Influence of step-surface visual properties on confidence, anxiety, dynamic stability, and gaze behaviour in young and older adults

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Abstract

Background

Step-surface visual properties are often associated with stair falls. However, evidence for decorating stairs typically concerns the application of step-edge highlighters rather than the entire step-surface. Here we examine the influence of step-surface visual properties on stair descent safety, with a view to generating preliminary evidence for safe stair décor.

Methods

Fourteen young (YA: 23.1±3.7 years), 13 higher (HAOA: 67±3.5) and 14 lower (LAOA: 73.4±5.7) ability older adults descended a seven-step staircase. Older adults were stratified based on physiological/cognitive function. Step-surface décor patterns assessed were: Black and white (Busy); fine grey (Plain); and striped multicolour (Striped); each implemented with/without black edge-highlighters (5.5 cm width) totalling six conditions. Participants descended three times per condition.

Confidence was assessed prior to, and anxiety following, the first descent in each condition. 3D kinematics (Vicon) quantified descent speed, margin of stability, and foot clearances with respect to step-edges. Eye tracking (Pupil-labs) recorded gaze. Data from three phases of descent (entry, middle, exit) were analysed. Linear mixed-effects models assessed within-subject effects of décor (×3) and edge highlighters (×2), between-subject effects of age (×3), and interactions between terms ($\alpha = p < .05$).

Results

Décor: Plain décor reduced anxiety in all ages and abilities ($p=.032$, effect size: $g_{av}=0.3$), and increased foot clearances in YA and HAOA in the middle phase ($p<.001$, $g_{av}=0.53$), thus improving safety. In contrast, LAOA exhibited no change in foot clearance with Plain décor. Patterned décor slowed descent (Busy: $p<.001$, $g_{av}=0.2$), increased margins of stability (Busy: $p<.001$, $g_{av}=0.41$; Striped: $p<.001$, $g_{av}=0.25$) and reduced steps looked ahead (Busy: $p=.053$, $g_{av}=0.25$; Striped: $p=.039$, $g_{av}=0.28$) in all ages and abilities. This reflects cautious descent, likely due to more challenging conditions for visually extracting information about the spatial characteristics of the steps useful to guide descent.

Edge highlighters: Step-edge highlighters increased confidence ($p<.001$, $g_{av}=0.53$) and reduced anxiety ($p<.001$, $g_{av}=0.45$) in all ages and abilities and for all décor, whilst removing them slowed descent in HAOA ($p=.01$, $g_{av}=0.26$) and LAOA ($p=.003$, $g_{av}=0.25$). Step-edge highlighters also increased foot clearance in YA and HAOA ($p=.003$, $g_{av}=0.14$), whilst LAOA older adults showed no adaptation. No change in foot clearances with décor or step-edge highlighters in LAOA suggests an inability to adapt to step-surface visual properties.

Conclusion: Patterned step surfaces can lead to more cautious and demanding stair negotiation from the perspective of visually extracting spatial information about the steps. In contrast, plain décor with step edge highlighters improves safety. We therefore suggest plain décor with edge highlighters is preferable for use on stairs.

Keywords: Falls risk; Margin of stability; Stair ambulation; Stair décor; Stair-tread pattern; Step-edge highlighters

Declarations of interest: none

1 Introduction

The visual properties of step surfaces have been cited as influencing falls risk on stairs (Jacobs, 2016). Stair safety literature frequently promotes the use of high contrast step-edge highlighters (Archea et al., 1979; Gov, 2013). Here we refer to step-edge highlighters as high-contrast strips positioned at the leading edge of the stair tread, rather than the 'nosing' of steps, which defines the radius of the curvature at the leading edge. Step-edge highlighters are thought to improve walkers' abilities to visually delineate the edges of steps more easily when compared to step edges with no defining features, e.g. that can appear to merge, which facilitates safer stair negotiation (Foster et al., 2014b). Visually delineating steps may be particularly important during stair descent, as injurious falls are three times more likely during descent compared to ascent (Startzell et al., 2000). Step-edge highlighters have been shown to cause increased foot clearances over step edges in young adults (Zietz et al., 2011), and a reduction in the number of very low heel clearances, and heel clearance variability in young adults with restricted vision (Foster et al., 2014b). They have also been shown to decrease centre of mass (CoM) movement variability, and to bring the body into a more dynamically stable position during stair descent (Zietz et al., 2011). Therefore, step-edge highlighters may reduce the chances of catching a foot on a step edge and tripping and falling.

Whilst delineating uniformly coloured steps with edge highlighters has been studied previously, the role of the remaining step-surface pattern has received less attention in laboratory studies. Indirect evidence for the effects of step-surface patterns during stair descent can be taken from a recent study of people negotiating a real-world glass staircase (Kim and Steinfeld, 2019). The study found higher rates of trips and missteps on the glass staircase when compared to a concrete staircase with similar dimensions (neither staircase had step-edge highlighters). The increase in stepping errors was partly attributed to reduced visibility of the step edges, because the participants spent more time looking at the glass steps when compared to the concrete steps. Compelling evidence for the effects of patterned steps on real-world falls risk can be found from a report in 1968 that compiled 1414 falls over a six-week period on a public staircase where users could not visually identify the edge of the step due to deceptive lines running perpendicular to the step edge. When these were replaced, no falls were reported over a 3-month period (Mowery, 1968, cited in Archea et al., 1979, p.45). Therefore, step-surfaces or patterns that make it more difficult to determine spatial characteristics of stairs are likely to be detrimental to stair safety.

Older adults may be at a particular disadvantage when faced with step-surface patterns that make it difficult to see the edges of steps. Common age-related declines in contrast sensitivity could lead to a reduced ability to see step edges (Owsley, 2011), which would presumably be exacerbated by ambiguous step surface patterns, and even healthy older adults look at steps for longer during stair descent compared to young adults (Zietz and Hollands, 2009). Older adults have also been shown to exhibit smaller and more variable foot clearances during stair descent with no step-edge highlighters, which increases the chances of tripping (Hamel et al., 2005). Some older adults do not increase their foot clearances when edge highlighters are applied to steps (Foster et al., 2014b; Zietz et al., 2011), or only exhibit minimal increases (average 1.8 mm; Simoneau et al., 1991). Furthermore, during a single stepping task (ascent), applying a fine-grained visual texture, which masked the shape of the step, brought about increased stepping height in younger adults, whilst older adults did not adapt (Schofield et al., 2017). This difference in stepping behaviour was suggested to be caused by reduced sensitivity for visual textures in the older adults who were less able to detect surface undulations in the fine-patterned surface. It is therefore clear that older adults' sensitivity to alterations in visual properties of stairs may be reduced, and that this could put them at an increased risk of falls on stairs with patterned décor.

A factor previously overlooked in studies about stair visual properties is the role of confidence and anxiety. Reduced confidence has previously been observed in conditions when subjects were less able to preview obstacles prior to stepping (Curzon-Jones and Hollands, 2018), and importantly, were less able to view stairs under poor as opposed to adequate lighting (Thomas et al., 2020). It thus follows that reduced step-edge contrast on steps with no edge highlighters or with patterned décor, which would make it difficult to determine the spatial layout of the steps, could also reduce confidence and increase anxiety. These threat-related factors have been associated slower walking (Brown et al., 2006) and increased stepping clearance (McKenzie and Brown, 2004) during obstacle negotiation tasks. Increased anxiety during stepping-down behaviour also causes older adults to adopt more conservative landing strategies at the expense of increase muscle force production (Kluft et al., 2020). Furthermore, anxiety has been shown to influence visuomotor behaviour. During targeted stepping, there is normally a close temporal relationship between the timing of the last gaze at a stepping target and initial foot contact on that target (Chapman and Hollands, 2006). Some older adults have been shown to exhibit an earlier transfer of gaze away from a stepping target towards future obstacles, which was associated with reduced foot placement accuracy such that they prioritised planning for future stepping actions to the detriment of immediate stepping constraints, and a potential explanation for this was heightened anxiety (Chapman and Hollands, 2007). Such an early transfer of gaze could have negative consequences on the risk of falling during stair descent in a heightened state of anxiety. As such, there is strong evidence to suggest that the effects of step décor on confidence and anxiety is an important factor to consider.

