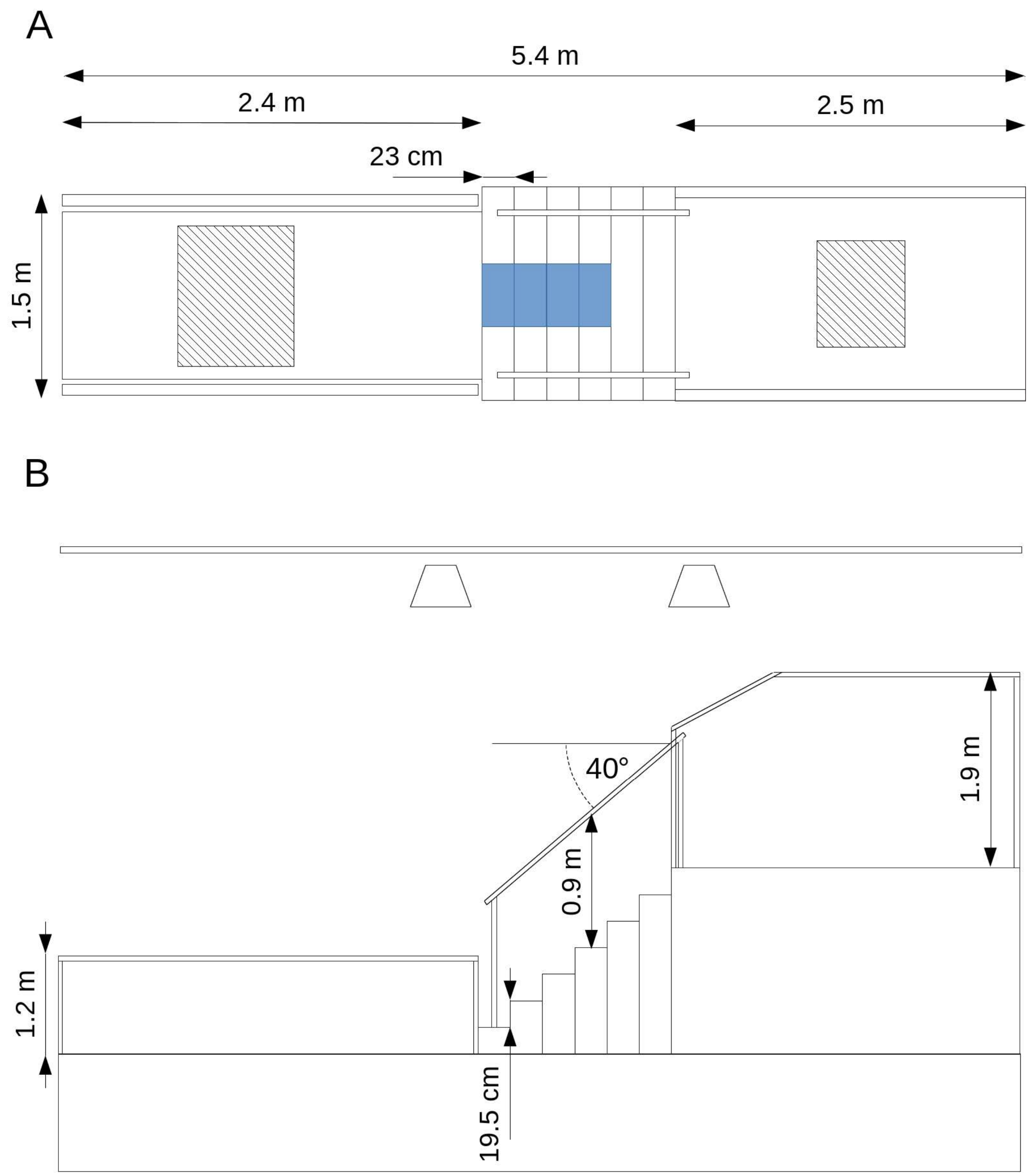

Figure 1. Layout of staircase. A: top view; B: side view. The shaded areas in A denote trial start (right) and end (left) areas. The shaded area over the stairs in A are force platforms. The trapezoids over the

stairs in B represent the custom-lighting rig, with the safety belay rail above. All indicated geometries are to scale.

2.4 Lighting

To ensure real-world applicability of the results, illumination from four commonly available lightbulbs (Diall, London, UK) was measured and then replicated over our experimental staircase. The bulbs used were low and high-powered CFL and LED bulbs. CFLs are unique in that they take time to reach full brightness. LEDs, on the other hand, reach full brightness instantaneously. Stair tread illumination (lux) was thus measured (Digital instruments lux-1108, Taiwan) in a standard UK home environment (2.23 m ceiling) from a low and a high power CFL bulb for two minutes yielding a warm-up curve for each. Lux was also recorded from a low and a high-power LED bulb at first turn-on. Power ratings for the CFL and LED bulbs were matched as closely as possible. Bulb characteristics are presented in table 2.

Table 2: Bulb type, power ratings, and measured stair tread illumination. Note that the CFL bulbs were very dim (low illumination) when first turned on, and increased by only one lux in the average time taken to descend the stairs in each respective condition. This contrasts with the instantaneous illumination from the LED bulbs.

Bulb	Rating		Illumination
CFL Low	50 Watt	630 lumens	9 – 10 lux (4.11 s)
CFL High	103 Watt	1450 lumens	19 – 20 lux (4.12 s)
LED Low	40 Watt	470 lumens	35 lux
LED High	100 Watt	1521 lumens	112 lux
Bright control	NA	NA	350 lux

A custom-made computer-controlled lighting rig (example code at https://github.com/N-M-T/LUX_light_dimmer) replicated the bulb illumination characteristics listed in Table 2, in addition to a bright control, over the experimental staircase. This set-up enabled us to repeatedly match the warm-up characteristics of the CFL bulbs. The temperature rating (Warm white; 3000 Kelvin) matched the original CFL and LED bulbs as closely as possible. The lighting rig consisted of an array of halogen bulbs positioned over the top and bottom landings to generate an even distribution of light over the staircase (Fig 1.). Each array received power from independent dimmer circuits controlled with the computer. During an initial calibration, a LUX sensor was positioned at the top and bottom transition steps, and at the middle step, which fed-back measurements to the computer. The computer subsequently modulated power to each light array until an even distribution of light at these phases was achieved for each bulb profile. This power modulation was then repeated during testing to replicate the bulb characteristics. Whilst every effort was taken to ensure an even distribution of light, there will have been subtle variations in some regions of the staircase which could not be controlled for with the present set-up, e.g. at the extremes of the landings. There were also shadows cast directly underneath the hand rails (but not walls or steps). Such variations are likely typical on real-world stairwells.

2.5 Testing protocol

Data collection took place in a single session lasting approximately two hours. Participants completed the visual, physical and cognitive assessments prior to the stair trials, except for maximal knee extensions. These were completed after the stair trials to eliminate fatigue.

