The Next Step in Optimising the Stair Horizontal-Vertical Illusion: Does a Perception-Action Link Exist in Older Adults?

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Abbreviations: HV, Horizontal-vertical; MOS, Margins of stability; SF, Spatial frequency; LogMAR, Logarithm of the Minimum Angle of Resolution; LogCS, Logarithm of the contrast sensitivity; AP, anterior-posterior; ML, mediolateral; CoM, centre of mass; xCoM, extrapolated centre of mass; pCoM, anterior-posterior/mediolateral position of the centre of mass; *vCoM,* instantaneous anterior-posterior/mediolateral velocity of the CoM; *g,* acceleration due to gravity; *l,* absolute distance between the CoM and ankle joint centre

Abstract

Introduction: Tripping on stairs results from insufficient foot to step edge clearance and can often lead to a fall in older adults. A stair horizontal-vertical illusion is suggested to increase the perceived riser height of a step and increase foot clearance when stepping up. However, this perception-action link has not been empirically determined in older adults. Previous findings suggesting a perception-action effect have also been limited to a single step or a three-step staircase. On larger staircases, somatosensory learning of step heights may be greater which could override the illusory effect on the top step. Furthermore, the striped nature of the existing stair horizontal-vertical illusion is associated with visual stress and may not be aesthetically suitable for use on public stairs. These issues need resolving before potential future implementation on public stairs. **Methods:** *Experiment 1.* A series of four computer-based perception tests were conducted in older (N=14: 70 ± 6 years) and young adults (N=42: 24 ± 3 years) to test the influence of different illusion designs on stair riser height estimation. Participants compared images of stairs, with horizontal-vertical illusions or arbitrary designs on the bottom step, to a plain stair with different bottom step riser heights and selected the stair they perceived to have the tallest bottom riser. Horizontal-vertical illusions included a previously developed design and versions with modified spatial frequencies and mark space ratios. Perceived riser height differences were assessed between designs and between age groups. *Experiment 2.* To assess the perception-action link, sixteen older (70 ± 7 years) and fifteen young (24 ± 3 years) adults ascended a seven-step staircase with and without horizontal-vertical illusions tested in experiment 1 placed onto steps one and seven. Foot clearances were measured over each step. To determine whether changes in perception were linked to changes in foot clearance, perceived riser heights for each horizontal-vertical illusion were assessed using the perception test from experiment 1 before and after stair ascent. Additional measures to characterise stair safety included vertical foot clearance, margins of stability, foot overhang, stair speed, and gaze duration, which were assessed over all seven steps.

Results: *Experiment 1.* All horizontal-vertical illusion designs led to significant increases in the perceived riser height in both young and older adults (12-19% increase) with no differences between age groups. *Experiment 2.* On step 7, each horizontal-vertical illusion led to an increase in vertical foot clearance for young (up to 0.8cm) and older adults (up to 2.1cm). On step 1 significant increases in vertical foot clearance were found for a single horizontal-vertical illusion when compared to plain (1.19cm increase). The horizontal-vertical illusions caused significant increases in the perceived riser height (young; 13% increase, older; 11% increase) with no differences between illusion design, group or before and after stair ascent. No further differences were found for the remaining variables and steps.

Conclusion: Results indicate a perception-action link between perceived riser height and vertical foot clearance in response to modified versions of the horizontal-vertical illusion in both young and older adults. This was shown with no detriment to additional stair safety measures. Further evaluating these illusions on private/public stairs, especially those with inconsistently taller steps, may be beneficial to help improve stair safety for older adults.

Keywords: Stair falls; vision; horizontal-vertical illusion; older adults; perception

Declarations of interest: none

1. Introduction

For older adults (60 years and above), falling on stairs can lead to serious injuries or a fatal consequence (Jacobs, 2016). From 2019 to 2020, around 63% of all stair fall hospital admissions in England occurred in those aged 60 years and above (NHS Digital, 2020). Stair falls are considered to occur more during stair descent but falls during stair ascent still account for ~23% of all older adult stair falls (Startzell et al., 2000). When ascending stairs, a trip will often occur from insufficient clearance of the foot over a step edge (Lord et al., 1993; Berg et al., 1997) . The foot clearance height is linked to the visual judgement of step heights (Foster et al., 2015). Stairs can often be seen covered with patterns or uniform designs (Kim and Steinfeld, 2019) that render step edge locations difficult to discern. This could lead to uncertain judgements of step heights and result in foot to step edge clearances that are dangerously low and/or variable, as has been shown during stair descent when a step edge is misrepresented (Foster et al., 2014). For an older adult, ambiguity in stair appearance presents an added visual challenge on top of age-related declines in visual function such as reduced contrast sensitivity (Lord and Dayhew, 2001).

Studies have previously used a version of the horizontal-vertical (HV) illusion on a step to increase the perceived step riser height and foot to step edge clearance (Elliott et al., 2009; Foster et al., 2015). Findings show increases of ~20% in the perceived riser height and ~0.5-1cm increases in foot clearance at no detriment to balance (Foster et al., 2015). This illusion was developed on the basis of the original HV illusion whereby the vertical line in a figure T is perceived to be up to 20% longer than the horizontal line despite both being of equal length (Avery and Day, 1969). The increases in perceived riser height due to the illusion is believed to cause the increase in foot clearance which is thought to represent a perception-action link, though studies so far have not explicitly documented this link yet in older adults. Whilst increases in foot clearance alone have been found in younger and older adults (Elliott et al., 2009; Foster et al., 2015), the effect of the HV illusion on perceived riser height has only been tested in younger adults (Foster et al., 2015). The two visual streams hypothesis (Goodale and Milner, 1992) suggests the dorsal visual stream is specialised in controlling motor actions whilst the ventral visual stream is specialised for visual perception, though each stream is not entirely independent (Milner and Goodale, 2008). The stream specialisation suggests motor actions may not always correspond to conscious perceptual responses. Early studies mostly with the Ebbinghaus illusion support a disassociation of both streams, showing a perceptual effect on target circle size but not on maximum grip aperture when the circle is grasped (Aglioti, DeSouza and Goodale, 1995; Gentilucci et al., 1996). Subsequent investigations however support no stream dissociation when methodological factors (such as the perception measurement or presentation of the illusion) are controlled for (Smeets and Brenner, 2006; Franz and Gegenfurtner, 2008; Kopiske et al., 2016). Other illusions however (such as the Ponzo and Müller-Lyer illusion) show dissociations even when controlling for methodological factors (Westwood, Heath and Roy, 2000; Franz, Scharnowski and Gegenfurtner, 2005; Bruno, Bernardis and Gentilucci, 2008; Ganel, Tanzer and Goodale, 2008; Bruno and Franz, 2009; Stöttinger et al., 2010).

When negotiating steps or stairs, initial judgment of the step riser height and subsequent appropriate foot clearance is required to clear the step edge suggesting both ventral and dorsal stream processing are required for this movement. However, presence of illusions or visual cues on a step or obstacle to assess perception-action links during the stepping action provide contrasting findings. Rhea, Rietdyk and Haddad (2010) showed in young adults that the presence of a height illusion on obstacles led to initial increases in perceived obstacle height (2cm) and foot clearances (2.7cm) during obstacle crossings. However, whilst the obstacle remained perceptually taller following many repeated trials, foot clearance increases diminished, possibly due to somatosensory adaptation. Schofield, Curzon-Jones and Hollands (2017) showed that younger adults allowed greater toe clearance over curved steps superimposed with a fine-grained texture to represent an incorrectly illuminated step than they did over a textured step representing correct illumination. Older adults made no such adjustment and there were no matching differences in perceptual estimates of step height. Separate psychophysical assessments show older adults have reduced perceptual sensitivity to fine striped surface textures compared to young adults which is thought to explain the toe elevation differences. These studies show foot clearances can operate independently of perceptually taller steps/obstacles and relate to age losses in visual sensitivity and the repeated stepping actions.