The present investigation examined if and how step-surface décor impacts confidence and anxiety, postural stability, stepping characteristics, and gaze behaviour in young and older adults, with a view to generating preliminary evidence for safer stair décor. To achieve this, we recorded whole-body movements and gaze allocation during stair descent in young and older adults over three commercially available flooring patterns, each with and without an edge highlighter. We hypothesised that: 1) patterned surfaces would be detrimental to descent safety – characterised by reduced confidence and increased anxiety, slower and more cautious gait, and reduced foot clearances; 2) patterned surfaces would cause participants to look less steps ahead, and at the steps for longer; 3) step-edge highlighters would lead to increased foot clearances; 4) older adults would be more ‘at risk’, with more adaptations than young necessary to negotiate patterned steps and steps with no edge-highlighters (e.g. slower descent), in addition to riskier stepping patterns (e.g. smaller foot clearances).

2 Methods

2.1 Participants

Fourteen young (18-35 years) and 27 community-dwelling independent older (≥65 years) healthy adults were recruited from the host institution and from older adult social, volunteer, and advocacy groups (participant characteristics are reported in Table 1). Apriori statistical power analysis (Gpower statistical software) was used to compute the required sample size to identify age-related differences in foot clearance with respect to step edges during stair descent with different step-surface visual properties. The test used the difference between two independent means (young vs older) of vertical foot clearance data from Zietz et al. (2011) and showed a required sample of 14 participants per group (Effect size: $d = 1.29$, $\alpha = 0.05$, power = 0.90). Cognitive function of the older adults was assessed using the Trail Making Test and all scores were within normative values (Tombaugh, 2004).

Participants were included if they could descend stairs without walking aids (canes or crutches), and in a step-over-step manner. They also had no self-reported balance or musculoskeletal issues which might have influenced stair negotiation. The investigation was approved by the host institution's Research Ethics Committee, and all participants gave written informed consent in accordance with the Declaration of Helsinki.

2.2 Assessments

Older participants were stratified into groups based on a sum of visual, physiological, and cognitive function scores. Visual function was assessed by 1) visual acuity, and 2) contrast sensitivity (FrACT). Physiological function was assessed by 3) three isometric knee extension maximal voluntary contractions, measured with a hand-held dynamometer (Bohannon, 1990), 4) lower limb matching task, and 5) 30 s quiet stance on a foam mat. Cognitive function was assessed by 6) Trail making test parts A and B to measure executive function, 7) Reaction time, and 8) Stair specific efficacy whereby participants scored from 1-100% how confident they felt negotiating stairs in everyday life. Tests 3, 4, 5 and 7 were measured according to the protocol outlined by Lord et al. (2003). However, instead of the custom measurement equipment used by Lord et al. (2003), we used a Vicon system to assess kinematics, with toe markers used to record position for the lower limb matching task, and the total path of the Pelvis CoM used to characterise postural sway. Reaction time was measured as the average of 10 timed trials where participants pressed a button in response to a computer-generated stimulus.

Outcomes of the physiological and visual function assessments have previously been associated with stair descent performance. For example, fear of falling, leaning balance, contrast sensitivity, reaction time, lower limb proprioception, and knee extension strength, are all significant and independent predictors of stair descent speed (Tiedemann et al., 2007), and visual function may be particularly important when faced with ambiguous step-surfaces.

We included executive function as an additional stratification parameter as there is growing evidence to suggest that reduced executive function is associated with an increased risk of falls in older adults, particularly under complex and/or challenging conditions (Mirelman et al., 2012). Moreover, when it is difficult to extract visuospatial information about stairs, e.g. with visually ambiguous stair coverings, it is not unreasonable to suggest that older adults may exhibit heightened anxiety and a shift towards movement reinvestment. This, in theory, would entail an internal reallocation of attention towards movement-specific processes, reducing attentional resources available for, e.g. feed-forward planning, and placing demands on cognitive resources (Ellmers et al., 2020a; Ellmers and Young, 2018; Uiga et al., 2020). Furthermore, reduced executive function has been shown to cause slower stair descent in dual tasking older adults (Gaillardin and Baudry, 2018), and poor executive function has been attributed to more anxious older adults who perceive themselves as being at a high risk of falling (Delbaere et al., 2010). Therefore, whilst a direct link is far from certain, executive function could play an important role in stair descent with patterned stair coverings.

To stratify the older adults based on these outcomes, we followed the protocol outlined in our previous work (Thomas et al., 2020). Briefly, the older participants were ranked from first to last (1 – 27) based on their scores for each test. Each older participant's ranks across the assessments were then summed, resulting in one cumulative ranking table. Those in the lower 50% percentile of this table were categorised as lower ability older adults (LAOA), and those in the higher 50% percentile categorised as higher ability older adults (HAOA; Zietz et al., 2011). Table 1 shows these results and participant anthropometrics.

Table 1. Participant characteristics and assessment outcomes (±SD). Significant difference ($p<.05$) between: *Young and high ability older adults (HAOA); †Young and low ability older adults (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 3 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.

	Young (*n*=14; 7×males)	HAOA (*n*=13; 6×males)	LAOA (*n*=14; 3×males)	Older adults combined (*n*=27, 18×males)
Age (years)	23.1±3.7*†	67±3.5§	73.4±5.7	70.3±5.7
Height (cm)	173.1±9.1	156.7±47	164.3±8.5	160.7±32.7
Mass (kg)	68.9±6.9	73.3±22.3	68±17	70.6±19.6
Visual acuity (logMAR)	-0.09±0.1*†	0.05±0.12	0.14±0.19	0.09±0.17
Contrast sensitivity (Weber)	1.91±0.15†	1.81±0.21§	1.6±0.21	1.7±0.23
Executive function (s)	29.5±18.7	27.5±19.3	33.4±12.4	30.6±16.1
Lower limb matching (SD)	6.2±6.1	7.1±10	6±2.4	6.5±7.1
Knee extension torque (Nm)	113.7±45.8†	117.2±34.4§	77.8±31.1	96.8±37.8
Quiet stance on foam mat (cm)	143.2±29.6†	155.9±41.3	178.8±49.8	167.7±46.5
Reaction time (s)	0.291±0.017†	0.294±0.04§	0.351±0.09	0.324±0.075
General stair confidence (%)	95.4±6.6†	93.3±8.6§	83.1±15	88±13.2

2.3 Staircase apparatus

Participants descended an instrumented seven-step staircase with handrails on each side. Each step had a riser height of 20 cm, and a going length of 25 cm, which conforms to current UK building regulations for commercial and private properties (Gov, 2013), and the top and bottom landings were large enough to complete an entry and exit phase. Force-platforms (Kistler) sampling at 1080Hz were positioned on the bottom four steps. A passive overhead safety harness worn by the participants when on the staircase was operated by a trained belayer. See Fig 1. for layout of staircase. Staircase illumination at the stair treads was measured at over 300 lux with all laboratory lights turned on.