For the stair trials, the participants were instructed to descend the stairs at a self-selected pace in a step-over-step manner. A trial began with the participants standing stationary on the top landing with feet side-by-side, whilst maintaining their gaze on a visual target located ahead and above of the staircase. This ensured standardisation of visuomotor planning across participants prior to each stair descent. Participants were then instructed to descend, at which point they could look where they wanted. They initiated gait with any foot so long as it was consistent throughout the remaining trials, and they were free to use the handrails throughout to ensure ecological validity. At the bottom of the stairs, the participants continued along to the end of the bottom landing, before coming to a stationary position and standing with feet side-by-side. This ensured there were at least two full steps following the last data analysis point (described below). Prior to testing, participants were familiarised with the experimental environment, and performed three practice stair descents.

There were three descent trials in each lighting condition. The three trials were performed consecutively in a block, which totalled five blocks (one for each lighting condition). There was a 2-5 minute rest between blocks, which were performed in a random order to eliminate practice and/or fatigue effects. The light levels were changed at the beginning of each new block. The CFL bulb warm-up profile was reset prior to each CFL bulb trial (i.e. the CFL replicated light was set to minimum representing first turn on, and then got brighter during a stair descent. It was subsequently reset to minimum ready for the next trial). The participants were informed of the change in illumination, but were not exposed to it prior to testing. The changes to illumination were visible to the eye.

2.6 State confidence and anxiety

Prior to the first descent in each new lighting condition, the participants were asked to rate from 1-100% how confident they felt about descending the stairs without falling or losing their balance. Following the first descent in each new lighting condition, participants were asked questions designed to probe their perceived anxiety, also rated on a scale of 1-100%. For worry-related anxiety: “how worried were you when descending the stairs in that light (e.g. about falling or losing your balance)?”; for somatic-related anxiety: “how physically anxious did you feel when descending the stairs in that light (e.g. tense or nervous)?”; and for focus-related anxiety: “how difficult was it to focus when descending the stairs in that light (e.g. distracting or intruding thoughts about falling)?”. These questions were adapted from a previous study of anxiety under conditions of postural threat (Johnson et al., 2019).

2.7 Kinematics

A 26-camera motion capture system (Vicon MX, Oxford Metrics, UK) collected whole-body kinematic data at 120Hz, with thirty-nine reflective markers placed on the feet, lower legs, thighs, pelvis, torso, head, upper arms, forearms and hands according to the conventional Plug-in Gait marker set. Additional markers (n=37) were placed in cluster arrangements on the lower limbs and head. This set-up ensured at least three markers were visible on segments with markers prone to occlusions from step-edges, the handrails and the harness. The heel markers (which are prone to catching on step edges) were removed to enable unhindered gait. They were then reconstructed in the movement trials based on their respective locations in relation to the rigid foot segment in the static calibration trial. Participants wore flat trainers/shoes and tight clothing.

Kinematic data were labelled, filtered for small gaps (<100 ms: Woltering quintic spline), and exported as c3d files (Vicon Nexus 2.6, Oxford Metrics). Subsequent analyses were performed with Python (Python Software Foundation). Gaps bigger than 100 ms were filled with a rigid-body gap filling protocol leveraging the extended marker set. All marker trajectories were then filtered with a fourth order zero-phase Butterworth filter (cut-off frequency 20Hz). Joint angles and whole-body CoM were calculated with the conventional gait model using pyCGM (Schwartz and Dixon, 2018).

Gait events identified on the staircase included initial contacts on the top landing, initial contact and toe off on each step, and initial contacts on the bottom landing. Initial contacts on the landings were determined using the methods of Zeni et al. (2008) using local maxima of the heel referenced to the pelvis segment. During stair descent, for the steps with no FP, local minima in the CoM vertical velocity trace defined initial contacts, and local maxima in the trailing knee flexion angle trace defined toe-offs (Foster et al., 2014a). For the steps with FPs, >20N or <20N defined initial contact and toe-off, respectively (Zeni et al., 2008). Three phases of stair descent were subsequently analysed: entry phase, steady-state phase, and exit phase. Entry phase was defined as the time period between the last heel strike on the top landing and initial contact on step two. Steady-state phase was defined as the time period between initial contact on step two and that on step five. Exit phase was defined as the time period between initial contact on step five and the first heel strike of the swing limb on the bottom landing, i.e. when the participant reached the bottom landing and took one subsequent step forward.

To examine the influence of illumination on stair descent safety, outcome measures which characterise dynamic balance and stepping were calculated. These were margin of stability (incorporating descent speed) and foot-step edge clearances. Margin of stability was defined as the distance between the extrapolated CoM (xCoM) and the forward boundary of the base of support. When the toe marker was within the confines of the step-edge, the toe marker defined the forward boundary. When the toe marker was outside the confines of the step-edge (foot overhang), the step-edge defined the forward boundary. Smaller (or more negative) margins of stability are considered to reflect a less dynamically stable pattern of stair descent (Bosse et al., 2012; Novak et al., 2016).

xCoM was defined as:

$$xCoM = pCoM + vCoM/\sqrt{(gl^{-1})}$$

where *pCoM* is the AP position of the CoM, *vCoM* is the instantaneous AP velocity of the CoM, *g* is acceleration due to gravity, and *l* is the absolute distance between the CoM and the ankle joint centre. Margin of stability was calculated at initial step contact. This is when the risk of falling during an overstep can be exacerbated by small margins of stability as the individual would have more forward momentum to counter (Novak et al., 2016). Foot-step edge clearances were defined as the minimum horizontal and vertical distances between the toe and heel markers on the lead limb and the step edges. Mean and variability (SD) across three successive trials on each step were calculated and used for further analysis. Increases in foot clearance variability are suggested to increase the risk of catching the heel or toe on the step edge.

2.8 Statistical analyses

Two-way mixed ANOVAs examined stair descent outcome measures for within-subject effects of lighting (×5; CFL Low or High; LED Low or High; Bright), between-subject effects of age (×3; YA; LAOA, HAOA), and interactions between terms. Each step was treated separately, i.e. individual analyses were performed for each of the seven steps. In the case of significant interactions, the larger model was broken down into one-way ANOVAs, and post-hoc tests were conducted where appropriate. Post-hoc analyses were Tukey's HSD tests to account for multiple comparisons. Where data were non-normally distributed, main effects were cross checked with robust ANOVAs based on trimmed means (Field et al., 2012) and post-hoc analyses were Wilcoxon signed rank tests with Holm-Bonferroni corrections. ANOVA effect sizes reported were partial eta squared (n^2_p), common indicative thresholds for which are: small (0.01), medium (0.06) and large (0.14; Field et al., 2012). Related post-hoc comparison effect sizes were Hedges' g_{av}, and for independent comparisons Hedges' *g*. Common indicative thresholds for these are small (0.2), medium (0.5) and large (0.8; Lakens, 2013). All statistical analyses were performed with the R software package (R, software for statistical computing and graphics) with an alpha level of ≤0.05.