It is not currently known whether ascending a staircase with many steps, or repeatedly ascending the same staircase, with the HV illusion present leads to a similar somatosensory adaptation as described by Rhea, Rietdyk and Haddad (2010) and/or perceptual adaption. The effect of the stair HV illusion may be lost following repeated physical foot contact on steps providing additional feedback about the step height (Chapman et al., 2010) in addition to the positional feedback from the raising of the lead limb. Findings demonstrating the effect of the stair HV illusion are from single raised surfaces or a three-step staircase (Elliott et al., 2009; Foster et al., 2015), meaning the evidence is supported for a limited number of steps only and not entirely for the top step on stairs with additional steps. This is important as stair falls most commonly occur on the transitional steps of stairs (first and last) (Startzell et al., 2000). If an effect still exists on stairs with several more steps, an understanding of whether this is linked to a corresponding step riser height perception should be explored to determine whether this adaptation occurred independently of perceptual information. This information will help to establish the conditions with which the HV illusion will be most effective on stairs.

Existing versions of the stair HV illusion include sine wave gratings (Elliott et al., 2009) and square wave gratings (with and without an additional top edge highlighter (Foster et al., 2015)) of varying spatial frequencies. Findings from young adults suggest the illusion is stronger as the spatial frequency increases (Foster et al., 2015), although this is likely to be limited by human visual acuity. Despite this correlative effect, a lower spatial frequency configuration may be easier for older adults to visually respond to. Schofield, Curzon-Jones and Hollands (2017) showed higher thresholds were needed for older adults to perceptually resolve finer textures due to declines in visual sensitivity. Increases in illusion spatial frequency result in concomitantly finer stripes (equidistant) which may place greater demand on visual acuity and contrast sensitivity to visually discriminate the square wave cycles on the gratings. Vision in older adults is typically reduced suggesting this may not be suited for this age group (Lord, 2006). The increased perceptual effect with increasing spatial frequency (Foster et al., 2015) suggests visual interpretation of the square wave cycle has importance. This additionally highlights the need for a perceptual assessment in older adults which is currently missing. Foster et al. (2015) selected a spatial frequency of twelve cycles per metre for increasing foot clearance on stairs, but also found perceptual and foot clearance increases (separately) at the lowest spatial frequency tested (four cycles per metre) on a single step, suggesting reduced designs still have a stair safety benefit. A design with modified features may also be better for those with photosensitivity to black and white stripes. The twelve-cycle design is characterised as a medium spatial frequency of black and white equidistant stripes with high luminance contrast. The combination of these visual properties in patterns can cause visual stress (such as nausea and dizziness) in observers, and in more severe cases photosensitive epilepsy and migraines (Wilkins et al., 1984; Hermes, Kasteleijn-Nolst Trenite and Winawer, 2017). A design with reduced features would also appear less complex which may be more aesthetically suitable for stairs where there is a preference to preserve appearance.

The aim of this study is two-fold; firstly, to determine whether there is a perception-action link between perceived step-riser height and foot clearance in older adults and to secondly determine whether modified versions of the HV illusion elicit effects suitable to enhance stepping safety. Two experiments were conducted to fulfil these aims. Experiment 1 included computer-based perception tests to assess perceived riser height responses to modified illusion designs. Experiment 2 included stair ascent assessments in response to illusion designs from experiment 1 and computer-based perception tests to identify links between foot clearance and perceived riser heights. For experiment 1, we hypothesised that HV illusions would increase perceived riser height and that this effect would be greater in young compared to older adults. For experiment 2, we hypothesised that young and older adults would show increases in perceived riser height and foot clearance in response to the HV illusions superimposed on stair-risers, and that this effect would be greater in young compared to older adults.

Experiment 1: Psychophysical Determination of Modified Stair HV Illusions

2. Method

2.1. Participants

Forty-two young adults and fourteen older adults (Table 1) were recruited from the university staff/student body and the local community and provided written informed consent to take part. Different young adults took part in the four sub-parts of this experiment (see below) and older adults only took part in experiment 1D. All participants were free from any neurological condition or low vision that would prevent them from being able to visually judge the height of step risers. Presence of low vision was assessed through tests of visual acuity and contrast sensitivity using The Freiburg Visual Acuity Test (Bach, 1996). Participants were excluded if scores were higher than 0.5 LogMar (WHO, 2019) for visual acuity, and lower than 1.5 LogCS (Parede et al., 2013) for contrast sensitivity. Statistical analysis showed young adults had better visual acuity (-0.08 ± 0.10 LogMar) than older adults (0.15 ± 0.37 LogMar) ($U = 39.5$, $p = .020$) and better contrast sensitivity (young: 1.95 ± 0.14, older: 1.67 ± 0.29 LogCS; $U = 25$, $p = .002$). Numerous tests were performed in experiment 1 therefore a sample size estimate was not performed. Such computer-based perception tests are often performed with small sample sizes to determine whether an effect is either present or absent (Anderson and Vingrys, 2001). This study received institutional ethical approval and conformed to the declaration of Helsinki.

Table 1. Participant demographics.

	Young	Older
No. of participants	42 (18 female)	14 (8 female)
Age (years)	24 ± 3 (range: 18-29)	70 ± 6 (range: 60-83)
Visual Acuity (LogMAR)	-0.08 ± 0.10*	0.15 ± 0.37
Contrast Sensitivity (LogCS)	1.95 ± 0.14*	1.67 ± 0.29

* = significant difference from a Mann-Whitney U test between young and older adults (Visual Acuity: $U = 39.5$, $p = .020$; Contrast Sensitivity: $U = 25$, $p = .002$).

2.2. *Experimental design*

We assessed perceived step riser heights on images of an outlined three-step staircase with bottom step HV illusions or arbitrary designs. A linked series of four computer-based perception tests (experiments 1A-D) were performed, using a forced choice psychophysical procedure, programmed in PsychoPy (Peirce et al., 2019). The HV illusion effect was firstly ascertained by replicating the previous design developed by (Foster et al., 2015) and by comparing differences in perceptual response to arbitrary patterns (experiment 1A) as well as through comparisons to reference steps with edge highlighters to assess its contribution to the perceptual effect (experiment 1B). The assessment of modified HV illusion designs included HV illusions with a reduced spatial frequency/number of vertical stripes (experiment 1B: representing a better visual aesthetic) and modified mark space ratios (experiment 1C: to reduce the visual stress potentially associated with the illusion). Four HV illusion designs from these perception tests were then chosen based on the presence of a perceptual effect, the design saliency and aesthetic and were used to assess perceptual differences between young and older adults (experiment 1D). Figure 1 shows the different step riser designs used and the participants for each perception test.

For each trial, participants were asked to compare an image of an outlined stair that had a fixed-height bottom riser with a HV illusion pattern or arbitrary design (test stimulus) to an image of a plain outlined stair (reference stimulus) that varied in bottom riser height (to control for response bias) and to then select the stair that appeared to have the taller bottom riser through a keyboard response. Each HV illusion was presented in its full form (vertical stripe(s) with an abutting step edge highlighter (see Figure 1) to maximise the perceptual effect (Foster et al., 2015)). This represented a treated step.