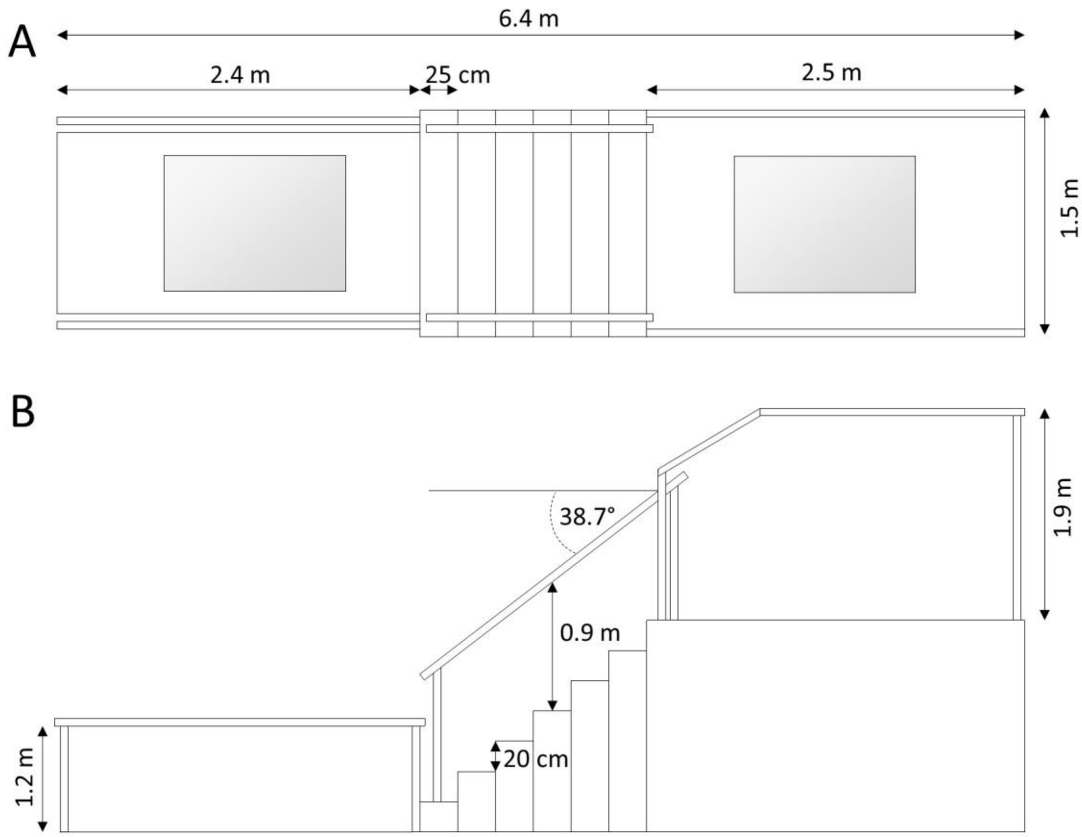

Figure 1. Layout of staircase. A: top view; B: side view. The shaded areas in A denote trial start (right) and end (left) areas. All indicated geometries are to scale.

2.4 Décor

To ensure real-world applicability and ecological validity of the results, three floor décor patterns were applied to the stair treads. These were: a ‘busy’ black and white pattern (Busy); fine textured plain grey typical of concrete stairs in public/private spaces (Plain); and striped multicolour with stripes orientated perpendicular to the step edge (Striped). Each was implemented with and without a step-edge highlighter (5.5 cm width abutting the leading edge of the step: British Standards Institution, 2010).

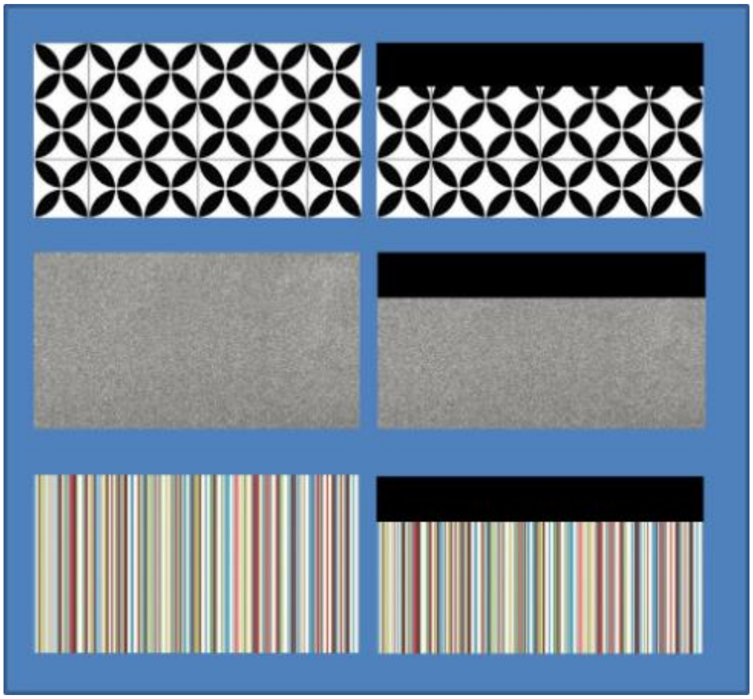

Figure 2. Stair-tread décor patterns. Top: Busy; middle: Plain; bottom: Striped. The left side shows décor without a step-edge highlighter, and the right side shows décor with a step-edge highlighter. The top edge of each décor is the leading edge of the step.

2.5 Testing protocol

Participants completed the protocol on a single visit to the laboratory (approximately two hours duration). Visual, physical, and cognitive assessments were completed before the stair trials with the exception of leg strength. To reduce effects of muscle fatigue on stair walking, this was assessed following the stair trials. Prior to testing, participants were familiarised with the experimental environment, and performed three practice stair trials. For the stair trials, the participants descended the stairs at a self-selected pace in a step-over-step manner. A trial was initiated on illumination of an LED located on the bottom left handrail whilst participants stood stationary on the top landing with feet side-by-side. At this time, participants maintained their gaze on the LED to ensure standardisation of visuomotor planning across participants prior to each stair descent. Stair descent was initiated with either foot in the first trial, which was then used consistently throughout the remaining trials, and they were free to use the handrails throughout. We report the influence of handrail use on margin of stability below. At the bottom of the stairs, the participants continued to the end of the bottom landing, before coming to a stationary position and standing with feet side-by-side.

Participants completed three descent trials with each décor. The three trials were performed consecutively in a block, which totalled six blocks (one for each décor). The blocks were performed in a random order to eliminate practice and/or fatigue effects. There was a 2-5 minute rest between blocks, at which time the participants sat facing away from the stairs, whilst the décor was changed.

2.6 State confidence and anxiety

We asked the participants questions designed to assess their state confidence and anxiety. These questions have been used in previous studies of anxiety under conditions of postural threat (Adkin et al., 2002; Johnson et al., 2019; Sibley et al., 2007) and stair descent under different lighting (Thomas et al., 2020), and were originally modified from the Sport-Anxiety Scale (Smith et al., 1990). Prior to the first descent in each new décor condition, the participants stood on the top step whilst viewing the décor for the upcoming trial and were subsequently 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 décor condition, participants were asked questions designed to assess their anxiety, also rated on a scale of 1-100%. For worry-related anxiety: "how worried were you when descending the stairs with that décor (e.g. about falling or losing your balance)?"; for somatic-related anxiety: "how physically anxious did you feel when descending the stairs with that décor (e.g. tense or nervous)?"; and for concentration-related anxiety: "how difficult was it to focus when descending the stairs with that décor (e.g. distracting or intruding thoughts about falling)?". Responses were averaged to give a measure of overall anxiety (Johnson et al., 2019). These assessments were administered in the first trial of each new décor condition to minimise respondent fatigue, as repeating them on every trial would likely reduce motivation and the quality of the responses.