3 Results

3.1 Confidence and anxiety

Self-reported confidence prior to the first descent in each new lighting condition is shown in Fig. 2. There was a significant interaction between lighting and age ($F_{(4,132)}=2.658$, $p=.01$, $n^2_p=.139$) on self-reported confidence. One-way ANOVAs showed effects of lighting for both groups of older adults ($F_{(4,88)}=9.438$, $p<.001$, $n^2_p=.3$), whereas YA were unaffected. Post-hoc analyses revealed less confidence for all light levels when compared to Bright ($p<.05$), with the exception of LED Low ($p=.09$). There were no main effects of lighting, age, or interactions between lighting and age for the remaining confidence and anxiety outcome measures.

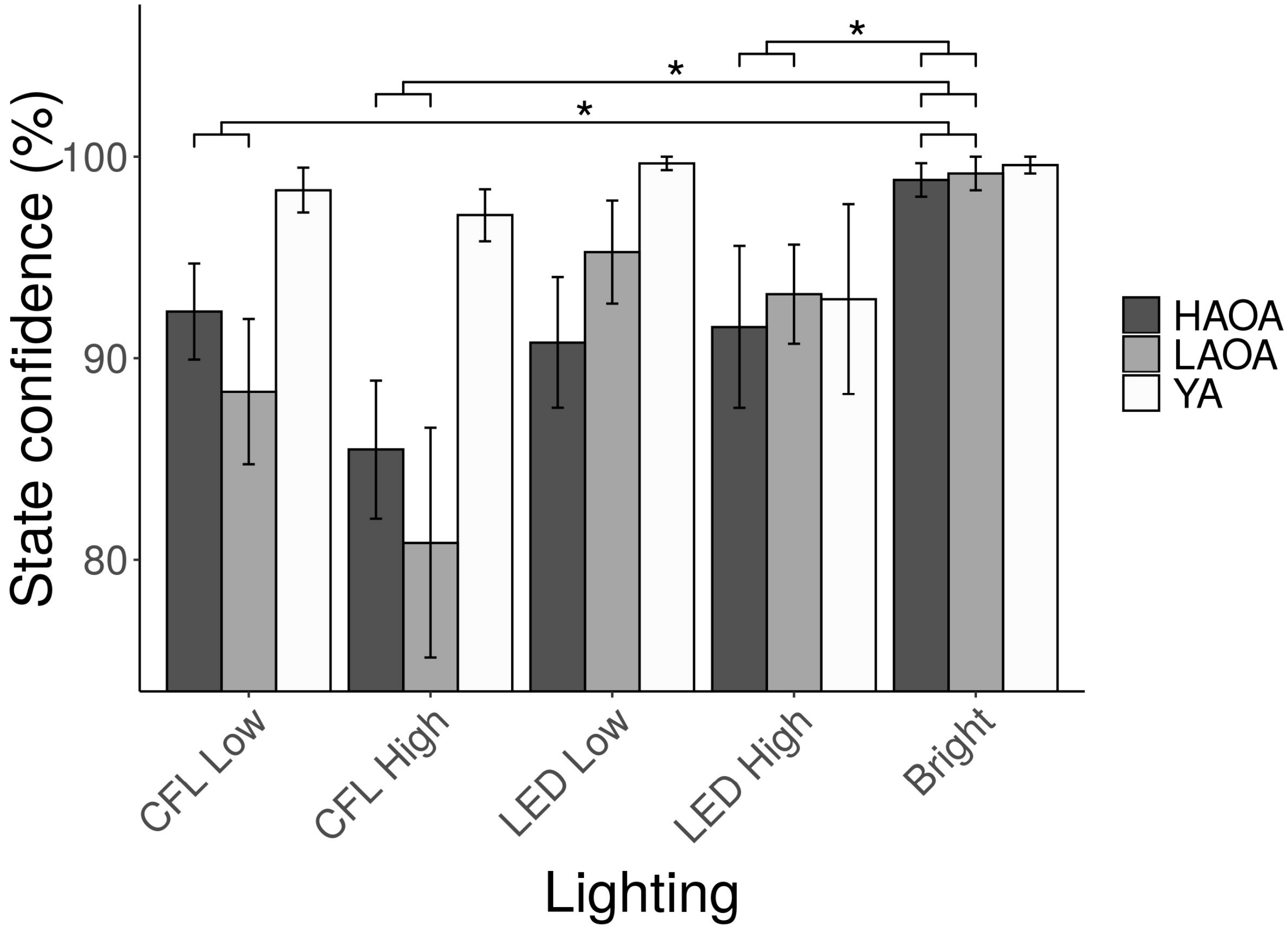

Figure 2. Self-reported confidence prior to the first stair descent in each new lighting condition. *Post-hoc analysis revealed HAOA and LAOA both exhibited significantly less confidence in CFL Low compared to Bright, CFL High compared to Bright, and LED High compared to Bright. YA were unaffected. Data are means ± SE

3.2 Descent speed

There were decreases to vCoM with CFL light in all phases of stair descent. For example, over step two (Fig. 3), there was a significant main effect of lighting ($F_{(4,132)}$=4.803, p=.001, n^2_p=0127). Post-hoc comparisons revealed reduced vCoM in CFL Low compared to Bright (p=.006, g_{av}=.308). vCoM was also reduced in CFL High compared to LED High (p=.039, g_{av}=.253) and Bright (p=.004, g_{av}=.318).