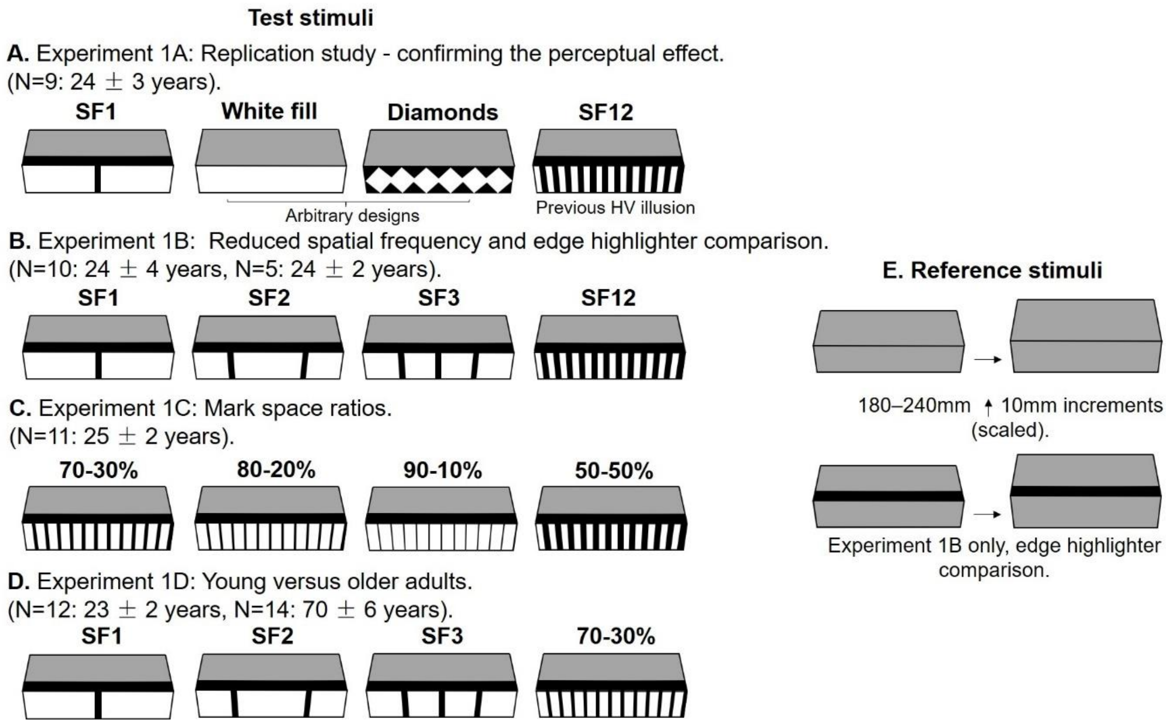

Figure 1. Bottom step riser designs (test stimuli) compared to plain bottom risers (reference stimuli) within each perception test. Test stimuli in experiment 1B were additionally compared to reference stimuli with edge highlighters. SF12 = previously developed HV illusion in young adults (Foster et al., 2015). All other HV illusions represent modified designs for a simpler appearance or to reduce the photosensitive trigger for the visual stress potential. Test and reference stimuli were presented over a grey background on screen, represented as grey fill on the steps. Numerical percentages represent the occupied space of white to black (mark space ratio) respectively on the riser. Young adults were used in experiments 1A-1C to preserve older adult recruitment for the age group comparison (experiment 1D). NB: SF= spatial frequency.

For experiments 1A, 1C and 1D, reference steps appeared plain to represent an untreated step and to represent how stairs would typically appear in the real world. For experiment 1B reference steps included an edge highlighter to assess the perceptual effect when the presence of edge highlighters were matched. Each stair appeared in succession on screen for 500ms in a randomised order with a 1000ms interval between the two stimuli in each trial.

Each perception test followed this trial procedure and contained four different test stimuli and seven reference stimuli which represented scaled riser heights found on physical stairs (test stimuli = 190mm, reference stimuli = 180 to 240mm in 10mm increments). Participants were positioned 33cm away from the monitor at a perpendicular eye level to the computer screen (BenQ XL2430 -B) to represent the viewing of physical steps from a distance of 1.4m away at an eye height of 1.6m (approximating that of an average older adult height; Elliott et al. (2015)). For all participants in experiments 1A-1C and the first five older adults in experiment 1D, 560 responses were initially obtained over four equal sittings of 140 trials. For each sitting, test stimuli were compared to each reference stimuli five times totalling 20 comparisons at each reference stimuli level across all sittings. Combinations of test and reference stimuli were randomised across trials such that all combinations appeared equally often. Statistical analysis (One-way Repeated Measures ANOVA: α=.05) revealed no differences in perceived riser heights between sittings for each experiment (P>.05), therefore the remaining participants in experiment 1D were instead asked to complete a minimum of one sitting but to then complete more if they were happy to do so. Data were recorded as binary responses (1 = test stimuli taller, 0 = reference stimuli taller) and were exported as CSV files.

2.3. Statistical analysis

A logistic function was fitted to the test stimuli taller responses plotted against the reference stimuli heights to estimate the perceived riser height of each test stimulus. Perceived riser height/point of subjective equality (PSE) was established as the point at which the test stimuli was judged taller on 50% of the trials. A One-way Repeated Measures ANOVA (α=.05) was used to compare perceived riser heights between test stimuli (experiment 1A-1C). A Two-way Repeated Measures ANOVA (α=.05) was used to compare perceived riser heights between test stimuli and age groups (experiment 1D). Following ANOVA testing, Bayes Factors were computed for experiment 1D to determine whether non-significance in perceived riser heights between test stimuli as well as age group were driven by similarities. A Bayesian Two Way Repeated Measures ANOVA using JASP with default priors (JASP Team (2020). JASP (Version 0.14.1) [Windows 10]) was performed with test stimuli and age group as factors. Bayes Factors (expressed as BF_{01}) are reported showing the probability of the data given the null hypothesis relative to the alternative. Lee and Wagenmakers classification scheme indicating levels of evidence was used for Bayes Factor interpretation (Quintana and Williams, 2018). Residual plots were used to visually inspect all variables for normality. Data sphericity was assessed using Mauchly's test of Sphericity. When data violated the estimate of sphericity, a Greenhouse-Geisser (<0.75) or Huynh-Feldt (>0.75) epsilon correction was used. Significant main effects were followed with post-hoc tests using a Bonferroni correction for multiple comparisons. In the presence of non-significance between test stimuli, data were pooled across test stimuli and a One Sample t test was used to compare the pooled perceived riser heights to the veridical riser height. For comparisons with repeated One Sample t tests, the alpha level was divided by the number of comparisons (experiment 1A α=.013; experiment 1B-1D α=.05). All frequentist statistical analyses were performed in SPSS 26 (SPSS version 26.0 IBM Corp, 2019).

3. Results

Figure 2 shows the perceived riser heights for each test stimulus from each experiment.

3.1. Experiment 1A: Replication study - confirming the perceptual effect

There was a significant main effect of test stimulus on perceived riser height ($F_{(1.214, 9.711)}$=34.218, $p<.001$, n^2_p=.811). SF1 and SF12 were perceived to be significantly taller than White fill (SF1=13%, p=.003; SF12=13%, p=.006) and Diamonds (SF1=18%, p=.001; SF12=18%, p=.002). White fill was perceived to be taller than Diamonds (p=.005). SF1 and SF12 led to significant overestimations in perceived riser height (19% increase from veridical riser height; $p<.001$). White fill was perceived to be taller than the veridical height (p=.001). No significant differences in perceived riser height were found between Diamonds and the veridical riser height (p=.505).