2.7 Kinematics

Whole-body kinematic data sampled at 120Hz were collected with a 26-camera motion capture system (Vicon MX, Oxford Metrics, UK). Thirty-nine reflective markers were securely attached on anatomical landmarks according to the conventional Plug-in Gait marker set. Thirty-seven additional markers were placed in cluster arrangements on the head and lower limbs to ensure at least three markers were visible on segments prone to marker occlusions (e.g. from step-edges). The heel markers were removed as they are prone to catching on step edges thus hindering normal gait. Reconstruction of the heel markers in the movement trials was performed based on their respective locations in relation to the rigid foot segment in the static calibration trial. Participants wore tight clothing provided by us and wore their own flat trainers/shoes.

Small gaps in kinematic data (<100 ms) were interpolated with a Woltering quintic spline (Vicon Nexus 2.6, Oxford Metrics), and exported for offline analysis with Python (Python Software Foundation). A rigid-body gap filling protocol leveraging the extended marker set was used for gaps longer than 100 ms. A fourth order zero-phase Butterworth filter (20 Hz cut-off frequency) was used to filter marker trajectories, and pyCGM software subsequently used to calculate joint angles and whole-body CoM according to the conventional gait model (Schwartz and Dixon, 2018).

Stair descent was separated into three phases: entry, steady-state, and exit. Entry was the time between the last heel strike on the top landing and initial contact on step two. Steady-state was the time between initial contact on step two and initial contact on step five. Exit was the time between initial contact on step five and the first heel strike of the swing limb on the bottom landing. For steps with no force platforms, 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 steps with force platforms, >20N or <20N defined initial contact and toe-off, respectively (Zeni et al., 2008).

Outcome measures used to characterise stair descent safety were descent speed, margin of stability (reported in the anteroposterior direction), and foot-step edge clearances. Descent speed was defined as the first derivative of the resultant CoM trajectory, which was averaged for the duration of each phase. Margin of stability was defined as anteroposterior distance between the forward boundary of the base of support and the extrapolated CoM (xCoM). When the toe marker was outside the confines of the step-edge (foot overhang), the step-edge defined the forward boundary. When the toe marker was within the confines of the step-edge, the toe marker defined the forward boundary. A less dynamically stable pattern of stair descent is thought to be characterised by smaller (or more negative) margins of stability (Bosse et al., 2012; Novak et al., 2016), whilst increased margins of stability could infer a more conservative balance strategy (Novak et al., 2016; Thomas et al., 2020).

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 contact on step 1 (entry); step 4 (steady-state) and step 6 (exit). Initial contact is when the risk of falling during a misstep (e.g. placing the foot too far forward) can be exacerbated by small margins of stability. This is because the individual would have more forward momentum to counter (Novak et al., 2016). Foot-step edge clearance was defined as the minimum absolute distance between the rear of the shoe sole on the lead limb and the edge of each step. The rear of the shoe sole was digitised in a static trial prior to stair descent and reconstructed in the movement trials like the heel markers described above. Mean and variability (SD) across three successive trials was calculated and used for further analysis. Small or variable foot clearances are suggested to increase the risk of catching the heel or toe on the step edge (Hamel et al., 2005).

2.8 Gaze

Gaze data were sampled at 120 Hz using mobile eye tracking glasses (Pupil Labs Core, Pupil Labs, Berlin) with the Pupil mobile application. The eye tracker was calibrated and validated prior to each new block of stair descent trials, with <2 ° error (reported by Pupil Labs software) considered acceptable. Gaze and motion capture data were synchronised using Pupil Remote timestamps. 2D video sequences consisting of the participants' point of view superimposed over the visual scene were subsequently analysed in Pupil Player software. Raw gaze data were filtered with the Pupil Labs offline fixation detector (2° maximum dispersion angle, 60 ms minimum duration). Gaze was considered to be allocated on a step when more than half of the gaze circle was located on that step. Generally, gaze on a particular step was evident owing to clear saccades between steps. In the case of truly ambiguous frames, allocation was not recorded for those frames. To examine the influence of décor on visual sampling, we calculated: 1) duration of gaze allocation on each step, which was expressed as a percentage of stair descent duration; 2) average number of steps looked ahead during the stance phase on each step, i.e. a person standing on step 3 (before initial contact on step 4) whilst looking at step 5 would be looking two steps ahead; 3) time interval between the last gaze on a step and initial foot contact on that step. Individual values for each step were then averaged over successive steps during the combined entry and steady-state phases (necessary because not all the steps were gazed by some participants). Only the entry and steady-state phase were included for analysis here because areas of the bottom landing gazed during the exit phase were not amenable to quantitative assessment.

Due to practical challenges with eye tracking, a subset of 11 young (23.2 ± 4.1 years; ×6 males) and 13 older (70.1 ± 6 years; ×2 males) adults were considered for further analysis, with the others being discarded due to poor data quality. The eye tracking data from older adults were thus not stratified to ability groups. There were 6 HAOA and 7 LAOA incorporated in the older adult group. No trials were excluded for these participants. These data were of excellent quality, with >80% of each trial containing recorded gaze points, and with >0.85 pupil detection confidence (reported by Pupil Labs software).

2.9 Statistical analyses

Linear mixed-effects models examined stair descent outcome measures for within-subject effects of edge highlighter (×2: with or without) and décor (×3: Busy, Plain, and Striped), between-subject effects of age (×3: Young, LAOA, and HAOA), and interactions between edge highlighter, décor, and age. For gaze data, between-subject effects of age were Young and Older (×2). In the case of significant interactions, contrasts compared outcome measures at each level of interaction where appropriate to identify which groups were affected at which level. Post-hoc analyses using pairwise t-tests with Holm-Bonferroni corrections then identified specific within/between group differences. Paired t-tests were performed to examine the influence of handrail use on margin of stability. Effect sizes for between and within group differences were Hedges' g and Hedges' g_{av}, respectively. Common indicative thresholds for these are small (0.2), medium (0.5) and large (0.8; Lakens, 2013). Where data were non-normally distributed, significant effects were cross-checked with robust ANOVAs based on trimmed means (Field et al., 2012), and post-hoc analyses were Wilcoxon tests with Holm-Bonferroni corrections. 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

Edge highlighters increased confidence and reduced anxiety with all décor patterns, as evidenced by significant main effects of edge highlighter for both outcomes (Figure 3. confidence: $x^2(1)=31.07$, $p<.001$, $g_{av}=0.53$; anxiety: $x^2(1)=24.96$, $p<.001$, $g_{av}=0.45$). This was consistent in all age groups. There was also a significant main effect of décor on anxiety ($x^2(1)=9.52$, $p=.049$). Post-hoc comparisons revealed increased anxiety with Busy compared to Plain ($p=.032$; $g_{av}=0.3$) and Striped ($p=.032$;

g_{av}=0.26) décor. There were no main effects of age or interactions between edge highlighter, décor, and age.