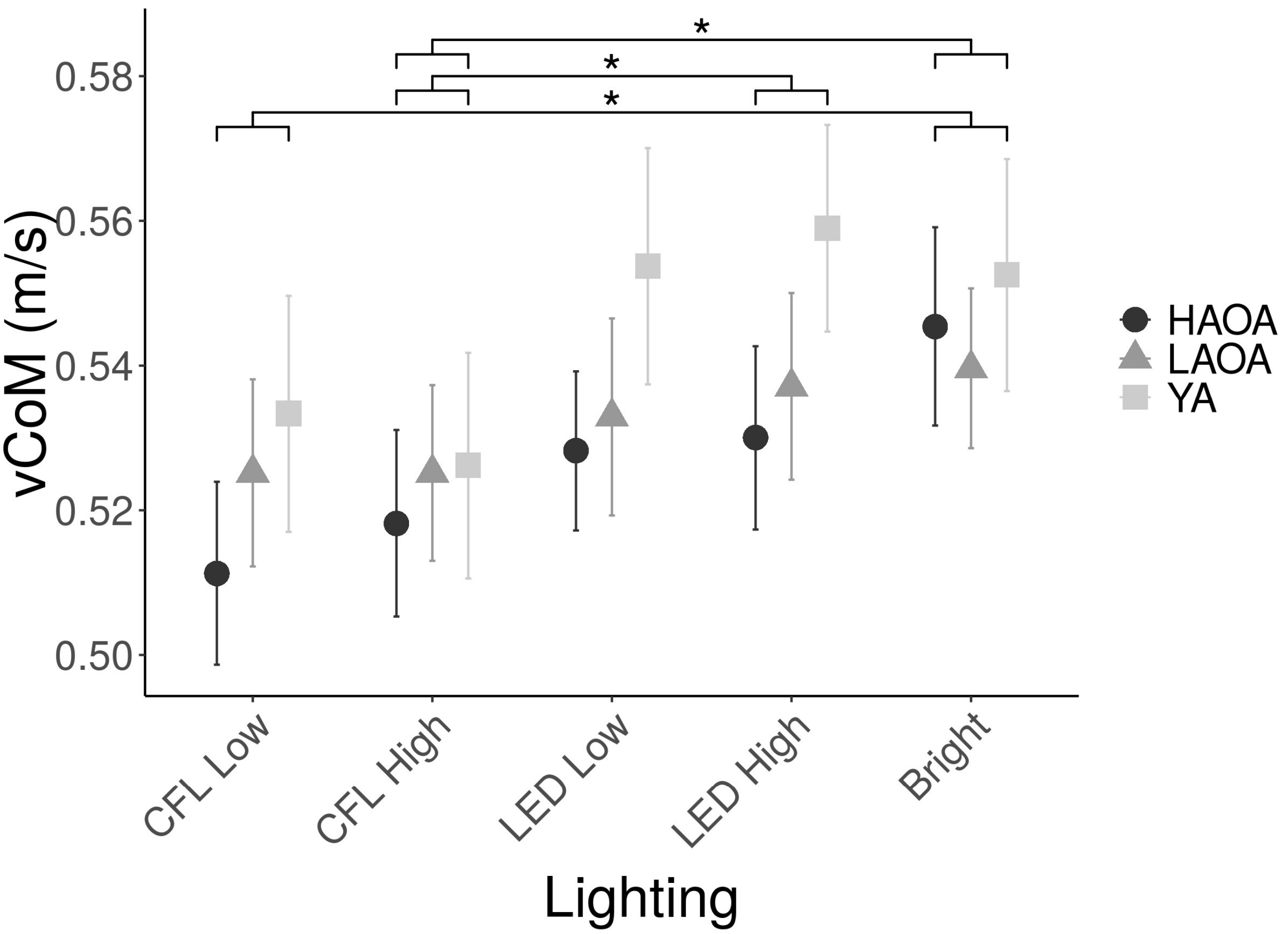

Figure 3. vCoM during stair descent over step two in different lighting conditions. *Post-hoc analysis revealed HAOA, LAOA and YA exhibited significantly slower descent speeds in CFL Low compared to Bright; CFL High compared to LED High, and CFL High compared to Bright. Data are means ± SE.

3.3 Margin of stability

All participants exhibited increased margins of stability in CFL Low illumination during the transition phases of stair descent. For example, there was a main effect of lighting over step two (Fig. 4: A; $F_{(4,132)}$=2.846, *p*=.027, n^2_p=.079), which corresponds to the second step of the entry phase. Post-hoc comparisons revealed increased margins of stability in CFL Low compared to LED High (*p*=0.015, g_{av}=0.269) and Bright (*p*=0.036, g_{av}=0.254). There were also main effects of lighting on steps four and five (step five; Fig. 4: B; $F_{(4,132)}$=3.423, *p*=.012, n^2_p=.094). However, no significant post-hoc results were found. Finally, there was a main effect of lighting over step six, which corresponds to the first step of the exit phase (Fig. 4: C; $F_{(4,132)}=4.358$, $p=.002$, $n^2_p=0.117$). Post-hoc comparisons revealed increased margins of stability in CFL Low compared to LED High ($p=.002$, $g_{av}=.269$) and Bright ($p=.032$, $g_{av}=.208$). No main effects of age or interactions between lighting and age were found for any step.