3.2. Experiment 1B: Reduced spatial frequency and edge highlighter comparison

No significant differences were found between each test stimulus for perceived riser height when compared to the plain reference stimulus ($F_{(3, 27)}$=1.672, p=.196, n^2_p=.157) and plain reference stimulus with an edge highlighter ($F_{(3, 12)}$=1.741, p=.212, n^2_p=.303). All spatial frequencies (SF1, SF2, SF3 and SF12) caused significant increases in the perceived riser heights when compared to the veridical riser height. However, the increases in perceived riser height were bigger when the test stimuli were compared to the plain stimulus with no edge highlighter (15-17% increase; p<.001), compared to the plain stimulus with an edge highlighter (6-9% increase; p =.024).

3.3. Experiment 1C: Mark space ratios

No significant differences in perceived riser height were found between each test stimulus ($F_{(1.813, 18.127)}$=.734, p=.481, n^2_p=.068). All mark-space ratios led to a significant increase in the perceived riser height when compared to the veridical riser height (16-18% increase; p=<.001).

3.4. Experiment 1D: Young versus older adults

There were no interaction effects of test stimuli and age group ($F_{(3, 72)}$=.829, p=.482, n^2_p=.033). No main effects were found for test stimuli ($F_{(3, 72)}$=.921, p=.435, n^2_p=.037) or for age group ($F_{(1, 24)}$=1.455, p=.239, n^2_p=.057). When compared to the veridical riser height, the pooled test stimuli led to a significant increase in the perceived riser height (12-15% increase; p<*.001*). Further investigation into the lack of main and interaction effects for test stimuli and age group using Bayesian inference showed the effect of age group and test stimuli to be 1.3 (BF_{01}= 1.349) and 6.3 (BF_{01}= 6.386) times more likely under the null hypothesis, representing anecdotal and moderate evidence respectively. The age group and test stimuli interaction was found to be 4.9 times more likely under the null hypothesis (BF_{01}= 4.981) representing moderate evidence.

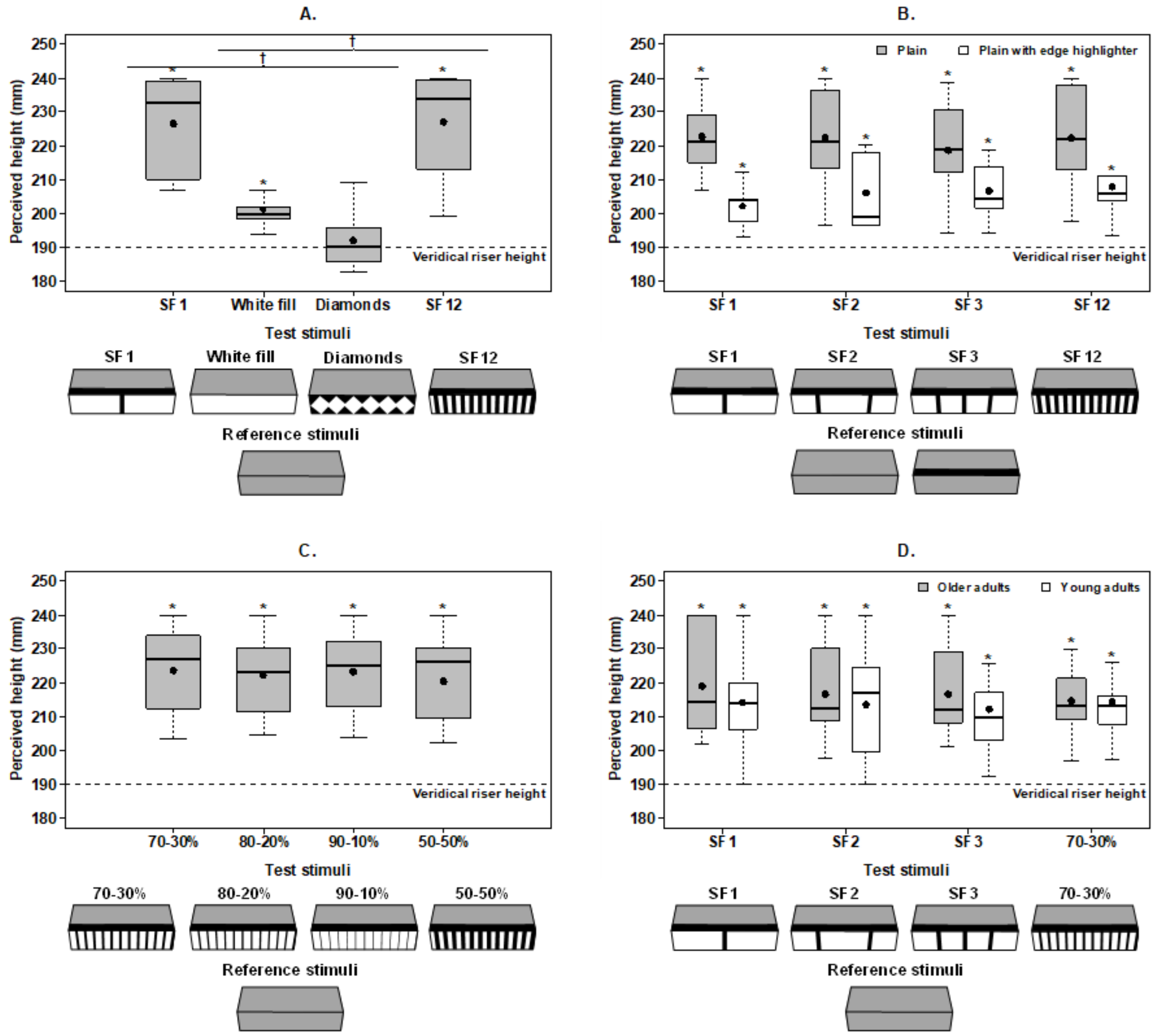

Figure 2. Perceptual responses to different test stimuli designs. A. Replication study - confirming the perceptual effect. B. Reduced spatial frequency and edge highlighter comparison. C. Mark space ratios. D. Young versus older adults. Each of the HV illusion designs led to a significant increase in the perceived riser height. Box plots present the mean (●) and median (–). * = Significant increase from the veridical riser height. † = significant difference between test stimuli.

4. Discussion

The main aim of experiment 1 was to assess whether the stair HV illusion was effective at increasing perceived riser heights, primarily in older adults. We hypothesised that the HV illusions would increase perceived riser heights in both young and older adults, but to a greater extent in young adults. The results show that modified versions of the HV illusion led to increases in the perceived riser height in both young and older adults with no difference between young and older adults. Our Bayes Factors show limited evidence for our no difference finding being driven by similarity. Our hypothesis is therefore partly supported.

The increased perceived riser heights with the HV illusions compared to the arbitrary designs in experiment 1A suggests the overestimations were due to the configuration of the stair HV illusion (i.e. the presence of vertical stripes with an abutting top edge highlighter). This is also strengthened by our HV illusion comparison to an edge highlighter reference stimulus (experiment 1B), whereby a reduced but significant increase in the perceived riser height was still observed. Reduced overestimations suggest the overall HV illusion effect is partly due to the edge highlighter which is consistent with Foster et al. (2015) who showed that edge highlighters present with vertical riser gratings reinforces the HV illusion, producing the greatest magnitude of riser height overestimation. The magnitude of overestimations found in this study are also similar to Foster et al. (2015) findings. These authors reported magnitudes of ~20% for HV illusion designs with spatial frequencies of four through to twenty cycles per metre. Interestingly, the White fill arbitrary pattern we tested in experiment 1A also elicited a perceptual effect as this was perceived to be significantly taller than the veridical height. A similar effect was reported by Rhea, Rietdyk and Haddad (2010) where a full obstacle was perceived to be taller than a perimeter obstacle. This is akin to our step comparisons whereby our reference stimuli unknowingly also represents the perimeter of a step and our White fill represents a full step.

