What You See Is What You Step: The Horizontal–Vertical Illusion Increases Toe Clearance in Older Adults During Stair Ascent

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Purpose. Falls on stairs are a significant cause of morbidity and mortality in elderly people. A simple safety strategy to avoid tripping on stairs is increasing foot clearance. We determined whether a horizontal–vertical illusion superimposed onto stairs to create an illusory perceived increase in stair-riser height would increase stair ascent foot clearance in older participants.

Methods. Preliminary experiments determined the optimum parameters for the horizontal–vertical illusion. Fourteen older adults (mean age ± 1 SD, 68.5 ± 7.4 years) ascended a three-step staircase with the optimized version of the horizontal–vertical illusion (spatial frequency: 12 cycles per stair riser) positioned either on the bottom or top stair only, or on the bottom and top stair simultaneously. These were compared to a control condition, which had a plain stair riser with edge highlighters positioned flush with each stair-tread edge. Foot clearance and measures of postural stability were compared across conditions.

Results. The optimized illusion on the bottom and top stair led to a significant increase in foot clearance over the respective stair edge, compared to the control condition. There were no significant decreases in postural stability.

Conclusions. An optimized horizontal–vertical visual illusion led to significant increases in foot clearance in older adults when ascending a staircase, but the effects did not destabilize their postural stability. Inclusion of the horizontal–vertical illusion on raised surfaces (e.g., curbs) or the bottom and top stairs of staircases could improve stair ascent safety in older adults.

Keywords: falls, stair safety, horizontal–vertical illusion, stair ascent, tread-edge highlighter

Falls when walking over surface level changes or stairs are a major cause of morbidity and mortality in elderly people.[1–3] Vision has been shown to be very important for safe negotiation of surface level changes and stairs,[1,2,4] with visual impairment making it difficult to determine the exact position of tread edges.[5–8] Previous studies have shown that increasing foot clearance is a common compensatory strategy that may reduce the risk of falling when stepping onto a raised surface or over an obstacle for participants with (real and/or simulated) impaired vision,[5,7,9] reduced visual field,[10,11] reduced illumination,[12] under dual-task conditions,[13] or when descending a raised surface/staircase under conditions of reduced vision.[6,14]

The present study determined whether increased foot clearance could be induced by changing the appearance, rather than the physical height, of a raised surface and/or stairs of a staircase. In a pilot study conducted on 21 young adults (mean age, 28.2 ± 8 years) we have found that superimposing high-contrast (black and white) vertical and horizontal sine-wave gratings onto the stair riser and stair tread, respectively, of a wooden block leads to an increase in perceived height of the block, resulting in an increase in foot elevation and foot clearance over the block edge in young participants.[15] This arrangement of gratings creates a bespoke version of the horizontal–vertical (HV) illusion (the simplest version of the illusion is a letter "T" with horizontal and vertical limbs of the same length; Fig. 1); the vertical limb will be perceived as 15% to 20% longer.[16] However, the study reports a relatively small increase in foot clearance of 0.5 cm, which may have been due to the rather complex HV illusion used.[15]

To determine the potential efficacy of using the HV illusion on public raised walkways and staircases, the present study focused on determining the optimum parameters for increasing foot clearance in older adults when ascending a raised surface or three-step staircase, without compromising their balance. The aims of the present study were (1) to determine the optimum spatial frequency of a simple square-wave grating version of the HV illusion for increasing toe clearance when walking onto a raised surface (comparable to a curb; experiment 1); (2) to determine whether the optimized HV illusion should be placed on the bottom, top, or both bottom and top stair of a three-step staircase (experiment 2); and (3) to determine whether any increased foot clearance due to the HV illusion caused postural instability (perhaps by the potential mismatch between the height of the stair riser suggested by the visual system versus the actual height of the stair riser indicated by the somatosensory system when the leading foot lands on the stair tread; experiment 2). These experiments were carried out on older adults (60 years and above) to establish whether the HV illusion could improve safety in this age group when ascending raised surfaces/staircases.

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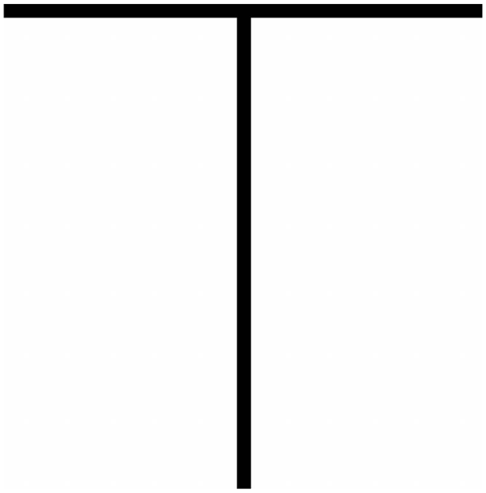

FIGURE 1. An example of the simplest version of the HV illusion. Note that both the horizontal and vertical lines that make the letter "T" are identical in length, yet the vertical line appears longer.