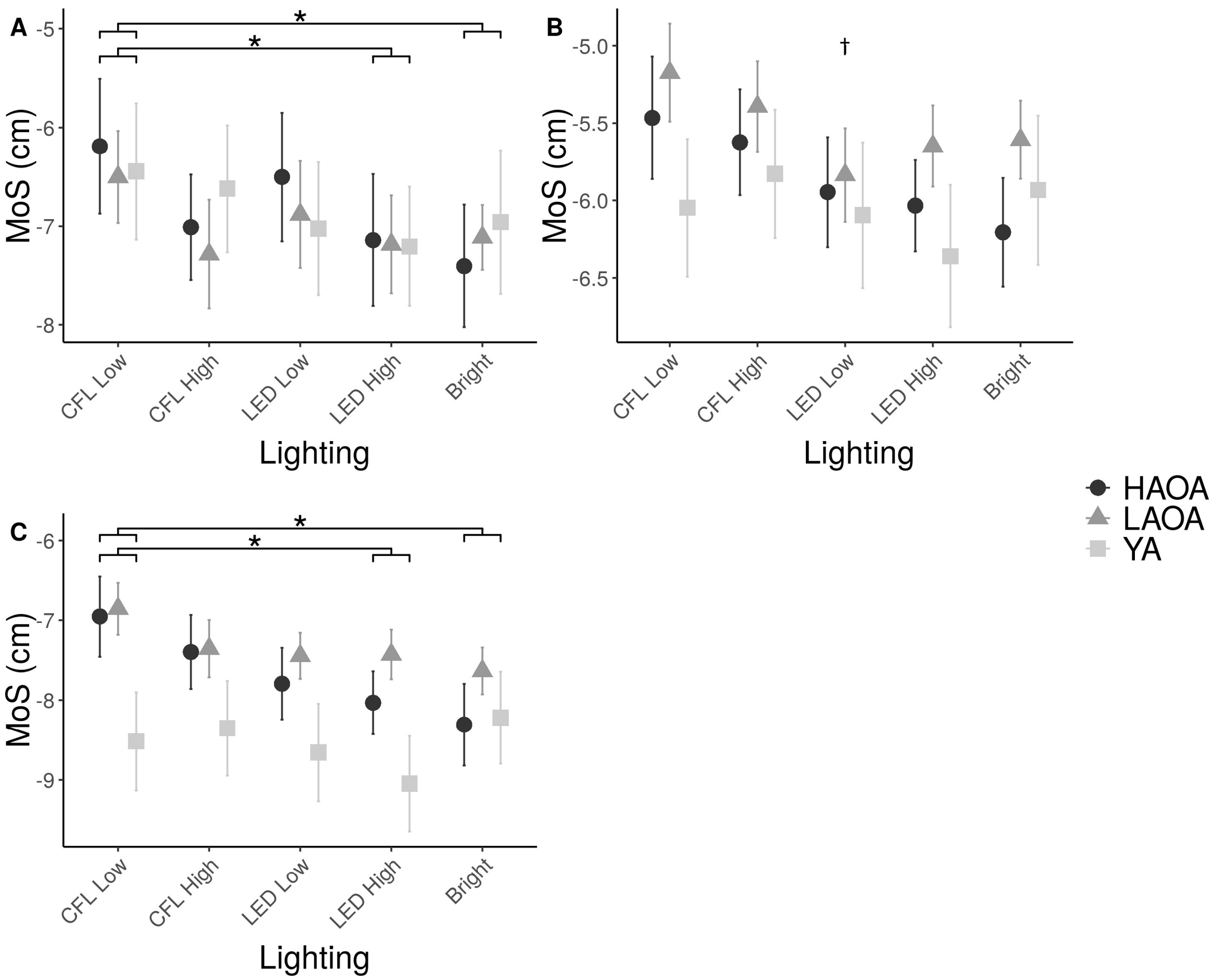

Figure 4. Margin of stability (MoS) during stair descent under different lighting conditions. A: entry phase; B: steady-state phase; C: exit phase. *Post-hoc analysis revealed HAOA, LAOA and YA exhibited significantly increased margins of stability in CFL Low compared to LED High, and Bright. †Significant main effect of lighting on MoS, but no significant post-hoc comparisons. Data are means ± SE.

3.4 Vertical heel clearance

Foot clearance data are presented in Tables 3 and 4. All participants increased their vertical heel clearances in CFL high and LED low light during the entry phase, and during CFL Low in the exit phase. For example, there was a main effect of lighting on vertical heel clearance over step one ($F_{(4,136)}$=3.507, p=.009, n^2_p=.093). Post-hoc comparisons revealed increased clearance in CFL High compared to Bright (p=.003, g_{av}=.430) and LED Low compared to Bright (p=.047, g_{av}=.351). There was also a main effect of lighting on vertical heel clearance during the exit phase over step seven ($F_{(4,136)}$=2.328, p=.049, n^2_p=.064). Post-hoc comparisons revealed increased clearance in CFL Low compared to Bright (p=.023, g_{av}=.277). There were no changes during the steady-state phase. These clearances were also not affected by ageing, and there were no interactions between lighting and age.

3.5 Vertical heel clearance variability

There were no changes to vertical heel clearance variability during the entry and exit phases. However, there was a main effect of age on vertical heel clearance variability during the steady-state phase, over steps three and four (step three: $F_{(2,34)}$=4.29, p=.022, n^2_p=.201). Post-hoc comparisons revealed greater variability in HAOA (p=.041, g=.512) and LAOA (p=.021, g=.604) when compared to YA. Lighting played no role in these changes, however, and there was no interaction between lighting and age.

Measure	CFL Low			CFL High			LED Low			LED High			Bright		
	HAOA	LAOA	YA	HAOA	LAOA	YA	HAOA	LAOA	YA	HAOA	LAOA	YA	HAOA	LAOA	YA
Vertical heel clearance (mm)															
Step one (entry phase)															
Mean	6.5±1.78	7.18±1.8	7.21±1.59	6.33±1.72*	7.56±1.78*	7.57±1.73*	6.43±1.66*	7.51±1.14*	7.01±1.91*	6.38±1.84	7.24±1.45	7.33±1.72	5.96±1.21	6.63±1.41	6.77±1.74
Variability	1.09±0.57	1±0.52	1.18±0.61	0.98±0.46	1.13±0.69	1.26±0.89	1.58±0.82	1.21±0.52	1.32±0.73	1.22±0.82	1.38±0.68	0.95±0.5	1.11±0.88	1.14±1.01	1.31±1.21
Step three (middle phase)															
Mean	6.16±1.49	6.48±3.32	6.64±1.76	5.83±1.36	6.67±1.47	6.5±1.77	6.06±1.7	6.45±2.01	6.21±1.61	5.69±1.82	5.86±1.82	6.33±1.82	5.73±1.8	6.27±1.22	6.68±1.83
Variability	0.86±0.6§	1.96±3.25§	0.85±0.43	1.2±0.7§	1.15±0.68§	0.69±0.15	0.98±0.51§	1.11±1.37§	0.83±0.48	1.14±0.58§	1.03±0.56§	0.68±0.33	0.97±0.62§	1.19±1§	1.05±0.6
Step seven (exit phase)															
Mean	8.77±7.48*	7.33±4.19*	8.87±5.24*	7.04±5.7	8.67±5.89	8.75±4.21	7.6±7.21	9.4±5.63	8.5±4.61	8.93±7.14	7.12±3.29	9.3±5.61	7.69±6	8.03±4.4	8.45±4.59
Variability	2.12±0.73	1.5±1.77	2.56±2.11	1.6±1.24	2.07±1.87	1.66±1.17	1.9±0.9	2.35±1.97	1.36±1.15	2.18±2.89	1.54±1.16	1.9±1.53	1.54±1.36	1.76±2.13	1.95±1.05
Horizontal heel clearance (mm)															
Step one (entry phase)															
Mean	6.29±1.97	7.51±3.03	6.48±1.72	6.28±2.46	7.76±2.93	7.03±2.12	6.39±2.33	7.87±3.12	6.67±2.15	6.55±2.53	7.65±3.07	6.75±2.02	6.25±2.48	7.49±3.34	6.53±2.27
Variability	1.11±0.58	1±0.64	0.68±0.44	0.67±0.48	0.79±0.47	0.75±0.67	1.01±0.5	0.77±0.55	0.62±0.37	0.85±0.44	0.96±0.8	0.69±0.54	0.88±0.58	0.87±0.76	0.83±0.38
Step three (middle phase)															
Mean	7.8±2.41	7.71±3.19	8.05±2	7.74±2.52	8.92±2.81	7.93±2.09	7.61±2.42	8.12±2.87	7.98±2.22	7.95±2.99	7.63±3.06	8.05±2.53	7.2±2.58	8.09±2.61	8.17±2.38
Variability	1.09±0.66	1.34±1.46	0.69±0.41	1.11±0.68	1.1±0.77	1.04±0.67	1.2±0.67	0.91±0.5	0.84±0.54	1.31±1.32	1.22±0.46	0.88±0.64	1.21±0.73	1.21±0.91	1.26±0.63
Step seven (exit phase)															
Mean	5.22±3.58	5.14±2.52	6.05±2.43	4.7±3.41	5.56±3.06	5.94±2.46	4.87±3.77	6.13±2.85	5.88±2.49	5.2±3.54	5.04±2.1	6.14±2.49	5.26±3.65	5.45±2.49	5.69±2.4
Variability	1.05±0.43	0.65±0.24	1.17±0.71	0.88±0.29	1.08±0.62	1.01±0.56	1.22±0.27	1.48±2.22	1.15±0.96	1.09±0.7	0.89±0.52	0.91±0.55	0.9±0.45	1.09±0.9	1.02±0.64

Table 3: Mean and variability (calculated across three successive trials) of the smallest horizontal and vertical distances between the heel markers on the lead limb and the step edges. *Post-hoc analysis revealed HAOA, LAOA and YA exhibited significantly increased vertical heel clearances during CFL High and LED Low compared to Bright (step one); and during CFL Low compared to Bright (step seven). §Post-hoc analysis revealed HAOA and LAOA exhibited significantly increased foot clearance variability when compared to YA (step three). Data are presented as means ± SD.