Experiment 1B showed similar overestimation magnitudes across all spatial frequencies whereas Foster et al. (2015) showed a general pattern for larger overestimations as the spatial frequency increased. This discrepancy may have resulted due to the stripe widths. Foster et al. (2015) used an equidistant grating configuration for each HV illusion design meaning their lowest spatial frequency configuration (four cycles) had wider stripes on the riser. Our lower spatial frequency configurations (SF1, SF2 and SF3) had black stripe widths equal to SF12, suggesting the overall perceptual effect is partly due to the stripe width. Other perception work shows rectangles of the same height are perceived taller when narrower and shorter when wider (Beck, Emanuele and Savazzi, 2013). This effect may have been present here with the riser stripes (viewed as rectangles). There may however be an upper ceiling effect with how much the stripe width contributes to the overall effect, as we did not find differences between our mark space ratios which represented a stripe width manipulation at the same spatial frequency. A significant perceptual effect with as few as one black riser stripe fulfils part of our aim in developing a design with reduced features which may be more aesthetically suitable for public use. Our mark space ratio findings in experiment 1C also show that the HV illusion design used previously (Foster et al., 2015) can be adapted to be more acceptable to those with visual stress and photosensitivity whilst retaining the perceptual effect at the same spatial frequency. High luminance contrast and equal mark-space widths are contributing factors in photosensitivity (Hermes, Kasteleijn-Nolst Trenite and Winawer, 2017). Importantly, the mark space ratio adjustments we used in experiment 1C reduces the luminance contrast of the HV illusion design. For experiment 1D, the HV illusions led to significant increases in riser height estimation across all designs. Furthermore, the lack of significant difference between age groups, despite significant differences in visual function, suggests the configurations of each HV illusion design are sufficient to elicit a perceptual effect in older adults despite the design reductions and modifications made.

Overall, experiment 1 established that modified HV illusion designs effectively increased perceived riser height, and that older adults perceptually respond to these illusions. The next experiment examined whether increases in perceived riser height led to physical increases in foot clearance in older adults on a seven-step staircase using modified HV illusions from experiment 1.

Experiment 2: Stair Analysis of Foot Clearance and Perceived Riser Heights

5. Method

5.1. Participants

Fifteen young adults and sixteen older adults (Table 2) were recruited from the University staff/student body and the local community and provided written informed consent to participate. A power analysis based on previous data (Foster et al., 2015) for the detection of a meaningful change in vertical toe clearance over a step edge, in response to a striped visual cue showed 14 participants were required (mean difference= 1.6, $\sigma = 1.95$, $\alpha = 0.05$, power = 80%). All participants met inclusion criteria for neurological and visual function described in experiment 1 and were free from any physical injury that would prevent them negotiating stairs. Tests of visual function were performed using the method outlined in experiment 1. This study was approved by the institutional research ethics committee and conformed to the Declaration of Helsinki.

Table 2. Participant demographics.

	Young	Older
No. of participants	15 (10 female)	16 (7 female)
Age (years)	24 ± 3 (range: 20-30)	70 ± 7 (range: 60-84)
Height (m)	1.62 ± 0.43	1.66 ± 0.84
Mass (kg)	69.69 ± 11.80	68.49 ± 16.46
Visual Acuity (LogMAR)	-0.06 ± 0.30*	0.13 ± 0.17
Contrast Sensitivity (LogCS)	1.83 ± 0.24	1.70 ± 0.24

* = significant difference from a Mann-Whitney U test comparing visual acuity between young and older adults ($U = 33$, $p =<.001$).

5.2. Experimental design

To determine i) how changes in perceived riser height link to changes in foot clearance, and ii) whether repeated stepping interactions with the HV illusion on physical stairs led to changes in perception, participants completed the previously described psychophysical assessment (experiment 1D) before and following the stair ascent assessment.

Participants were asked to ascend a seven-step custom-built instrumented staircase at a self-selected speed under five different stair visual conditions. Each HV illusion design from the previous experiment 1D (Figure 2; 70-30% design referred herein as SF12) represented an individual condition alongside a plain condition (control). These designs were selected based upon the presence of a perceptual effect in older adults from experiment 1D. Figure 3 shows examples of how the HV illusions appeared on the staircase. Three successful ascent trials were collected for each visual condition (totalling fifteen trials) which were performed consecutively as a block and randomised for each participant. For each block condition, the HV illusion design was superimposed onto the first and last step as these represent transitional steps where most trips/falls occur (Startzell et al., 2000). Participants began each trial approximately two/three steps away from the staircase from the same fixed position. Participants were instructed to cross the first step with the same self-selected foot for each trial, ascend the stairs in a step overstep manner and continue walking to the end of the top landing after crossing the last step. Participants were free to use the handrails if preferred. Following the completion of a trial, participants were asked to walk back down the stairs to the starting position and to step over one or two low-height obstacles placed on the starting walkway to disrupt any somatosensory interference from the stair descent (Foster et al., 2015). When changing visual condition, participants were instructed to look away from the staircase to minimise out-of-trial visuomotor planning. When on the stairs, participants were secured into an overhead safety harness operated by a trained belayer positioned adjacent to the staircase. Participants were asked to wear tight fitted clothing, flat soled shoes and were familiarised with the testing protocol prior to data collection. Rest periods between trials were offered throughout and the data collection took place in a single session lasting two hours.

For visual consistency, the laboratory staircase was covered with a commercially available grey covering to create a uniform appearance. Each step had a riser height of 20cm and a going length of 25cm which falls within current stair building regulations (Gov, 2010). Each of the HV illusion designs were paper printed in a matte finish, cut to size and reinforced onto card. A black 5.5cm edge highlighter (size conforming to building regulations) was placed onto the going above the riser abutted to the step edge to complete each HV illusion design (Foster et al., 2014; Foster et al., 2015). All other steps (steps 2-6) remained plain with the grey covering.

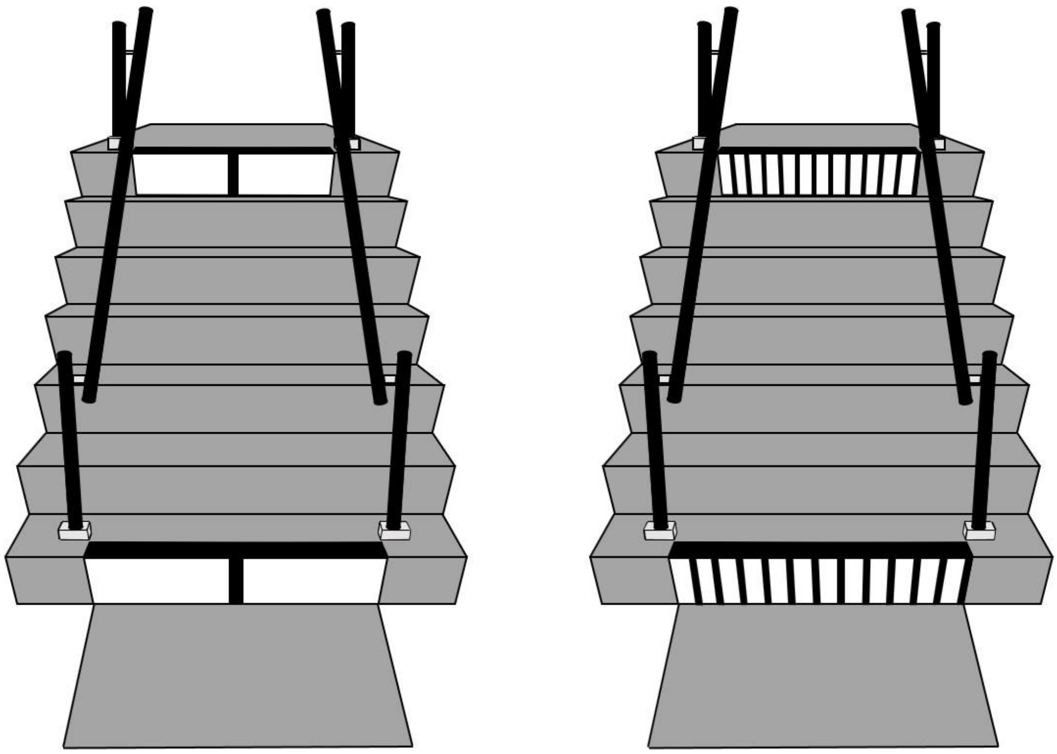

Figure 3. Examples of the HV illusion (SF1 and SF12) superimposed onto the first and last step of a seven-step staircase with handrails.