METHODS

Participants

Group average (±1 SD) characteristics of the older adults participating in each experiment are provided in Table 1. Participants were excluded from taking part if they had any neurologic, musculoskeletal, cardiovascular, or vestibular disorders; any significant vision impairments; or a previous history of falling. All participants had a binocular visual acuity better than 0.10 logMAR (Snellen 20/25). The tenets of the Declaration of Helsinki were observed, both experiments received institutional ethical approval, and all participants provided informed written consent before taking part in the experiments.

Stair Design and Apparatus

Experiment 1. Participants ascended a custom-built raised surface, which was 1 m wide, 16.5 cm high, and consisted of a raised surface measuring 2 m in length. The raised surface represented a surface level change typically encountered during activities of daily living, such as ascending a curb or public transport, and was painted a uniform gray color. Crash mats were placed on both the left and right sides of the raised surface in case of a trip or fall, though no trips or falls occurred during the experiment.

Experiment 2. Participants ascended a three-step staircase (henceforth referred to as "stair ascent"), custom built for stair negotiation research within the gait laboratory environment,[8] which was painted a uniform gray color. A handrail was positioned on the left side of the staircase (as viewed during ascent), and crash mats were placed on the right side in case of a trip or fall. No trips or falls occurred during the experiment and none of the participants used the handrail at any time during the trials.

Preliminary Psychophysical Assessments. Given that our previous study (Elliott et al.[15]), along with previous walking and stepping studies,[17,18] have provided evidence of an association between perception and action, a number of psychophysical assessments (see Supplementary Material) were completed, which aimed to determine the following: (1) the optimum spatial frequency of black and white square-wave gratings on the stair riser, and (2) the optimum location and thickness of a high-contrast horizontal black strip positioned on the stair-tread in combination with the black and white square-wave gratings on the stair riser. The results of the assessments were used to set the parameters of the HV illusion to be superimposed onto the raised surface in experiment 1 and stair risers in experiment 2. Schematic representations of a three-step staircase were presented on a Macintosh Cinema Display (Apple, Inc., Cupertino, CA, USA), and standard psychophysical forced-choice methods allowed us to evaluate the perceived height of the bottom stair riser for a variety of parameters for the horizontal–vertical illusions used subsequently. All observers in "assessment A" displayed significant overestimations of the true height of the stair riser for the five differing square-wave spatial frequency versions (4, 8, 12, 16, and 20 cycles per stair riser) of the black and white grating, and the magnitude of the overestimation increased with increasing spatial frequency for all but one observer. "Assessment B" demonstrated that observers overestimated stair-riser height by up to 20% when a high-contrast horizontal black strip was placed flush with the stair-tread edge to complete the HV illusion, in comparison to having no black strip present or present but placed away (gap equivalent to strip thickness) from the stair-tread edge.

TABLE 1. Group Average Characteristics of Participants Taking Part in Each Experiment (Mean ± 1 SD)

	Experiment 1	Experiment 2
No. of participants	11 (3 female)	14 (9 female)
Age, y	69.8 ± 7.3	68.5 ± 7.4
Height, m	1.73 ± 0.1	1.66 ± 0.09
Mass, kg	81.3 ± 17.4	68.8 ± 14.3
Binocular VA, logMAR	−0.07 ± 0.08	−0.08 ± 0.07
Contrast sensitivity, log CS	1.85 ± 0.14	1.84 ± 0.13

Eight of the participants from experiment 1 also took part in experiment 2, and there was at least a 3-month period between measurements. CS, contrast sensitivity; VA, visual acuity.

Gait Assessments

Experiment 1: Negotiation of Raised Surface. Five visual illusion conditions were superimposed on the riser of a raised surface (Figs. 2a–e): (1) no illusion on the raised surface riser (RS-riser) and no tread-edge highlighter (plain, Fig. 2a); (2) a 5.5-cm-wide high-contrast black strip placed flush with the leading edge of the tread (abutting, Fig. 2b)[8]; the edge highlighter was also present for the following conditions, which all had a vertical black and white square-wave gratings placed on the RS-riser, with a spatial frequency of (3) 4 cycles per RS-riser (SF4, Fig. 2c); (4) 12 cycles per RS-riser (SF12, Fig. 2d); or (5) 20 cycles per RS-riser (SF20, Fig. 2e). This range of spatial frequencies was used given that the initial psychophysical assessment had determined that all spatial frequencies resulted in a perceived increase in stair-riser height (see Supplementary Material; assessment A). Note that the 5.5-cm-wide high-contrast black strip placed flush with the leading edge of the tread (see Supplementary Material; assessment B) was necessary (in conditions 3–5) to complete the HV illusion.