	CFL Low			CFL High			LED Low			LED High			Bright		
Measure	HAOA	LAOA	YA	HAOA	LAOA	YA	HAOA	LAOA	YA	HAOA	LAOA	YA	HAOA	LAOA	YA
Vertical toe clearance (mm)															
Step one (entry phase)															
Mean	7.46±1.59	6.94±1.32	6.9±1.48	7.32±1.88	7.06±1.06	7.31±1.85	7.41±1.81	6.79±1.63	6.92±1.54	7.17±1.52	6.9±1.6	6.9±1.66	6.73±1.34	6.81±1.4	6.95±1.87
Variability	0.94±0.59	0.65±0.44	0.75±0.34	0.69±0.39	0.59±0.36	0.75±0.42	0.57±0.3	0.63±0.47	0.61±0.33	0.76±0.7	0.59±0.45	0.61±0.27	0.72±0.68	0.55±0.44	0.68±0.74
Step three (middle phase)															
Mean	6.07±1.75	6.08±1.77	6.09±2.01	6.14±1.96	5.97±1.7	6.04±1.94	5.84±1.79	6.20±2.19	5.99±2.02	5.89±2.02	5.94±1.89	6.02±2.37	6.03±1.49	6.44±1.72	6.02±2.07
Variability	1.04±0.55	1.08±0.79	0.79±0.36	1.01±0.61	0.78±0.35	0.79±0.43	1.25±0.37	1.24±1.81	0.74±0.41	1.09±0.42	0.99±0.38	0.76±0.38	0.73±0.51	0.73±0.45	0.76±0.39
Step seven (exit phase)															
Mean	7.3±1.32	7.16±1.62	6.98±2.01	6.94±1.1	7.19±1.64	6.82±1.96	7.17±1.54	6.87±1.56	6.86±1.3	7.12±1.56	7.23±1.6	6.77±1.82	6.98±1.3	6.74±1.8	6.4±1.58
Variability	3.03±2.36*	2.8±1.21*	1.9±1.06*	1.97±1.23	2.4±1.32	1.95±1.19	2.26±1.2	2.08±1.64	2.02±0.88	2.17±2.84	1.65±0.94	1.77±1.31	1.87±1.06	1.6±0.83	1.62±0.96
Horizontal toe clearance (mm)															
Step one (entry phase)															
Mean	27.94±1.93	25.68±5.89	26.37±2.8	26.37±2.8	27.37±2.06	27.24±1.98	26.63±2.48	26.29±4.58	26.51±2.36	26.92±2.55	26.97±4.34	26.12±3.11	25.99±4.55	27.27±2.41	25.68±3.03
Variability	1.41±1.47	2±3.59	1.33±1.14	1.97±2.55	1.99±2.67	1.92±1.57	2.32±3.43	2.94±4.64	1.67±1.39	2.47±3.13	1.89±3.56	1.41±0.99	2.31±3.81	2.52±3.81	1.53±1.07
Step three (middle phase)															
Mean	19.88±5.4	21.8±5.22	18.78±3.47	20.45±5.15	21.04±5.31	19.09±3.35	19.02±4.53	21.38±5.46	18.74±3.45	18.91±5.22	20.36±5.3	18.03±3.68	19.01±4.4	20.91±5.43	19.2±3.21
Variability	2.08±1.61	2.5±1.51	1.37±0.73	1.85±1.22	1.78±1.15	1.66±0.8	2.23±1.09	1.57±1.08	1.49±0.56	1.87±1.43	1.89±0.92	1.47±0.58	1.99±1.25	1.66±1.1	1.4±0.9
Step seven (exit phase)															
Mean	13.89±4.72	13.46±4.43	11.65±3.46	12.72±3.67	14.46±6.99	11.71±3.65	12.21±3.87	13.43±6.46	12.03±2.53	12.78±4.63	13.69±5.29	11.97±3.64	12.14±3.46	12.86±5.03	11.01±2.95
Variability	0.89±0.55	1.1±0.5	0.71±0.36	0.77±0.48	0.81±0.47	0.87±0.44	1.13±0.53	0.98±0.79	0.81±0.45	0.68±0.38	0.75±0.59	0.7±0.38	0.79±0.51	0.62±0.4	0.65±0.4

Table 4: Mean and variability (calculated across three successive trials) of the smallest horizontal and vertical distances between the toe markers on the lead limb and the step edges. *Post-hoc analysis revealed HAOA, LAOA and YA exhibited significantly increased vertical toe clearance variability during CFL Low compared to LED High and CFL Low compared to Bright. Data are means ± SD.

3.6 Vertical toe clearance variability

Importantly, vertical toe clearance variability was affected by lighting during the exit phase, as shown by a main effect of lighting over step seven (Fig. 5: $F_{(4,136)}$=3.905, p=0.022, n^2_p=0.062). Post-hoc comparisons revealed increased variability in CFL Low compared to LED High (p=.046, g_{av}=.416) and CFL Low compared to Bright (p=.033, g_{av}=.658). This change, however, was not influenced by age, and again, there was no interaction between lighting and age.