5.3. Data collection

A 26-camera motion capture system (Vicon MX, Oxford Metrics, UK) captured whole body kinematics at 120 Hz. The conventional Plug-in Gait marker set was used to model whole body kinematics with additional markers and clusters placed on the head and lower limbs for marker redundancy and to avoid occlusion from stair apparatus. A static calibration (anatomical pose) was captured to acquire whole body marker coordinates. A digitising wand (C-Motion, Germantown, MD, USA) was used to create virtual landmarks on the toe and heel-tips of participants' shoes in a separate dedicated capture. Toe-tip landmarks were created on the most anterior, inferior aspect of the shoe, heel-tip landmarks were created at the most posterior, inferior aspect of the shoe. The digitising wand was also used to create virtual landmarks that defined the location of each individual step edge on the staircase.

Previous video analysis indicates one of the differences between fallers and non-fallers results from insufficient visual scanning of stairs (Templer, 1995). Gaze duration was therefore measured using a mobile binocular eye tracker (Pupil Labs Core, Pupil Labs, Berlin) to assess whether the presence of the HV illusions on steps attract greater visual attention. The eye tracker cameras were adjusted, calibrated, and validated for each participant prior to stair ascent trials and captured gaze activity at 120Hz. No eye tracking was used with participants wearing contact lenses or glasses to avoid potential distortion of the pupil image captured from the eye cameras.

5.4. Data processing & analysis

All marker data were labelled, and gap filled in Vicon (Vicon Nexus 2.6, Oxford Metrics), and exported as c3d files for analysis using Visual 3D (C-Motion, Germantown, MD, USA). Raw gaze data were filtered with the Pupil Labs offline fixation detector (2° maximum dispersion angle, 60ms minimum duration) and then subsequently analysed in Pupil Player software. Step fixations were defined as continuous gaze for a minimum of two video frames on either the riser or going of the step. Gaze was considered to be directed onto a step when half of the gaze circle was overlapping a step.

Marker data were filtered using a fourth order Butterworth bidirectional filter (cut-off frequency 6Hz). In addition to lead vertical foot clearance, we measured margins of stability (MOS) in the anterior-posterior (AP) and mediolateral (ML) directions, foot overhang and stair speed. These measures determined whether the mismatch of information from the perceived riser height and the actual riser height from the HV illusions disrupted normal dynamic stability and stepping characteristics. Outcome measures were calculated on each of the seven steps. Lead vertical foot clearance, defined as the vertical distance of the virtual toe tip landmark to the step edge was extracted at the point where the difference in AP position between the step edge and virtual toe tip landmark was zero. Whole body centre of mass (CoM) was generated as a link model-based item in Visual 3D. Stair speed was calculated as the first derivative of the CoM AP trajectory from the start of the trial to initial contact on the top landing of the trailing foot. MOS were calculated and defined in the AP direction as the distance between the extrapolated CoM (*xCoM*) and the virtual toe tip landmark and in the ML direction as the distance between the *xCoM* and 5th Metatarsal head (Hof, Gazendam and Sinke, 2005; Bosse et al., 2012; Novak et al., 2016).

xCoM was defined as:

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

where *pCoM* is the AP/ML position of the CoM, *vCoM* is the instantaneous AP/ML velocity of the CoM, *g* is acceleration due to gravity, and *l* is the absolute distance between the CoM and the ankle joint centre.

MOS were calculated at the point of lead vertical foot clearance over each step which represents the most hazardous point for a trip. Foot overhang was defined as the distance between the virtual heel tip landmark and the virtual step edge location(s), calculated as a percentage of foot length. Gaze duration was calculated for each step as percentages of the trial summed fixation duration. Due to technical issues with tracking of the pupil during the stair movement (for example, gaze being directed below the cameras), gaze data for young adults was discarded and data from six older adults were excluded from analysis.

5.5. Statistical analysis

A Two Way Mixed ANOVA compared kinematic variables for within-subject effects of visual condition (x5: plain, SF1, SF2, SF3, SF12), between-subject effects of age group (x2: young and older adult) and interactions between visual condition and age group. For gaze data, a One Way Repeated Measures ANOVA compared total step gaze durations for older adults within-subject effects of visual condition. Separate ANOVAs were performed for each of the seven steps. Residual plots were used to visually inspect all variables for normality. Data sphericity was assessed using Mauchly's test of Sphericity. When data violated sphericity, a Greenhouse-

Geisser (<0.75) or Huynh-Feldt (>0.75) epsilon correction was used. Significant main effects were followed with post-hoc tests using a Bonferroni correction for multiple comparisons. For the computer-based perception tests, a Three Way Mixed ANOVA compared perceptual responses for within-subject effects of test stimulus, (x4: SF1, SF2, SF3 and SF12), time (x2: pre and post stair ascent), and between-subject effects of age group (x2: young and older). In the presence of non-significance between test stimuli, data were pooled across test stimuli and time within each group and a One Sample t test was used to compare the pooled perceived riser height of the test stimuli to the veridical step height. Following ANOVA testing, Bayes Factors were computed for the perception test to determine whether non-significance in perceived riser heights between test stimuli as well as age group and time were driven by similarities. A Bayesian Three Way Repeated Measures ANOVA using JASP with default priors (JASP Team (2020). JASP (Version 0.14.1) [Windows 10]) was performed with test stimuli, age group and time as factors. Bayes Factors (expressed as BF_{01}) are reported showing the probability of the data given the null hypothesis relative to the alternative and were interpreted using the Lee and Wagenmaker's classification scheme indicating levels of evidence (Quintana and Williams, 2018). Calculation of the PSE followed the same procedure outlined in experiment 1. All frequentist statistical analyses were performed in SPSS 26 (SPSS version 26.0 IBM Corp, 2019) with an alpha level of .05.

Five older adults and one young adult preferred to use the handrail during the stair ascent trials which may influence dynamic stability, therefore data from these participants were not included in statistical comparisons for MOS. In the perception tests, five older adults and four young adults showed a very high proportion of test stimulus taller responses, skewing the typical response distribution required for an accurate PSE. These data were therefore removed from all the statistical comparisons.

6. Results

6.1. Lead vertical foot clearance

Figure 4 shows vertical foot clearances across each visual condition and each individual step. There was a visual condition-by-age interaction effect on vertical foot clearance on step 7 ($F_{(4, 116)}=5.431$, $p<.001$, $n^2_p=.158$). Each visual condition led to an increase in vertical foot clearance for young and older adults when compared to the plain condition, but this increase was greater in older adults (1.2-2.1cm) compared to young (0.2-0.8cm). There was also a significant main effect of visual condition on lead vertical foot clearance on step 1 ($F_{(2.611, 75.731)}$=6.36, *p*=.001, n^2_p=.18). SF12 increased lead vertical foot clearance by 1.19 cm when compared to plain (*p*=.017) and increased by 1.16 cm when compared to SF1 (*p*=.033). No other differences between visual condition on step 1 were found.