Experiment 2: Stair Ascent. Participants completed repeated trials ascending the stairs with an optimized version of the HV illusion, determined in experiment 1 to be vertical black and white stripes with a spatial frequency of 12 cycles per stair riser, and accompanied by a 5.5-cm-wide high-contrast black strip placed flush with the leading edge of the tread. This was used in three separate arrangements (Fig. 3): (1) HV illusion on the bottom stair only (Fig. 3c); (2) HV illusion on the top stair only (Fig. 3d); and (3) HV illusion placed on both the bottom and top stair simultaneously (Fig. 3b). A higher incidence of falls on stairs occur on the bottom stair during the

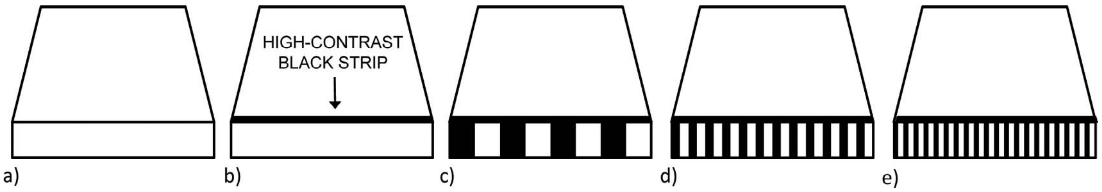

FIGURE 2. The RS-riser conditions presented during experiment 1. The HV illusions were compared to a plain RS-riser (**a**) and a plain RS-riser with a 5.5-cm-wide high-contrast black strip placed flush with the leading tread edge ([**b**], abutting). The three sets of gratings placed on the RS-riser as part of the HV illusion had a spatial frequency of 4 (**c**), 12 (**d**), or 20 (**e**) cycles per RS-riser. They were all accompanied by a 5.5-cm, horizontal, high-contrast, black strip along the tread edge that completed the HV illusion.

transition from overground walking to stair negotiation, or on the top stair during the transition from stair negotiation to overground walking.[1,2] Thus, placing the illusions on the bottom only, top only, and bottom and top together provided evidence of whether the HV illusions lead to changes in gait before or after the illusion. Owing to a greater dependency on somatosensory feedback and less reliance on vision during midstair negotiation,[19,20] the HV illusion was not placed on the middle stair. A fourth arrangement (control condition) had the vertical stripes of the HV illusion removed from all stair risers, leaving only the 5.5-cm-wide high-contrast black strip placed flush with the leading edge of the tread for each stair. Such tread-edge highlighters are commonly used to aid stair descent safety[8] (Fig. 3a).

Protocol

In experiment 1 (negotiation of raised surface) and experiment 2 (stair ascent) participants completed three repetitions of each condition. All stair condition repetitions in each experiment were presented in a random order. Starting from a standing position approximately two-and-a-half walking steps away from the leading edge of the raised surface or bottom stair of the staircase, participants walked up to and ascended the raised surface or staircase by using a "step-over-step" gait (i.e., alternative lead limb on each stair) and were instructed to come to a halt at the top of the raised surface or staircase. Participants led with the same self-selected lead limb to begin each trial and were instructed to use their vision to help ascend the raised surface or staircase. Several strategies were used to counter participants using somatosensory feedback regarding raised surface/stair-riser height and tread-edge position that can be gained when completing the repetitive trials that are needed to allow comparison of conditions in experiments. The strategies involved (1) varying start position for each trial by ± 5 cm (in randomized order)[8,20]; (2) implementing "dummy trials" after every third trial, in which the raised surface riser height or stair-riser height (bottom or middle riser) was altered by $+1$ cm[8,20,21] (data were not collected during dummy trials); and (3) ensuring participants descended the staircase to return to the ground from the top landing, using custom-built "stepping stones"[8] positioned to the right of the staircase, the height of which varied between trials. Participants were informed throughout the protocol that the height and appearance of the raised surface/staircase would vary between some trials.

A 10-camera motion capture system (Vicon MX; Oxford Metrics, Oxford, UK) was used to capture whole-body kinematic data at 100 Hz. Participants wore sensible/comfortable flat shoes and clothing, and used their habitual vision correction throughout each experiment. Reflective markers (1.4-cm diameter) were placed directly onto the skin, clothing, or shoes in accordance with the lower body and thorax segments, which are defined in Vicon's "plug-in-gait" full-body marker set.[22] Additional markers were placed on each leg at the greater trochanter, second metatarsal head and distal phalange of the second toe, and a cluster of four markers were placed on the sacrum. A digitizing wand (C-Motion, Germantown, MD, USA) determined virtual landmarks at the anterior–inferior point of each shoe (shoe tip), and the tread edge of the raised surface (experiment 1) or bottom, middle, and top stair-tread edge (experiment 2).