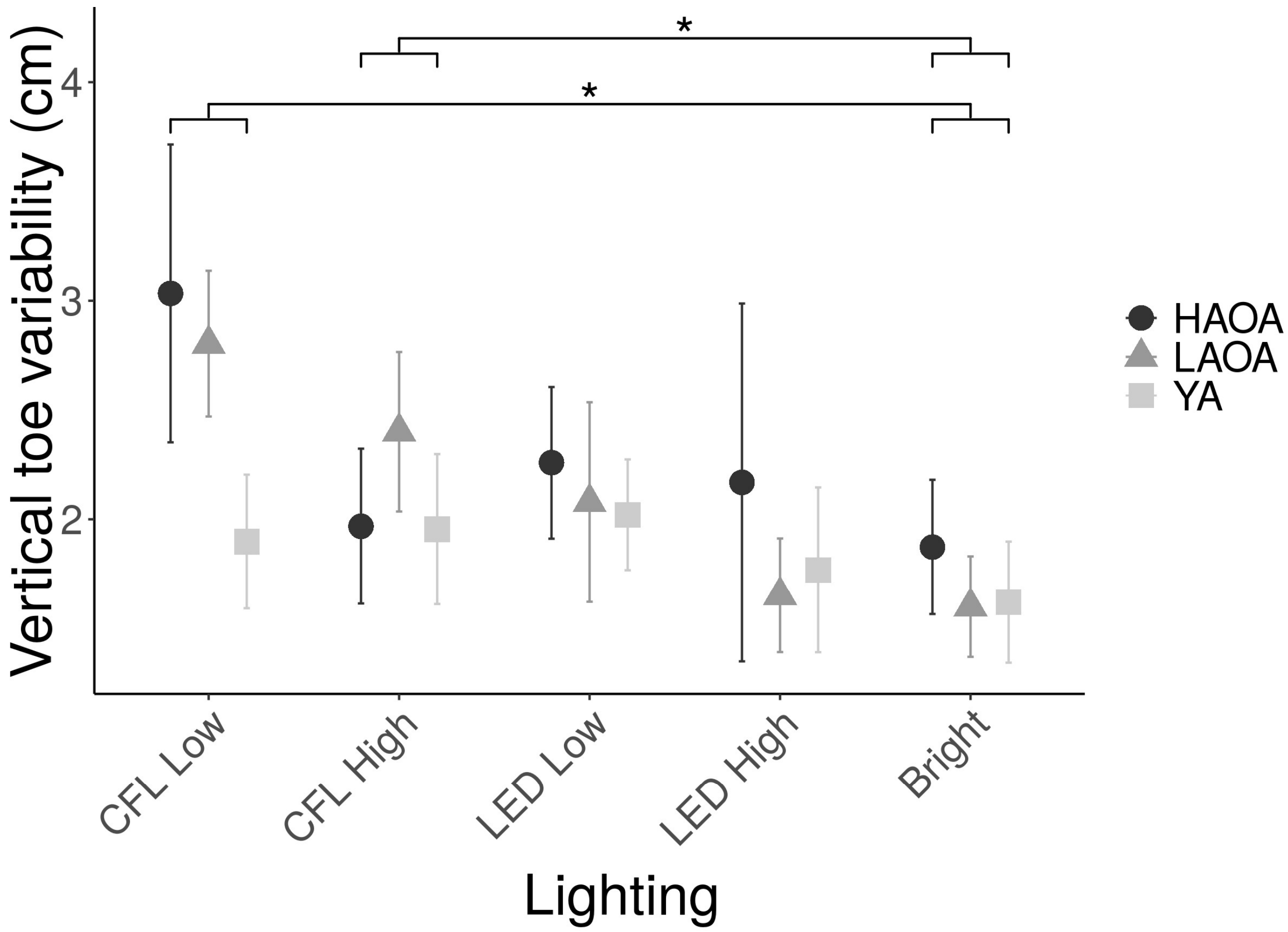

Figure 5. Vertical toe clearance variability during stair descent over step seven (exit phase) in different lighting conditions. *Post-hoc analysis revealed HAOA, LAOA and YA exhibited significantly increased toe clearance variability in CFL Low and CFL High compared to Bright. Data are means ± SE.

4 Discussion

This is the first study to examine the influence of real-world bulb illumination on confidence and anxiety, dynamic balance, and stepping characteristics in young and older healthy adults during all phases of stair descent. This was important to understand how specific lighting impacts stair safety.

4.1 State confidence and anxiety

Both groups of older adults reported less state confidence in lower light (CFL Low, CFL High and LED High) prior to descending the stairs for the first time in each condition, whereas young adults demonstrated no change in confidence across conditions. This shows that the light produced by these bulbs immediately after turn on decreased the older adults' perceived ability to descend the stair safely. This coincides, to some extent, with the observation by Curzon-Jones and Hollands, (2018) of increased self-confidence reported in young and older adults when they were able to visually preview an obstacle prior to stepping, when compared with having to step without previewing the obstacle. In both cases, an improved ability to adequately view a step hazard (stairs with improved lighting or obstacles with a preview) had a significant effect on an individual's confidence prior to the task. However, worry and somatic state anxiety measures were unaffected by lighting in either age group. This observation is also consistent with a lack of self-reported cognitive or somatic anxiety changes between obstacle stepping conditions with and without a visual preview (Curzon-Jones and Hollands, 2018). The lack of observed changes in anxiety may be due to a small effect size, or the nature of the state-anxiety questions. I.e. perceived anxiety was probed after the completion of the first descent in each condition, and thus may have been biased by the successful completion of the task (no trips or falls occurred during testing) and protective strategies such as decreased descent speed and increased margins of stability.

4.2 Margin of stability

Margin of stability was increased in all participants in lower light. This change coincided with a reduction in the instantaneous velocity of the CoM at initial step contact, and ultimately reflects a more cautious stair descent strategy to improve dynamic stability. In support of this, previous studies have shown margins of stability during stair descent to be task-dependent. Novak et al. (2016) showed increasing margins of stability during descent of a staircase, the magnitudes of which were dependent on step length and height. Therefore, the more challenging and risky the staircase was, the more cautious the strategy that was adopted. In our study, low illumination levels resulted in a similar adaptation.

Adopting a more cautious pattern of stair descent in lower light is logical. Visual information about the external environment is directly dependent on the amount of light reaching the retinae, and vision is relied upon during stair negotiation (Zietz and Hollands, 2009). Poor illumination generated by the CFL bulbs is thus directly linked to visual information available about the staircase, e.g. edges of the steps, step height, and intended foot placement locations, and potentially a reduced ability to locate these visual cues. In conditions where visual information is less, or more difficult to extract, adopting a slower speed and increasing the margin of stability has two benefits. Firstly, it allows more time to plan an appropriate foot placement based on the spatial layout of the steps, thus ensuring a safer stepping pattern. Secondly, given that the chances of not accurately detecting the step edge are higher, it enables a safer posture in relation to the base of support should something go wrong. I.e. it would be easier to reduce the already lower CoM forward momentum. If the margin of stability at initial foot contact were too small, a forward loss of balance could occur during a misstep, and this would have more severe consequences when compared to falling laterally on stairs (Jacobs, 2016).

Both age groups showed similar adaptations to margins of stability. Yet, Bosse et al. (2012) found that older adults exhibited smaller margins of stability when compared to younger adults, which was ultimately riskier. A likely explanation for this difference pertains to the demands of the staircases used. The staircase used by Bosse et al. (2012) had two steps, which could be considered as easier to negotiate. Therefore, it is likely that their older participants were not as cautious on the stairs when compared to ours owing to the increased number of steps on our bigger staircase. In support of this, Novak et al. (2016) (who also used more steps on a bigger staircase) showed older adults exhibited similar margins of stability to young adults during the entry and exit transitions, and increased margins of stability compared to young adults during the steady-state phase.

4.3 Vertical heel clearance

Vertical heel clearances tended to increase over step edges during the entry and the exit phases in lower light. This adaptation is likely related to the mechanisms of reduced visual information about the stairs described in *Margin of stability*. This shows that poorer illumination led to more cautious stepping behaviour. These adaptations were typically made when compared to the Bright control condition, which suggests that the Bright condition induced the least cautious stepping pattern. The fact that the older adults seemed to adapt in line with the younger adults in lower light is promising, despite exhibiting more risky patterns in other areas, which will be discussed later.