6.2. Computer based perception tests

The Three-way mixed ANOVA did not find any interaction effects ($F_{(3, 63)}$=2.396, *p*=.077, n^2_p=.102), main effects between test stimuli ($F_{(3, 63)}$=2.462, *p*=.071, n^2_p=.105) , between groups ($F_{(1, 21)}$=1.439, *p*=.244, n^2_p=.064) or between time points ($F_{(1, 21)}$=.002, *p*=.969, n^2_p=.000). Data for each test stimulus and time were subsequently pooled for each group and compared to the veridical riser height. The test stimuli led to a significant overestimation of the riser height when compared to the veridical riser height in older adults (11% increase; *p*<.001) and young adults (13% increase; *p*<.001). Further investigation into the lack of main and interaction effects for test stimuli, age group and time using Bayesian inference showed the effect of test stimuli was 2.2 (BF_{01}= 0.453) times more likely under the alternate hypothesis than the null representing anecdotal evidence. The effect of age group and time were found to be 1.4 (BF_{01}= 1.459) and 2.3 (BF_{01}= 2.352) times more likely under the null hypothesis, each representing anecdotal evidence. The best performing interaction model of test stimuli, age group and time was found to be 3.2 (BF_{01}= 3.233) times more likely under the null hypothesis representing moderate evidence.

6.3. MOS, foot overhang, gaze and stair speed

Table 2 shows values for MOS, foot overhang and gaze duration for step 1 and step 7 across visual conditions. MOS remained unaffected by the visual conditions across all steps for both groups (*p*>.05). No differences were observed in foot overhang across visual conditions, steps or group (*p*>.05). Gaze duration on each step was not significantly different across each of the visual conditions (*p*>.05). Stair ascent speed was not significantly different between visual conditions or between groups (Older: 0.484-0.511 $m.s^{-1}$, young: 0.539-0.545 $m.s^{-1}$; *p*>.05).

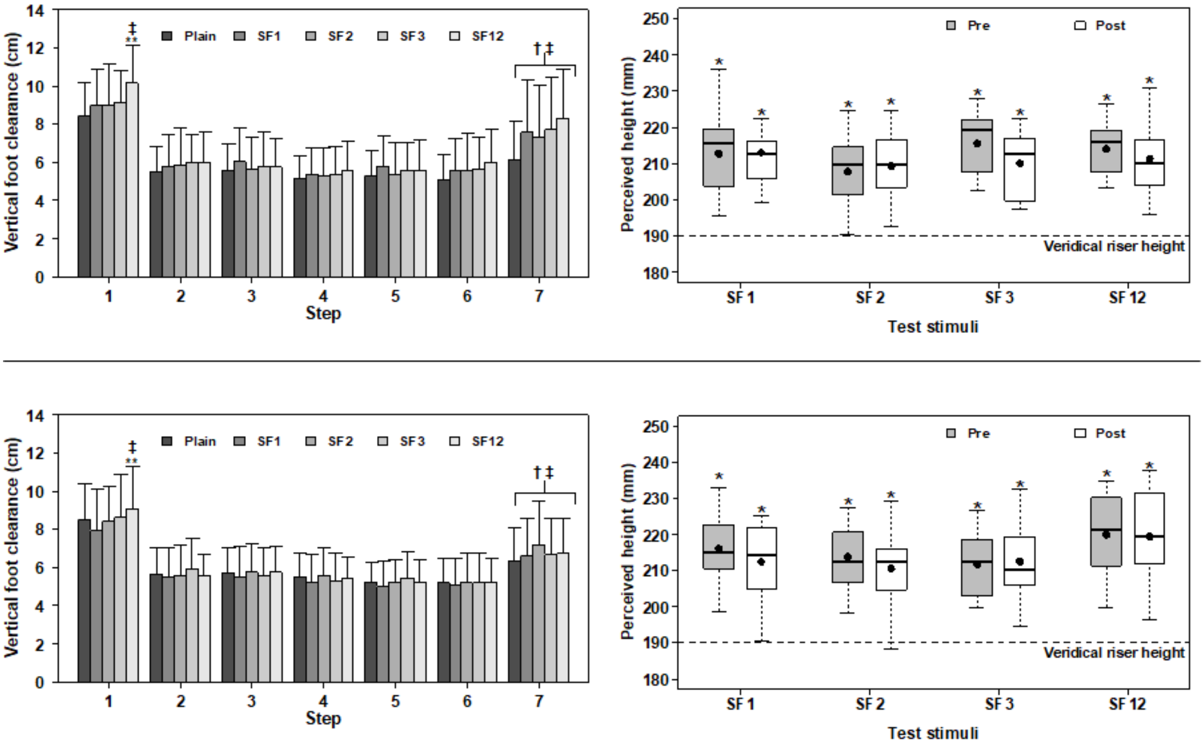

Figure 4. Older (top panel) and young (bottom panel) lead vertical foot clearances over seven steps and perceived riser heights in response to each HV illusion. Box plots present the mean (●) and median (–). † Denotes an interaction effect of visual condition and age on step 7. For both groups on step 7, each HV illusion led to increased vertical foot clearances compared to plain, with greater increases in older adults compared to young. ‡ Denotes significant increases in vertical foot clearance across all HV illusions on step 7, and SF12 for step 1 when compared to plain. ** Represents significant increases in vertical foot clearance on step 1 with SF12 compared to SF1. * Denotes significant increases in perceived riser height compared to veridical riser height across test stimuli for young and older adults.

Table 3. MOS, foot overhang and gaze durations on step 1 and step 7 across visual conditions. Negative and positive MOS values represent an extrapolated centre of mass ahead (A/P) and inside (M/L) the boundary of support respectively. Foot overhang values represent percentages of foot length, with negative values indicating no overhang. Gaze duration values represent percentage of total fixation durations summed.

	Step 1					Step 7				
	Plain	**SF1**	**SF2**	**SF3**	**SF12**	**Plain**	**SF1**	**SF2**	**SF3**	**SF12**
MOS A/P (m)										
Older	-0.13 ± 0.06	-0.14 ± 0.06	-0.15 ± 0.07	-0.14 ± 0.06	-0.12 ± 0.07	-0.11 ± 0.03	-0.13 ± 0.04	-0.13 ± 0.04	-0.13 ± 0.04	-0.12 ± 0.05
Young	-0.13 ± 0.07	-0.13 ± 0.06	-0.12 ± 0.06	-0.12 ± 0.06	-0.13 ± 0.07	-0.16 ± 0.04	-0.17 ± 0.04	-0.17 ± 0.04	-0.16 ± 0.03	-0.16 ± 0.04
MOS M/L (m)										
Older	0.11 ± 0.02	0.10 ± 0.02	0.11 ± 0.01	0.11 ± 0.02	0.10 ± 0.02	0.10 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.10 ± 0.02	0.10 ± 0.02
Young	0.11 ± 0.01	0.11 ± 0.01	0.10 ± 0.02	0.10 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.11 ± 0.01	0.11 ± 0.02
Foot overhang (%)										
Older	27.42 ± 17.91	26.46 ± 11.57	26.33 ± 13.51	26.76 ± 11.03	24.83 ± 14.75	-42.71 ± 28.88	-49.86 ± 32.47	-50.50 ± 30.62	-50.86 ± 28.68	-51.00 ± 26.52
Young	28.17 ± 7.34	28.94 ± 6.35	27.69 ± 6.56	30.17 ± 15.18	27.95 ± 8.71	-58.07 ± 33.96	-54.92 ± 33.85	-61.83 ± 36.36	-58.14 ± 37.89	-52.77 ± 34.25
Gaze duration (%)										
Older	17.72 ± 14.11	16.21 ± 12.45	18.09 ± 13.72	15.03 ± 9.54	21.18 ± 11.20	17.21 ± 8.90	21.95 ± 9.94	21.79 ± 12.02	19.64 ± 11.40	17.75 ± 11.56

7. Discussion

The main aim of this experiment was to assess the perception-action link between perceived riser height and foot clearance in response to modified HV illusion designs, primarily in older adults. We hypothesised that both young and older adults would show increases in perceived riser height and foot clearance, but to a greater extent in young adults. Findings show increases in perceived riser height with no age group differences and increases in foot clearance in both age groups, though older adults showed larger increases in foot clearance compared to young. Our hypothesis is therefore partly supported.