Data Analysis

Marker trajectories were labeled and gap filled within Vicon Nexus (Oxford Metrics) and the resultant C3D files were uploaded to Visual 3D (C-Motion) for further analysis. Marker trajectories were smoothed with a two-pole 6-Hz Butterworth low-pass digital filter using two passes. Existing kinematic event detection algorithms for stair ascent were used to determine instants of touch-down and foot-off during ascent of the raised surface or staircase.[23]

The following dependent variables were then determined in Visual 3D (Fig. 4):

Penultimate foot placement: The horizontal distance between the shoe tip and edge of the raised surface (experiment 1; Fig. 4a)/bottom stair (experiment 2; Fig. 4b) for the penultimate foot placement before the raised surface edge or edge of the bottom riser of the staircase,

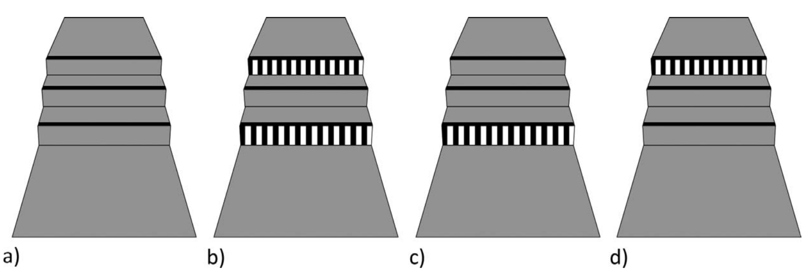

FIGURE 3. The four staircase appearances presented to participants in experiment 2: (**a**) a 5.5-cm-wide high-contrast black strip was placed flush with the leading edge of each tread (control condition), (**b**) an optimized version of the HV illusion was placed on the bottom and top stair simultaneously, (**c**) on the bottom stair only, or (**d**) on the top stair only.

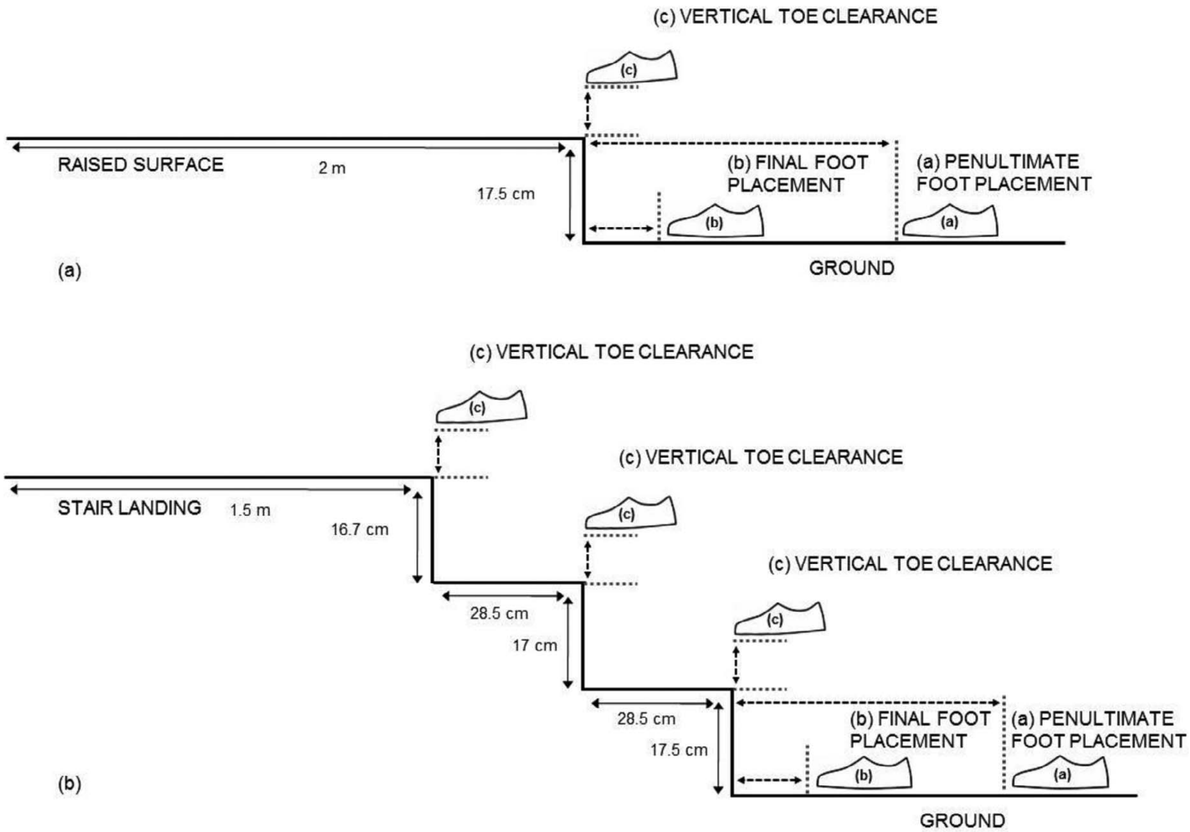

Figure 4. Schematic illustrating how foot placement and clearance parameters were determined during (**a**) negotiation of raised surface (parameters a–c) and (**b**) stair ascent (parameters a–c).

and determined when the foot was motionless on the ground.

Final foot placement: The horizontal distance between the shoe tip and edge of the raised surface/bottom stair for the final foot placement before the raised surface edge or edge of the bottom riser of the staircase, and determined when the foot was motionless on the ground (Figs. 4a, 4b).