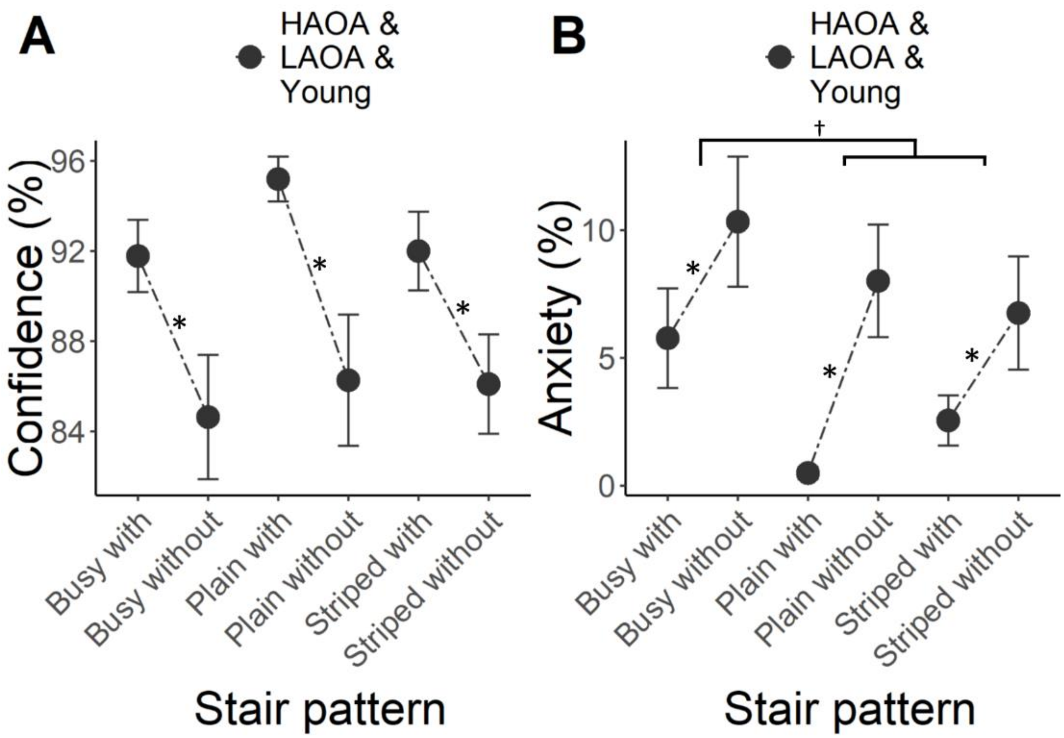

Figure 3. A: Confidence prior to stair descent with different décor. *All age groups (Young, HAOA and LAOA) reported more confidence when an edge highlighter was applied to Busy, Plain and Striped décor (p<.001, g_{av}=0.53). **B**: Anxiety following stair descent with different décor. *All age groups reported less anxiety when an edge highlighter was applied to Busy, Plain and Striped décor (p<.001, g_{av}=0.45). †All age groups reported more anxiety with Busy décor compared to Plain (p=.032; g_{av}=0.3) and Striped (p=.032; g_{av}=0.26) décor. Data are means ± SE.

3.2 Descent speed

There was a significant main effect of edge highlighter (x^2 (1)=9.49, p=.002) and a significant edge highlighter × age interaction in the middle phase (Figure 4. x^2 (2)=9.49, p=.002). Contrasts revealed the effects of edge highlighter for HAOA and LAOA differed compared to Young ($t_{(114)}$= -2.33, p=.022). Post-hoc comparisons showed removing edge highlighters slowed descent in HAOA (p=.01, g_{av}=0.26) and LAOA (p=.003, g_{av}=0.25), whilst Young were unaffected. In the exit phase, there was a significant main effect of edge highlighter (x^2 (1)=6, p=.014), a significant main effect of age (x^2 (3)=6.3, p=.043), and a significant edge highlighter × age interaction (x^2 (3)=6.3, p=.043). Contrasts revealed the effects of edge highlighter for HAOA differed compared to LAOA and Young ($t_{(114)}$= -2.52, p=.013). Post-hoc comparisons showed removing edge highlighters slowed descent in HAOA (p=.005, g_{av}=0.3), whilst LAOA and Young were unaffected. Additionally, LAOA descended slower than HAOA (p=.012, g=0.56), and HAOA descended slower than Young (p=.016, g=0.31), overall. Finally, there were significant main effects of décor in the middle (x^2 (2)=8.57, p=.014) and exit (x^2 (2)=8.12, p=.017) phases. Post-hoc comparisons revealed slower descent with Busy compared to Plain décor in all age groups (middle: p<.001, g_{av}=0.2; exit: p=.005, g_{av}=0.19).

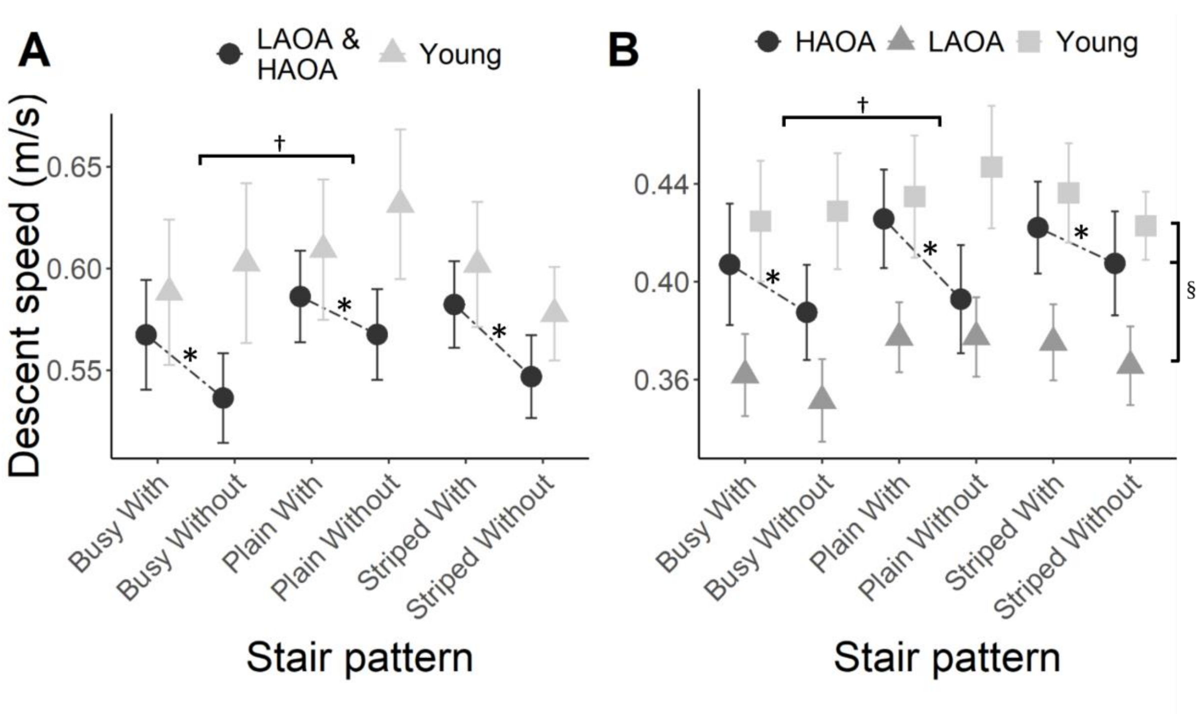

Figure 4. Descent speed with different décor. **A.** Middle phase: *Removing edge highlighters from all décor patterns (Busy, Plain and Striped) slowed descent in HAOA (p<.001, g_{av}=0.26) and LAOA (p=.011, g_{av}=0.25), whilst Young were unaffected. †All age groups (LAOA, HAOA and Young) descended slower with Busy compared to Plain décor (p=.015, g_{av}=0.2); **B.** Exit phase: *Removing edge highlighters slowed descent in HAOA (p<.001, g_{av}=0.2), whilst LAOA and Young were unaffected. †All age groups descended slower with Busy compared to Plain décor (p=.02, g_{av}=0.19). §LAOA descended slower than HAOA (p=.012, g=0.56), and HAOA descended slower than Young (p=.016, g=0.31), overall. Data are means ± SE; black circles in subplot A shows mean of HAOA and LAOA combined, whereas subplot C shows means of individual age groups separately.