The findings here show indications of a perception-action link in older and young adults responding to the stair HV illusions. We found increases in foot clearance across all HV illusions on step 7 and with SF12 on step 1 alongside increases in perceived riser heights that remained unaffected after exposure to ascending stairs with the illusion. This perception-action link is notable for step 7, where a foot clearance increase occurred despite the increased step contacts from a longer staircase, suggesting somatosensory information here does not override the visual effects of the illusion. This may also mean that increases in foot clearance may still occur if stairs with superimposed HV illusions are encountered again by a stair user, though this requires further testing. The increases in foot clearance varied in magnitude dependent upon the HV illusion design. For step 1, SF12 resulted in a significant and larger increase in foot clearance whereas the remaining illusions resulted in foot clearances that did not increase significantly compared to plain. On step 7, SF12 resulted in the largest increase in foot clearance compared to the other designs. The foot clearance changes in response to the HV illusions here are akin to Foster et al. (2015) showing increased foot clearances with higher spatial frequency designs. We show here however significant increases in the perceived riser height with no significant differences between each visual condition from the perception test. The smaller foot clearances with SF1, SF2 and SF3 and statistical significance on step 7 only, therefore suggests the perception-action link for these HV illusions is not as strong when compared to SF12. For applications on public/private stairs, this may suggest a balancing of aesthetic design and foot clearance effect should be considered, i.e. for the simplest design (SF1) an increased foot clearance is still possible, though a stronger effect (and link between perception and action) will be achieved with a slightly more featured design (SF12). This could be beneficial for choosing on stairs with extensive history of falls or where step inconsistencies mean that one step is slightly raised compared to the rest. The HV illusion designs may also have the added benefit of aiding safe stair descent as it incorporates an edge highlighter, positioned on the tread-edge, which helps for delineating a step edge during descent and may lead to safer foot clearances (Foster et al., 2014).

Increases in foot clearance were found to be greater in older adults (2.1cm) than in young 0.8cm) in response to HV illusions. The foot clearance magnitudes we report are similar to Elliott et al. (2009), where a 0.5cm increase in young adults was found on a single step, and Foster et al. (2015) where up to a 2cm increase in older adults was found. These age differences in foot clearances have similarly been found by Lu, Chen and Chen (2006), who showed foot clearance over an obstacle increased with increasing height of an obstacle in older but not young adults. The visually taller steps (due to the HV illusions) in experiment 2 may have caused a similar effect with our older adults. These findings also corroborate the step specific effect that was found by Foster et al. (2015) on a three-step staircase whereby the increased foot clearances were pertinent to the step superimposed with the HV illusion. Here we show the same effect where significant increases in foot clearance were found across step 1 and 7 and no differences on steps 2-6.

The indication of a perception-action link found in this study suggests an association between the two visual streams during stair negotiation. In line with many other studies, this may be due to task specific factors and/or the type of illusion. Where perception-action disassociations are reported, online feedback of the moving limb has been found with some illusions to fine tune the motor estimation of the target illusion to the correct size (Glover, 2002; Hughes, Bates and Aimola Davies, 2008). In the absence of this feedback, the motor estimate corresponds to the illusory effect (Aglioti, DeSouza and Goodale, 1995; Gentilucci et al., 1996; Otto-de Haart, Carey and Milne, 1999). On stairs, vision is used in a feedforward manner to plan for approximately two to three steps ahead (Zietz and Hollands, 2009). Here it is likely the participants relied on visual memory of the riser heights from feedforward scanning when crossing the superimposed steps.

Older adults responded perceptually and through increased foot clearances to most of our stair/step visual treatment whereas Schofield, Curzon-Jones and Hollands (2017) did not find this. These authors did not present a HV-illusion stimulus but rather used subtle variations in a fine-grained texture to alter the apparent illumination of a step. Older adults are less able to see fined-grained textures and may thus not have observed the subtle changes presented. The authors reported that their participants observed no subjective differences between step conditions during the execution of the step-up task. The HV illusions from the current study and from Foster et al. (2015) show noticeable differences from the plain uniform condition and between HV illusion designs: the experimental manipulation is far more visible here than in the Schofield, Curzon-Jones and Hollands (2017) study. This suggests older adults may show more adaptive foot clearances when visual cues are noticeably different to a comparison step. This also highlights how visual information used for an action is not always guided by conscious report of visual perception (Goodale, 2014). The adaptations found here compared to Schofield and colleagues are also unlikely related to the task as Foster et al. (2015) reported a foot clearance effect in older adults with HV illusions on a single step also.

The present findings show no indication that the HV illusions lead to compromises in other measures of stair safety in young and older adults. The lack of difference in MOS suggest at the critical instance when a trip could occur, the difference in perceived and actual height do not disturb normal stair stability. Similarly, the presence of the HV illusions do not introduce alterations or hesitancy in stair speed or affect foot overhang. Despite the illusions also appearing visually salient to the other steps, this does not change the length of visual step inspection in older adults as supported through the lack of significant finding in gaze duration. These findings together suggest that the HV illusion designs do not adversely affect normal stair behaviour in older and young adults despite the benefit of increased and safer foot clearances.

8. Limitations and future considerations

The loss of gaze data resulted in a limited analysis of gaze behaviour, whereby a between age-group comparison of gaze durations was not possible. Although young adults show similar conscious reports of perceived riser heights to older adults, it is not certain whether they acquire this visual information during the stepping task in the same way, especially considering the age group differences in foot clearance. An informative measurement of somatosensory adaptation here could have included superimposing the HV illusions on every step to determine whether foot clearances readjust back to the physical rather than perceived step height. However, this could result in a more exhausting stair action that compromises stair safety for an older adult. Linear increases in metabolic cost are found with increased foot lift during over ground walking (Faraji, Wu and Ijspeert, 2018). Stair walking is a more metabolically expensive form of locomotion (Bassett et al., 1997; Teh and Aziz, 2002) suggesting repeatedly increasing foot clearance could have a considerable energy expenditure consequence for older adults. Future research should also examine the effectiveness of the HV illusion on stairs with an inconsistently taller step which is a known and common hazard for stair falls (Cohen, LaRue and Cohen, 2009). Francksen et al. (2020) showed older and young adults do not adjust foot trajectories over a single mid-stair step, inconsistently taller by 1cm, suggesting slightly taller steps are not visually detected. In this scenario, increasing foot clearance using a HV illusion could help to increase foot clearance and reduce fall-risk. Participants wore a safety harness during the stepping task to arrest a potential stair fall which could affect the typical stair walking behaviour and margins of stability. Future research should examine the effectiveness of the HV illusions on public/private stairs which circumvents harness restrictions.

9. Conclusion

Modified versions of the HV illusion were effective at increasing the perceived riser height and foot clearance on a seven-step staircase, indicating a perception-action link in older adults. This was at no detriment to other stair safety measures. The modified HV illusion designs may be helpful in reducing older adult stair falls, but this should be evaluated next on public/private staircases, most importantly where there are inconsistently taller risers known to be hazardous for a fall.

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