Why was foot clearance only increased during the entry and exit phases, but not the steady-state phase? One explanation is the known change in tasks demands associated with different phases of stair descent (Alcock et al., 2015; Lee and Chou, 2007). In the middle portion of stairs, the pitch angle typically remains consistent. This means the walker can aim to orientate their trunk at a relatively consistent angle and maintain a regular pattern of stepping. Indeed, descent speed typically reaches a steady-state, and foot clearances are fine-tuned to minimise energy cost (Hamel et al., 2005). In contrast, the entry phase requires motor planning for the final foot placement prior to entry into a sloped plane (Telonio et al., 2014). At this time, the first step depth must be judged and the foot guided, and the trunk must be reorientated to accommodate the change in pitch. Subsequently, the exit phase involves transition from a sloped plane to the level, which involves another reorientation of the trunk and a change in foot positioning. Indeed, increased demands in executive functioning are known in these transition phases (Miyasike-daSilva and McIlroy, 2012). In addition, both groups of older adults in the present study had significantly reduced executive function compared to the younger adults, which suggests they were operating at a higher proportion of their capacity. In lower light, thus, more cautious foot clearances to cope with the bigger demands (more resources taken from foot trajectory planning/control) would seem prudent when less visual information about the step edges is available.

Whilst other young and older populations also did not increase their foot clearances during the steady-state phase of stair descent in lower light (Zietz et al., 2011), it should be noted that Hamel et al. (2005) found that they did. With that said, their study used very dim lighting (1 lux). It could be that the young adults in their study were accommodating for a riskier situation which caused the increase. Differences between the methods (occlusion goggles disrupting peripheral vision) may also go some way to explaining the discrepancy between their study and ours.

4.4 Vertical heel clearance variability

Whilst not influenced by lighting, the older adults demonstrated more vertical heel clearance variability during the steady-state phase when compared to the younger adults. This shows that the older adults could be at a greater risk of tripping even in normal light. Because the older adults generally had poorer visual acuity and contrast sensitivity when compared to the younger adults, one could hypothesise that poor vision might exacerbate detriments to foot clearance control in lower light, particularly seeing as though increasing edge contrast with step-edge highlighters has previously led to increased foot clearances (Zietz et al., 2011), and that stairs with high-contrast edge highlighters improved safety, particularly for those with age-related visual impairment (Foster et al., 2014b). Further investigation into the role of visual function for foot step-edge clearances in low light, or in conditions of peripheral visual field occlusion, may certainly be warranted.

4.5 Vertical toe clearance variability

The key finding from the present work is that vertical toe clearance variability increased over the bottom step in all age groups in CFL bulb light. Therefore, despite an increase in vertical heel clearance, a more risky stepping pattern was induced, and this could increase the chances of a trip. Since the bottom transition step is a common place for falls (Templer, 1992), ensuring adequate lighting in this region could be of paramount importance.

Because the change occurred due to lower light, it is expected that diminished visual information played a role. Foveation of steps directly underneath a walker is typically low in good lighting conditions, and peripheral vision or ‘covert’ attention can be used to acquire information about the stepping surface whilst stepping over it (Miyasike-daSilva and McIlroy, 2012). Lower light may thus have had a detrimental influence on peripheral detection of the step edges used for online guidance of the limb in balance critical circumstances. This likely explains why foot clearance increased over the bottom step in the same light as a precautionary measure.

One obvious question is why was the increased variability only apparent over the bottom step? We hypothesise this is related to planning. Transition steps are associated with increased demands (Miyasike-daSilva and McIlroy, 2012), and motor planning for stepping can occur prior to the stepping action (Patla and Vickers, 1997). In contrast to stair entry, which would allow planning during overground gait, exit from the stairs must be planned whilst already descending the stairs. This could utilise more cognitive resources, which ultimately leads to bigger foot clearances (Hamel et al., 2005), particularly when visual attention is diverted (Telonio et al., 2014), and in our study, it led to more variability exacerbated by poor illumination. It should also be noted that despite there being a short rest period between changing the illumination, and the fact that a visual target was used to prevent visuomotor planning immediately prior to stair descent, the participants did descend our staircase over 15 times in addition to the familiarisation trials. This might have increased the amount of somatosensory information regarding step height and position gained when completing a large number of trials, thus reducing the influence of planning on foot clearance variability.

4.6 Lightbulb use

The low powered CFL bulb illumination used in the present study, replicating a CFL bulb being turned on from cold immediately prior to stair descent, had only increased by around one lux in the time taken to descend the staircase, reaching a total of 10 lux. Whilst descending the stairs in this light, the older participants reported less confidence, and all of the participants adapted their movement patterns to accommodate a reduction in light from that produced by the brighter 100 Watt LED bulb. Importantly, all participants also exhibited more risky stepping patterns over the bottom step in the low powered CFL bulb light, which could increase the risk of a trip or a fall. Since a high proportion of falls are thought to occur during this phase, appropriate lighting here may be important. We therefore suggest that LED bulbs may offer a safer alternative to CFL bulbs for use over stairwells. In addition to reaching full brightness instantaneously, LED bulbs are also energy efficient and have a longer lifespan when compared to CFL bulbs. The higher power (100W) LED bulb generated over 100 lux on our typical UK home staircase. 100 lux has previously been recommended as a minimum illumination at the stair tread. Our findings support this with evidence, and may justify the higher cost associated with higher wattage LED bulbs to home owners and fall-prevention services. When purchasing bulbs, consideration should be given to the fact stair illumination may depend on environmental factors such as stair design, ceiling height and scattering of light. Thus, it will always be preferable to assess illumination at the stair tread. It should also be noted that for large commercial properties which use non-standard bulbs, the LED bulbs featured in the present work are not appropriate. Nevertheless, the minimum of 100 lux shown here supports recommendations from previous literature for illuminating such spaces.

5 Conclusions and future directions

More cautious descent patterns were observed in both young and older participants in lower light, as evidenced by slower descent speeds, increased margins of stability and increased foot clearances. Importantly, there was an increase in foot clearance variability over the bottom step in young and older adults, which is where a number of falls are reported to occur. This indicates that the stair tread illumination from CFL bulbs at first turn on is ultimately sub-optimal for stair descent safety and that high-powered LED bulbs may offer an alternative that optimises stair walking safety. These findings can be used to guide further research of lighting and stair safety in different populations and settings, which will be important for generating evidence-based guidelines. Larger studies are also needed to assess real-world lightbulb illumination and incidences of falls (in commercial and domestic properties), which will elucidate whether certain bulbs or illumination are associated with real-world fall rates. Inconsistent step geometries found in the real world, which could further exacerbate light driven variability in foot clearances, should also be accounted for. This could be important to reduce the proportion of stair falls caused or related to poor lighting.

6 Funding

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