3.3 Margin of stability

There were significant main effects of décor in the entry (x^2 (2)=7.12, p=.029), middle (x^2 (2)=36.16, p<.001), and exit phases (x^2 (2)=18.43, p<.001). Post-hoc comparisons revealed increased MoS with Busy compared to Plain (entry: p=.03, g_{av}=0.18; middle: p<.001, g_{av}=0.41; exit: p<.001, g_{av}=0.23) and Striped (entry: p=.016, g_{av}=0.19; middle: p<.001, g_{av}=0.25; exit: p<.001, g_{av}=0.29) décor, and increased MoS with Striped compared to Plain décor (middle: p=.001, g_{av}=0.17). This shows more adaption was required to negotiate stairs with these décor patterns. There was also a significant main effect of age during the exit phase (x^2 (2)=7.86, p=.02). Post-hoc comparisons revealed LAOA exhibited increased MoS compared to HAOA (p<.001, g=0.57), and HAOA exhibited increased MoS compared Young (p=.017, g=0.37), overall. Edge highlighters had no effect on MoS with Busy, Plain or Striped décor in any phase. There were also no significant interactions between edge highlighter, décor, and age. Finally, LAOA who used the handrails (n=7) exhibited significantly smaller MoS compared to those who did not (mean±se; handrail use: -4.13±2.77 cm; no handrail use: -1.99±1.34 cm; p<.001; g=0.97). MoS in HAOA who used the handrails (n=2) was not different to HAOA who did, and no Young used the handrails.

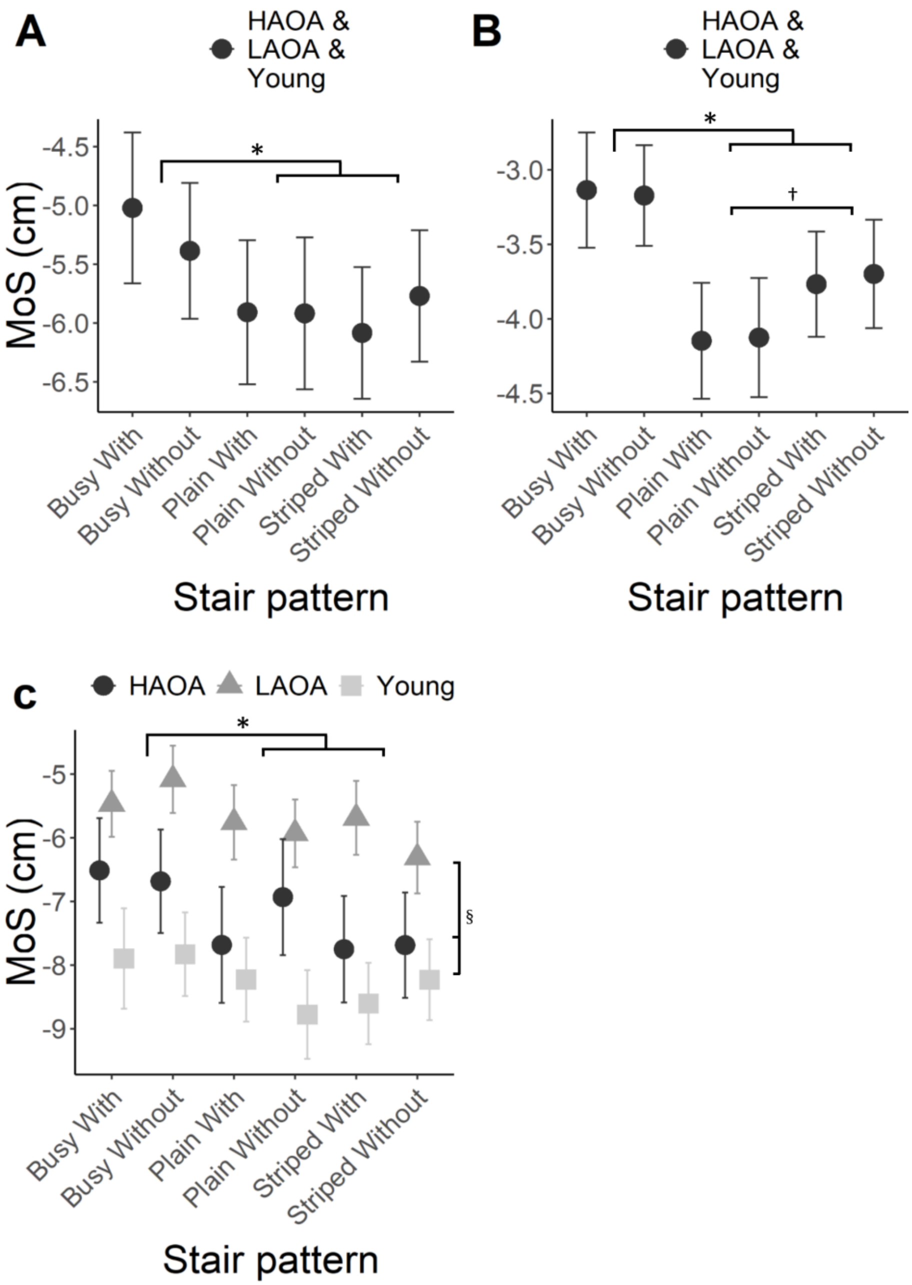

Figure 5. Margin of stability (MoS) with different décor. **A**: Entry phase; **B**: Middle phase; **C**: Exit phase. *Post-hoc analysis revealed all age groups (Young, HAOA and LAOA) exhibited increased MoS with Busy compared to Plain (entry: p=.03, g_{av}=0.18; middle: p<.001, g_{av}=0.41; exit: p<.001, g_{av}=0.23) and Striped (entry: p=.016, g_{av}=0.19; middle: p<.001, g_{av}=0.25; exit: p<.001, g_{av}=0.29) décor. †All age groups exhibited increased MoS with Striped décor compared to Plain décor (p=.001, g_{av}=0.17). §LAOA exhibited increased MoS compared to HAOA (p<.001, g=0.57), and HAOA exhibited increased MoS compared Young (p=.017, g=0.37), overall. Data are means ± SE; black circles in subplots A and B show mean of all age groups combined, whereas subplot C shows means of individual age groups separately.

3.4 Heel clearance

There was a significant main effect of edge highlighter (x^2 (1)=5.02, p=.025), a significant main effect of décor (x^2 (2)=23.41, p<.001), and a significant décor × age interaction (x^2 (2)=18.46, p=.001) in the middle phase. Contrasts revealed evidence for differing effects of Plain vs Busy and Striped décor for LAOA compared to HAOA and Young ($t_{(76)}$= -1.93, p=.058). Post-hoc comparisons showed HAOA and Young increased heel clearance with Plain compared to Busy (HAOA: p<.001, g_{av}=0.42; Young: p<.001, g_{av}=0.53) and Striped (HAOA: p<.001, g_{av}=0.29; Young: p<.001, g_{av}=0.36) décor, whilst LAOA were unaffected. Post-hoc analysis also showed HAOA and Young increased heel clearance when edge highlighters were applied to all décor conditions (p=.003, g_{av}=0.14), and again, LAOA were unaffected. In the exit phase, there was a significant main effect of décor (x^2 (2)=14.94, p<.001). Post-hoc comparisons showed increased heel clearance with Plain compared to Busy (p=.002, g_{av}=0.27) and Striped (p=.003, g_{av}=0.18) décor in all ages.