Vertical toe clearance: The vertical distance between the leading-limb shoe tip and edge of the raised surface or bottom, middle, and top stair as the limb passed over (swing phase) the edge of the raised surface or each stair edge of the staircase (Figs. 4a, 4b).

The following variables were chosen to determine whether any changes in gait due to the HV illusion led to increases in instability during stair ascent[19,24]:

Single-limb support duration: From the instant of leading-limb foot-off up to touch-down. That is, the duration of the leading-limb foot swing phase before touch-down on each stair.[23]

Ascent duration: From the instant of leading-limb foot-off from the ground to the instant of leading-limb touch-down on the stair landing.[23]

Mediolateral foot and trunk variability: The amount of variation (determined as 1 SD) in mediolateral displacement of the foot or trunk during leading-limb foot swing phase before touch-down on each stair.

Foot and trunk path-length: The cumulative mediolateral displacement of the foot or trunk during leading-limb foot swing phase before touch-down on each stair.

Statistical Analysis

Data from experiment 1 were analyzed by using two-way repeated-measures analysis of variance (ANOVA, Statsoft; Statistica, Tulsa, OK, USA) with illusion condition/configuration (plain, abutting, SF4, SF12, SF20) and repetition (repetition 1, 2, 3) as repeated factors. Post hoc analyses were carried out with Tukey's honest significant difference (HSD) test and the level of significance was set at $P < 0.05$. There were no

Table 2. Foot Placement and Clearance During Negotiation of Raised Surface: Effects of Manipulating the Spatial Frequency of the Horizontal-Vertical Illusion (Experiment 1)

	Mean ± 1 SD				
	Plain	**Abutting**	**Spatial Frequency 4**	**Spatial Frequency 12**	**Spatial Frequency 20**
Penultimate foot placement, cm	81.4 ± 15.1	82.8 ± 14.7	81.8 ± 13.1	82.0 ± 14.3	84.4 ± 16.0
Final foot placement, cm	24.2 ± 6.1	24.9 ± 6.8	24.5 ± 5.5	24.4 ± 5.9	25.8 ± 7.1
Vertical toe clearance, cm	6.9 ± 2.0	7.1 ± 2.0	8.5 ± 2.5*	8.5 ± 1.9*	8.9 ± 2.4*

* Denotes a significant difference ($P < 0.05$) between spatial frequency and plain/abutting conditions.

TABLE 3. Gait Parameters During Stair Ascent: Effects of Horizontal-Vertical Illusion When Presented on Specific Stair Riser(s) (Experiment 2)

	Mean ± 1 SD			
	Control (i.e., Abutting)	**Bottom and Top**	**Bottom**	**Top**
Foot placement				
Penultimate, cm	73.4 ± 12.8	73.1 ± 11.3	73.2 ± 12.6	73.7 ± 11.6
Final, cm	22.3 ± 5.2	22.0 ± 5.2	22.0 ± 5.3	21.8 ± 4.5
Vertical toe clearance				
Bottom, cm	6.3 ± 2.1	7.5 ± 1.9*	7.3 ± 1.6*	5.8 ± 1.9
Middle, cm	5.2 ± 1.4	5.0 ± 1.4	5.0 ± 1.3	5.0 ± 1.4
Top, cm	5.3 ± 2.0	6.1 ± 1.9*	5.3 ± 1.9	6.3 ± 1.9*
Ascent duration, s	2.01 ± 0.29	2.05 ± 0.29	2.06 ± 0.29	2.05 ± 0.30
Single-limb support				
Ground, s	0.46 ± 0.05	0.48 ± 0.05	0.48 ± 0.06	0.46 ± 0.06
Bottom, s	0.48 ± 0.07	0.49 ± 0.06	0.49 ± 0.06	0.49 ± 0.08
Middle, s	0.53 ± 0.06	0.53 ± 0.05	0.52 ± 0.05	0.54 ± 0.07
Mediolateral foot variability				
Bottom, cm	0.9 ± 0.4	1.1 ± 0.4	1.1 ± 0.4	1.1 ± 0.4
Middle, cm	1.2 ± 0.3	1.1 ± 0.3	1.1 ± 0.3	1.3 ± 0.5
Top, cm	1.1 ± 0.4	1.0 ± 0.3	1.1 ± 0.5	1.2 ± 0.6
Mediolateral trunk variability				
Bottom, cm	0.6 ± 0.3	0.6 ± 0.2	0.7 ± 0.3	0.6 ± 0.3
Middle, cm	0.6 ± 0.2	0.7 ± 0.3	0.6 ± 0.3	0.6 ± 0.3
Top, cm	0.8 ± 0.2	0.7 ± 0.3	0.7 ± 0.2	0.7 ± 0.3
Foot path-length				
Bottom, cm	6.7 ± 2.1	7.5 ± 2.9	8.0 ± 3.0	7.2 ± 2.2
Middle, cm	8.3 ± 2.1	7.8 ± 1.9	8.4 ± 2.1	8.5 ± 2.8
Top, cm	8.6 ± 3.1	7.5 ± 2.3	8.4 ± 3.7	8.5 ± 3.6
Trunk path-length				
Bottom, cm	4.8 ± 2.3	5.0 ± 2.2	5.0 ± 2.1	4.8 ± 2.3
Middle, cm	4.9 ± 2.0	5.1 ± 2.3	4.8 ± 2.2	5.1 ± 2.3
Top, cm	6.2 ± 1.9	6.0 ± 2.2	5.5 ± 1.6	6.0 ± 2.1

* Denotes a significant difference ($P < 0.05$) between the Horizontal-Vertical illusion stair arrangement and the control condition.

interactions between illusion condition and repetition in experiment 1.