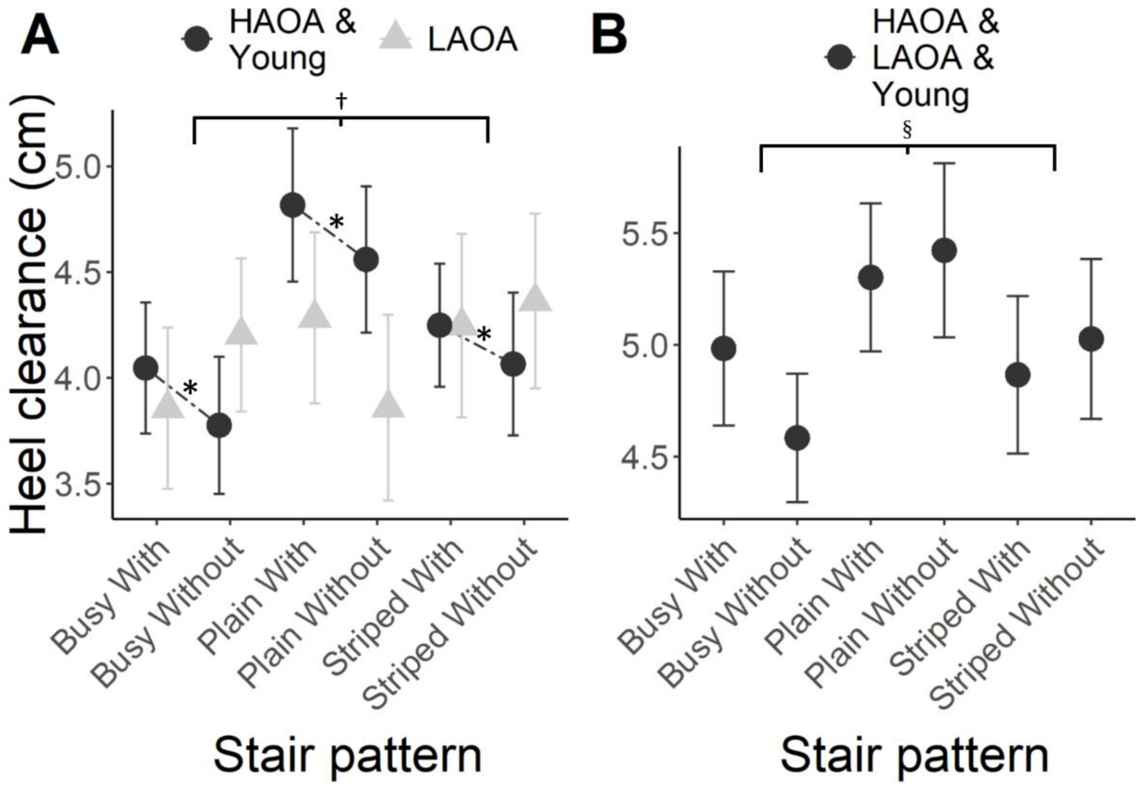

Figure 6. Heel clearance during stair descent with different décor. **A.** Middle phase: *HAOA and Young increased heel clearance when an edge highlighter was applied to all décor patterns (p=.003, g_{av}=0.14). †HAOA and Young increased heel clearance with Plain compared to Busy (HAOA: p<.001, g_{av}=0.42; Young: p<.001, g_{av}=0.53) and Striped (HAOA: p<.001, g_{av}=0.29; Young: p<.001, g_{av}=0.36) décor. LAOA were unaffected. **B.** Exit phase: §All age groups increased heel clearance with Plain compared to Busy (p=.002, g_{av}=0.27) and Striped (p=.003, g_{av}=0.18) décor. Data are means ± SE; black circles in subplot A show means of HAOA and Young combined, whereas subplot B shows mean of all age groups combined.

3.5 Gaze

There was a significant main effect of décor (x^2(2)=7.35, p=.025) and a significant décor × edge highlighter interaction (x^2(2)=8.88, p=.012). Contrasts revealed no evidence for differing effects of edge highlighter on steps looked ahead with different décor patterns. However, post-hoc comparisons showed evidence for fewer steps looked ahead with Busy (p=.053, g_{av}=0.25) and Striped (p=.039, g_{av}=0.28) décor compared to Plain décor, overall. There were no main effects of age, or interactions between décor, edge highlighter and age.

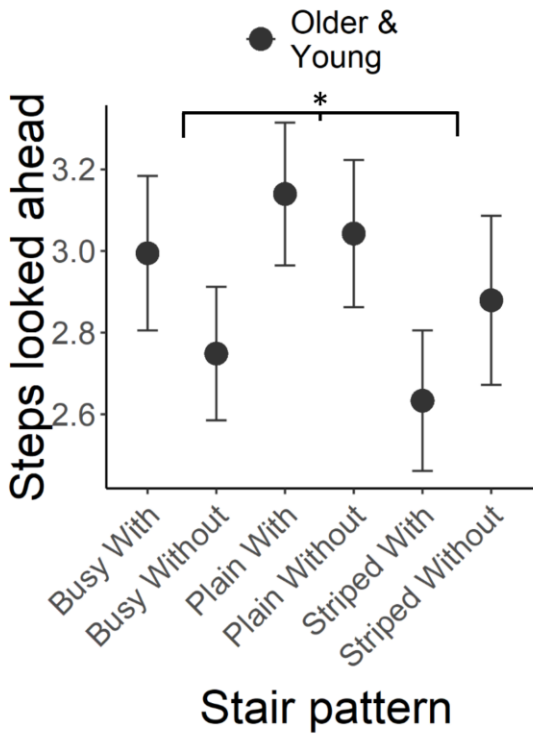

Figure 7. Steps looked ahead with different décor patterns. *Post-hoc analysis revealed evidence that all age groups (Young and Older) looked fewer steps ahead with Busy (p=.053, g_{av}=0.25) and Striped (p=.039, g_{av}=0.28) décor compared to Plain décor. Data are mean of all age groups ± SE.

4 Discussion

This is the first study to examine the influence of step-surface décor patterns with and without step-edge highlighters on stair descent characteristics in young and older adults.

4.1 State confidence and anxiety

Confidence was increased, and anxiety reduced, when step-edge highlighters were applied to all décor patterns. Of note is that Busy décor led to more anxiety compared to Plain and Striped décor, which was evident even with step-edge highlighters present. Of the patterns studied, therefore, Busy décor was the least optimal for promoting confidence and reducing anxiety. These findings align with previous observations of more confidence reported in young and older adults descending stairs in good light when compared to poor light (Thomas et al., 2020). In both cases, an improved ability to adequately view step hazards (stairs with step-edge highlighters/Plain décor or good lighting) significantly increased confidence prior to the task. In our previous lighting study, however, the participants reported no change to anxiety following stair descent in poor light (the step surfaces in that study were dull blue in colour and had no step-edge highlighters), which we suggested could have been due to bias from successful completion of the task. That is, no trips or falls occurred during testing. In contrast, the present participants reported significantly more anxiety, which reinforces the notion that décor can have a significant influence on how people perceive their safety on stairs, and that busier patterns may be inappropriate for creating a user-friendly environment. Moreover, a combination of poor lighting and busier patterns could be severely detrimental.

4.2 Descent speed and Margin of stability

Participants descended the stairs slower and increased their margin of stability with Busy décor compared to Plain décor, and during the middle phase, increased their margin of stability with Striped décor compared to Plain décor. Slower descent was also observed when edge highlighters were removed from all décor patterns, but this was specific to age group. In the middle phase, HAOA and LAOA older adults slowed, and in the exit phase, just HAOA. Slower stair descent and increased dynamic stability would be expected in conditions where it is more difficult to visually identify important features about steps (e.g. the edges of the steps, step height, and intended foot placement locations). Specifically, these adaptations, which are usually considered to be more cautious, allow more time to plan an appropriate foot placement based on the spatial layout of the steps, thus ensuring safer stepping. They also provide a more optimal position of the CoM in relation to the base of support to counter forward momentum during missteps. In support of this, previous studies of poor lighting (Thomas et al., 2020) and increased step heights (Novak et al., 2016), which can be considered as more challenging and/or risky, also led to slower descent speeds and increased margins of stability. It thus follows that Plain décor required the least adaptation to negotiate in all ages. Further, step-edge highlighters might be beneficial for older adults, at least in the middle phase of stair descent, and indeed for HAOA older adults in the exit phase, as removing them caused these age groups to descend slower.