Data from experiment 2 were analyzed by using a random effects regression model with maximum likelihood estimator, using Stata Release 13.0 (StataCorp LP, College Station, TX, USA). All categorical variables in the model were treated as nominal data. Owing to the exploratory nature of the study, a "type I" error adjustment of the α level was not deemed necessary and the level of significance was set at $P < 0.05$. Factors of interest were incorporated sequentially and their statistical significance was tested by using a likelihood ratio test. Factors with a P value less than 0.1 were provisionally retained, whereas those above 0.1 were dropped. The final model adopted was the most parsimonious one that was felt to adequately explain the data. The P values quoted in the article are those associated with the specific terms (using likelihood ratio χ^2 values, LRχ^2, or the Wald z-score) and interactions between the specific terms, in the final regression model, which were as follows:

1. Staircase appearance: Fixed factor with four levels: plain (the control condition) and the HV illusion placed in the following configurations: on the top and bottom stair simultaneously, bottom stair, or top stair only;
2. Stair number: Fixed factor with three levels (bottom, middle, and top stair); and
3. Repetition: Fixed factor with three levels (trials 1, 2, and 3).

RESULTS

The mean (±1 SD) kinematic and temporal measures for each stair condition during negotiation of a raised surface (experiment 1) or during stair ascent (experiment 2) are provided in Tables 2 and 3, respectively.

Experiment 1: Negotiation of Raised Surface

There were no significant effects of trial repetition across all dependent variables ($P > 0.05$). The HV illusion had no significant effect on penultimate ($P = 0.083$) or final foot placement ($P = 0.40$). The HV illusion had a significant effect on vertical toe clearance (VTC; $F_{4,40} = 13.74$, $P < 0.001$; Table 2). Vertical toe clearance was significantly higher over the surface edge for each HV illusion (SF4, SF12, and SF20) than for plain ($P < 0.001$) or abutting ($P \leq 0.004$). No significant differences in VTC were found between the three HV illusion conditions ($P \geq 0.64$), or between plain and abutting conditions ($P = 0.98$). Between-subject variability was reduced for SF12 (SD = ±1.9 cm) compared to SF4 (SD = ±2.5 cm) and SF20 (SD = ±2.4 cm).

Experiment 2: Stair Ascent

Vertical toe clearance data for each staircase appearance are shown in Figure 5 and Table 3. Vertical toe clearance was affected by staircase appearance, but only over the bottom

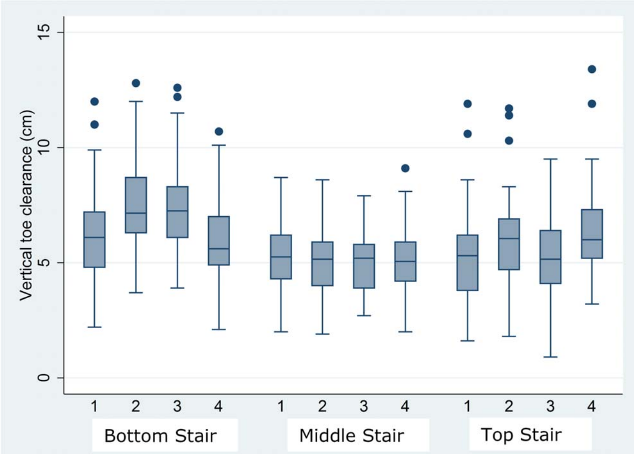

FIGURE 5. *Box and whisker plot* of vertical toe clearance data for each staircase appearance condition and for each stair (bottom, middle, top). Key: 1, control condition with horizontal high-contrast edge highlighter on tread edge only; 2, illusion on top and bottom stairs; 3, illusion on bottom stair only; 4, illusion on top stair only.

($LR\chi^2 = 53.6$, $df = 3$, $P < 0.0001$) and top ($LR\chi^2 = 41.0$, $df = 3$, $P < 0.0001$) stairs and not over the middle stair ($LR\chi^2 = 1.4$, $df = 3$, $P = 0.71$). When going over the bottom stair, VTC increased when the illusion was placed on the bottom stair only ($z = 4.2$, $P < 0.0001$), or when placed on both the top and bottom stair ($z = 4.9$, $P < 0.0001$), but was similar to the control (but showing a trend to be slightly reduced; $z = -1.9$, $P = 0.063$) when on the top stair only. When going over the top stair, VTC increased when the illusion was placed on the top stair only ($z = 5.3$, $P < 0.0001$), or when placed on both the top and bottom stair ($z = 4.2$, $P < 0.0001$), but was similar to the control ($z = -0.1$, $P = 0.92$) when on the bottom stair only.

The most parsimonious model for VTC ($LR\chi^2 = 313.8$, $df = 17$, $P < 0.0001$) indicated significant effects of staircase appearance, stair number, and repetition, with significant interaction terms of stair number*staircase appearance and stair number*repetition (Table 4). There was no significant staircase appearance*repetition effect ($LR\chi^2 = 2.1$, $df = 6$, $P = 0.91$). Vertical toe clearance was significantly reduced on the middle (by on average 1.75 cm, SE = 0.27 cm; $z = -6.4$, $P < 0.001$) and top (by on average 1.64 cm, SE = 0.27 cm; $z = -6.0$, $P < 0.0001$) stairs compared to the bottom stair across all conditions (Table 4).

Penultimate and final foot placements were unaffected by staircase appearance or repetition ($df = 5$, $LR\chi^2 = 3.1$, $P = 0.68$; $LR\chi^2 = 3.9$, $P = 0.56$). All measures of postural stability/control did not change with staircase appearance. Single-limb support ($LR\chi^2 = 4.0$, $df = 3$, $P = 0.26$), ascent duration ($LR\chi^2 = 5.3$, $df = 3$, $P = 0.15$), mediolateral foot variability ($LR\chi^2 = 2.7$, $df = 3$, $P = 0.44$), mediolateral trunk variability ($LR\chi^2 = 0.7$, $df = 3$, $P = 0.86$), foot path-length ($LR\chi^2 = 2.9$, $df = 3$, $P = 0.41$), and trunk path-length ($LR\chi^2 = 2.2$, $df = 3$, $P = 0.53$) were unaffected by changes in staircase appearance (Table 3). The variability of VTC is shown in Figure 5. Inspection of the boxplot suggests there was no systematic difference in variation across staircase appearance or stair number. Similarly, inspection of the boxplots for penultimate foot position, final foot position, single-limb support, ascent duration, mediolateral foot or trunk variability, and foot or trunk path-length all showed no systematic difference in variation across staircase appearance or stair number.

DISCUSSION

Gait Assessments

Experiment 1: Negotiation of Raised Surface. All three spatial frequencies of the HV illusion resulted in significant increases in VTC compared to when negotiating the raised surface with no illusion positioned on the RS-riser (plain) or when just a high-contrast black edge highlighter was positioned flush with the edge of the tread (abutting). The stripes would be easily seen by virtually all older people, as the resolution required to see the narrowest stripes (at 20 cyc/RS-riser) from ~2.5 walking steps was ~1.65 logMAR (Snellen 20/900), similar to the level of visual acuity used by the World

TABLE 4. Output From the Random Effects Regression Model With Maximum Likelihood Estimator for the Analysis of Vertical Toe Clearance (VTC)

VTC_cm	Coefficient	Standard Error	z	P > |z|	95% Confidence Interval, Lower, Upper
_Istair_2	−1.75	0.27	−6.42	0.000	−2.28, −1.21
_Istair_3	−1.64	0.27	−6.03	0.000	−2.18, −1.11
_Icondition_2	1.18	0.22	5.31	0.000	0.75, 1.62
_Icondition_3	1.01	0.22	4.55	0.000	0.58, 1.45
_Icondition_4	−0.45	0.22	−2.01	0.044	−0.88, −0.01
_IstairXcon_2_2	−1.31	0.31	−4.16	0.000	−1.93, −0.69
_IstairXcon_2_3	−1.20	0.31	−3.80	0.000	−1.81, −0.58
_IstairXcon_2_4	0.31	0.31	0.99	0.321	−0.31, 0.93
_IstairXcon_3_2	−0.37	0.31	−1.17	0.244	−0.98, 0.25
_IstairXcon_3_3	−1.03	0.31	−3.28	0.001	−1.65, −0.41
_IstairXcon_3_4	1.49	0.31	4.72	0.000	0.87, 2.10
_Irepetitio_2	−1.15	0.19	−5.99	0.000	−1.53, −0.78
_Irepetitio_3	−1.65	0.19	−8.56	0.000	−2.03, −1.27
_IsteXrep_2_2	0.80	0.27	2.94	0.003	0.27, 1.34
_IsteXrep_2_3	1.06	0.27	3.88	0.000	0.52, 1.59
_IsteXrep_3_2	0.93	0.27	3.42	0.001	0.40, 1.46
_IsteXrep_3_3	1.01	0.27	3.70	0.000	0.48, 1.54
_Cons	7.22	0.44	16.53	0.000	6.37, 8.08

All conditions were compared to stair 1 (bottom stair) condition 1 (control, i.e., abutting) and repetition 1 (the first trial). Stair 2 and stair 3 represent the middle and top stair, respectively. Conditions 2, 3, and 4 represent the HV illusion on the bottom and top stairs (2), the bottom stair only (3), and the top stair only (4). IstairXcon are interactions between stair number and condition. Repetitions 2 and 3 are the second and third trials. IsteXrep are interactions between stair number and repetition.