Slower and more cautious descent with Busy décor (and the removal of step-edge highlighters in older adults) typically coincided with increased anxiety. This falls in line with previous work showing an increased fear of falling leads to slower stair descent in older adults (Tiedemann et al., 2007). The extent to which anxiety drives cautious descent is an ongoing debate. A noteworthy discrepancy between confidence and anxiety reported and descent strategies adopted was apparent in LAOA who did not alter descent speed with step-edge highlighters in the exit phase, despite reporting more confidence and less anxiety. This could stem from a disparity between confidence/anxiety and physiological ability. In previous work, some older adults have perceived themselves as being at a low risk of falling, but exhibited physiological characteristics suggesting a high risk (Delbaere et al., 2010). In the present work, LAOA might have felt more confident in the presence of edge highlighters but did not descend faster owing to inherent performance limits. Indeed, the exit phase is associated with increased task demands (Miyasike-daSilva and McIlroy, 2012) and is a common place for falls (Templer, 1992), and LAOA descended in this phase significantly slower than HAOA and Young overall.

LAOA who used the handrails exhibited smaller margins of stability. Additional safety gained from handrails as an earth fixed aid likely offset the need for bigger margins of stability, rather than relying solely on leg support like LAOA who avoided the handrails. Previous literature has shown older adults who are deemed at higher risk of falling use handrails to control their CoM during stair descent (Zietz et al., 2011). This prioritisation highlights the importance of appropriate handrails on stairs.

4.3 Heel clearance

Heel clearance was shown to increase over step edges with Plain décor when compared to Busy and Striped décor. In the middle phase, this was specific to HAOA and Young, whilst in the exit phase, all age groups increased their clearances. Also, in the middle phase, applying step edge highlighters increased foot clearances in HAOA and Young. Increased foot clearances over steps, in addition to better foot clearance precision (Foster et al., 2014b), is typically shown in conditions where walkers can delineate the edges of steps more easily, e.g. with the application of step-edge highlighters (Zietz et al., 2011). Therefore, bigger clearances might, to some extent, result from more accurate visuospatial representation of the steps and a better ability to extract self-motion characteristics from optic flow. Patterned décor, on the other hand, likely renders step edges more difficult to identify, and in which case would elicit more active visual sampling, which we provide evidence for below. Since increased foot clearance can reduce the chances of a trip and a fall, and the increases shown in our results were not detrimental to dynamic stability, they can be considered beneficial.

An import finding is that LAOA did not alter foot clearances to any décor or edge highlighter in the middle phase. Therefore, they seemed unable to adapt to steps with different patterns like the other participant groups. Previous work has shown similar results (Zietz et al., 2011). This could be related to reduced visual function in LAOA, since they possessed significantly less contrast sensitivity when compared to HAOA and Young. Therefore, there is a need to further examine the optimal design of step-edge highlighters regarding colour and contrast, particularly in lower ability older adults, in order to improve stair safety in this group. It should be noted that despite its apparent ineffectiveness for lower ability older adults, the addition of edge highlighters did nothing to compromise their safety. Due to increasing confidence, it might also promote independence in people who are generally deemed unlikely to fall on stairs.

4.4 Gaze

Participants tended to look further ahead with Plain décor when compared to Busy or Striped décor. The Busy and Striped décor, therefore, elicited more visual sampling at the steps closer to the walker, rather than more ‘covert’ detection of the steps through the lower peripheral visual field, like with Plain décor. It is thought that walkers tend to utilise more active visual sampling as task demands increase (such as stepping in balance critical circumstances; Marigold and Patla, 2007), which supports the notion that patterned décor is more visually ambiguous, and that foot clearances were increased with Plain décor due to better facilitation of the extraction of self-motion characteristics from optic flow. Recent data from Ellmers et al. (2020) may help further contextualise these results. Ellmers et al. (2020) show that older adults can prioritise visual scanning of their immediate walking path over future stepping constraints, and that this was associated with heightened fall-related anxiety. Since our participants reported more anxiety with patterned décor, looking fewer steps ahead may also have been (in part) driven by anxiety, in addition to simply facilitating more accurate extraction of the dimensions of the steps useful to guide descent. Distinguishing the relative contribution of anxiety would require further experimental manipulation.

It is perhaps surprising that there were no changes between the last gaze on a step and initial foot contact on that step, like the early transfers of gaze we detailed in the introduction (Chapman and Hollands, 2007, 2006). It is therefore likely that descending stairs (with an increased number of repetitive steps and more confined nature of the step dimensions) drives a somewhat different gaze-stepping relationship when compared to those targeted stepping tasks.

We also did not find evidence for a change in duration of fixation at each step. This suggests that stair walkers adopt a constant ‘time look-ahead’ window (as the gaze vector progresses from step to step), similar to that shown over varying complexities of terrain in real-world environments (Matthis et al., 2018).

From these results, it is clear that the lower peripheral visual field is intrinsically linked with how someone negotiates stairs. This has obvious implications for situations in which the lower peripheral visual field is occluded, either in full or in part, such as when carrying loads. Future work should assess the interplay between load carrying and the lower visual field during stair negotiation, which will elucidate more on visual control of stair negotiation and falls risk.

4.5 Limitations

A potential limitation following stratification of our older adults is that not each classified group contained only participants with high (or low) scores for each assessment. However, based on recent literature, this is expected. This is because older adults can show better function in certain areas (e.g. lower limb strength) whilst having worse outcomes in others (e.g. visual function), and these differences often vary between individuals (Ackermans et al., 2019). Therefore, even more advanced stratification techniques will classify groups that contain those with both high and low scores in different assessments. Therefore, we combined the measures to obtain two ‘general’ ability groups, and we chose them as they have all previously been shown to influence stair descent in older adults. Therefore, ignoring certain outcomes could have obscured a better classification regardless of a lack of significant differences in certain assessment results between groups. It should also be noted that the resulting risk profile was primarily a measure of physiological risk, and removing cognition from the stratification method had little influence on any statistical outcome based on internal testing. Therefore, it is unclear whether executive function does play a role in altered stair negotiation with patterned stair coverings. To inform future stratification methods, whilst elucidating more on the underlying mechanisms associated with altered stair descent in older adults, it would be necessary to examine the links between executive function and movement characteristics/reinvestment in demanding stair negotiation not explicitly associated with dual tasking.

Another potential limitation is that because we only assessed confidence and anxiety during the first trial of each new décor condition, there may have been increased confidence and reduced anxiety after successful completion of consecutive trials in each block (Zaback et al., 2019). Therefore, the responses from the first trial cannot be generalised to the entire block. However, by always assessing the first trial of each condition, we have kept this constant for the purposes of comparisons across blocks. We also feel that this was a necessary trade-off to preserve motivation and quality of the responses, as detailed in the methods.

5 Décor use

Plain décor with step-edge highlighters used in the present study was clearly beneficial for stair descent safety, as evidenced through improved confidence and anxiety, and stepping biomechanics outcomes. These are the first kinematic results to show how patterned décor can be detrimental to stair safety and offer insights into the causes of numerous case studies and reports of people falling on patterned stair coverings and steps with no visually defining features. The findings can be used as evidence to guide future stair safety design guidelines.

6 Conclusions and future directions

Patterned décor and steps with no edge highlighters led to more cautious stair descent, as evidenced by lower confidence, greater anxiety, slower descent, increased margins of stability, and more active visual sampling directed at the steps closer to the walker. These results suggest that stair descent is more demanding with patterned and potentially more visually ambiguous stair coverings. Importantly, there was an increase in foot clearances when a plain pattern was used which was further increased with edge highlighters in young and higher ability older adults, with no detrimental influence on dynamic stability. This may reduce the chances of unintentionally catching a foot on the step edge and falling. We therefore suggest plain décor is preferable in stair design, and that step-edge highlighters should be used to further the benefits. Future research should seek to determine the optimal design of step-edge highlighters in older adults with poor visual function who do not seem to adapt to step-surface visual properties, and the interactions of these with poor illumination.

7 Funding

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