Health Organization to define legal blindness (1.40 logMAR, Snellen 20/500). For the spatial frequencies of 4 and 12 cycles per RS-riser, VTC increased by 23% (plain) or 20% (abutting). At the higher spatial frequency of 20 cycles per RS-riser, VTC increased by 29% (plain) or 25% (abutting). There was minimal difference between each spatial frequency in foot clearance/placement parameters, suggesting any of the three spatial frequencies would be suitable for experiment 2. However, we considered that the intersubject variability was slightly reduced at a spatial frequency of 12 cycles per RS-riser (±1.9 cm) in comparison to the lower and higher spatial frequencies (±2.5 cm and ±2.4 cm), which infers slightly more consistency in VTC. We therefore chose 12 cycles per stair riser for the HV illusions used in experiment 2, but suspect that a spatial frequency of 4 or 20 cycles per stair riser would likely have a similar impact on the results of experiment 2.

Experiment 2: Stair Ascent. During stair ascent the positioning of the HV illusion on the bottom or top stair only or bottom and top stair simultaneously led to significant increases in VTC over the pertinent stair edge when compared to a black edge highlighter positioned flush with the edge of the tread (the control condition). The increase in VTC (by approximately 17.5%) with the presence of the HV illusion was similar for the different staircase appearances and similar in magnitude to the results of experiment 1. Although VTC increased over the bottom and top stair edge when the illusion was present on the respective stair, VTC over the middle stair edge did not change for each of the different staircase appearances.

Changes to VTC over the stair edges in response to the arrangement of the HV illusion appear to have not significantly affected other gait parameters. Despite increases in VTC, single-limb support duration and stair ascent duration were consistent across all staircase appearance conditions and there were no significant changes to mediolateral foot or trunk variability or foot or trunk path-length. This suggests that the desired increase in VTC over the pertinent stair edge increases the margin of safety in older adults while having no appreciable destabilizing effects on gait.

Vertical toe clearance was seen to decrease with repetition and became reduced between the bottom stair and the middle stair. However, these repetition/learning effects were not sufficient to cloud the effect of the HV illusion and there were no interaction effects between staircase appearance and repetition, indicating that the repetition effect had no bearing on the main outcome measures of the study.

Psychophysical Assessments

The results of both psychophysical assessments (see Supplementary Material) carried out before commencement of experiments 1 and 2 indicated that (1) observers perceived the height of the stair riser to be greater when the HV illusion was present, with higher spatial frequencies resulting in higher perceived stair-riser heights, and (2) a 5.5-cm-wide high-contrast black strip placed flush with the leading edge of the tread, in combination with the black and white square-wave gratings placed on the stair riser, produced the largest magnitude of perceived stair-riser height increase. The actual physical increase in toe clearance by participants in experiments 1 and 2 demonstrated that a strong association between action and perception exists for the HV illusion. It is worth mentioning that the near-perfect agreement that we found between illusory visual estimates of stair-riser height and stair ascent behavior is completely at odds with the traditional view that actions are immune to perceptual illusions—a view that has necessitated the proposition of two separate visual streams, one dealing with vision-for-action, the other vision-for-perception.[25] Nevertheless, our findings support an ever-growing body of literature that is critical of this divergent pathway model.[26,27]

Conclusions

The average increase in VTC across illusion conditions of 1.0 cm represented an average increase of approximately 17.5% compared to the control conditions (6.3 cm, bottom stair; 5.3 cm, top stair). This increase could be considered relatively small, but dangerous levels of foot clearance over raised surfaces and stairs have previously been reported at less than 0.5 cm,[8,12] suggesting that changes to VTC in the present study were relatively large in comparison. It is difficult to predict or comment on whether the HV illusion would increase VTC for older adults who are limited by restricted joint range of movement, and this should be considered as a limitation of the current study. Since there was minimal change in toe clearance when an edge highlighter was present (control condition), compared to the plain condition, this indicates that the increases in VTC were due to the presence of the HV illusion rather than simply an increase in stair edge visibility. The design of the HV illusion used in the present study is multifaceted, being ideal for both stair descent and ascent gait safety. A high-contrast edge highlighter placed flush with the edge of a raised surface/stair tread has been shown to lead to safer gait during stair descent,[8] while the present experiments showed that a combination of the edge highlighter on the tread coupled with vertical black and white gratings on the raised surface/stair riser (the HV illusion) increases toe clearance during ascent.

In summary, our results indicate that toe clearance over the raised surface/stair edge increased owing to the presence of a HV illusion on the surface/stair, which could improve gait safety in older adults. Use of such HV illusions may be particularly warranted on curb edges at pedestrian road crossings, on surface level changes within nursing and/or domestic homes, on the top and bottom stair of staircases with a history of trips, or on staircases that have less than ideal dimensions owing to space restrictions or because of building constraints.

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