The addition of stripes (a version of the 'horizontal-vertical illusion') increases foot clearance when crossing low-height obstacles

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Abstract

Trips over obstacles are one of the main causes of falling in older adults, with vision playing an important role in successful obstacle negotiation. We determined whether a horizontal-vertical illusion, superimposed onto low-height obstacles to create a perceived increase in obstacle height, increased foot clearances during obstacle negotiation thus reducing the likelihood of tripping. Eleven adults (mean±1SD: age 27.3±5.1 years) negotiated obstacles of varying heights (3, 5, 7 cm) with four different appearance conditions; two were obstacles with a horizontal-vertical illusion (vertical stripes of different thickness) superimposed on the front, one was a plain obstacle and the fourth a plain obstacle with a horizontal black line painted on the top-edge. Foot clearance parameters were compared across conditions. Both illusions led to a significant increase in foot clearance when crossing the obstacle, compared to the plain condition, irrespective of obstacle height. Superimposing a horizontal-vertical illusion onto low-height obstacles can increase foot clearance and its use on the floor-section of a double-glazing door frame for example, may reduce the incidence of tripping in the home.

Practitioner summary

Low-height obstacles such as the floor-section of a double-glazing door frame are potential tripping hazards. In a gait lab-based study we found that a horizontal-vertical illusion superimposed onto low-height obstacles led to significantly higher foot clearances; indicating their potential as a useful safety measure.

Key words

Tripping, Obstacle crossing, Horizontal-vertical illusion, Toe clearance, Door-frame

Introduction

Tripping over obstacles is reported to be one of the main causes of falling in older adults (Van Dieen, Pijnappels, and Bobbert 2005; Pijnappels et al. 2008; Kovacs 2005). Evidence suggests that vision plays a vital role in successful obstacle and stair negotiation (Templer 1992; Patla and Vickers 1997; Startzell et al. 2000; Marigold 2008; Elliott 2014). Essentially vision is used in a feed-forward manner to plan negotiation of the obstacle and then information from the lower visual field is used online to update/fine-tune foot placement before the obstacle and clearance over it (Graci, Elliott, and Buckley 2010), with information regarding final foot placement being critical to such fine-tuning (Buckley et al. 2011; Timmis and Buckley 2012).

Previous research suggests that the presence of a horizontal-vertical illusion (Avery and Day 1969) superimposed on to the front face (riser) of a single wooden block led to a perceived increase in height of the block and a resulting increase in toe elevation when participants (mean age ± 1 SD: 28.2 ± 8 years) walked up to and onto the block (Elliott et al. 2009). The simplest version of the horizontal-vertical illusion is a large letter T with limbs of equal size, where the vertical limb appears noticeably longer than the horizontal one (Figure 1).

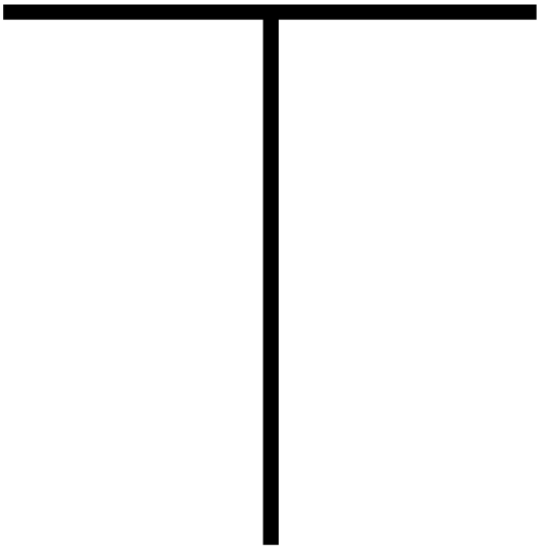

Figure 1. An example of the simplest version of the horizontal-vertical illusion.

Extending these findings, Foster et al. (2015) reported that vertical toe clearance was increased in 14 older adults (mean age 68.5 ± 7.4 years) by an average of 17.5% (~1.0 cm) when high-contrast horizontal-vertical illusions (with varying frequencies / thickness of vertical stripes on the stair riser) were superimposed on to the bottom and/or top stair of a 3-step staircase. Whilst these studies report that the horizontal-vertical illusion had a beneficial effect on toe clearance when stepping onto a raised block or during stair negotiation, it is yet to be determined whether the HV illusion can increase foot clearance over small/low-height obstacles such as the floor-section of double-glazing door-frames, i.e. the lowest part of an integrated door-frame, the section that is fixed to the floor and requires negotiation during locomotion (sometimes referred to as a ‘door-threshold’ or ‘door-sill’). These types of double-glazing door-frame (often made of unplasticised polyvinyl chloride) have become ubiquitous in the home environment and have been shown to be a significant cause of accidental falls in older people (Lim and Sung 2012).

In the present study we superimposed vertical black and white stripes on to the face (riser) of low-height obstacles to create the vertical component of the illusion. A high-contrast black line was painted on the top-edge of the obstacle to complete the horizontal component of the illusion. Obstacle heights were representative of the size of the floor-section of double-glazing door frames (3 cm, 5 cm, 7 cm) and were considerably less than the height of the stair risers used in previous research (~17 cm (Elliott et al. 2009)). We also investigated whether the spatial frequency of the illusion affected the illusions effectiveness, by varying the spatial frequency (thickness) of the vertical stripes to 12 or 20 per metre (SF12 and SF20, Figure 2c and 2d respectively). These were compared to a plain obstacle (Figure 2a) and a plain obstacle with a high-contrast black horizontal line painted on the top-edge of the obstacle (Figure 2b). We hypothesised that superimposing the HV illusion on to an obstacle would lead to an increase in vertical toe clearance when crossing the obstacle. Based on our previous research findings (Foster et al. 2015), we further hypothesised that there would be little or no change in vertical toe clearance between the plain and top-edge conditions or between SF12 and SF20.

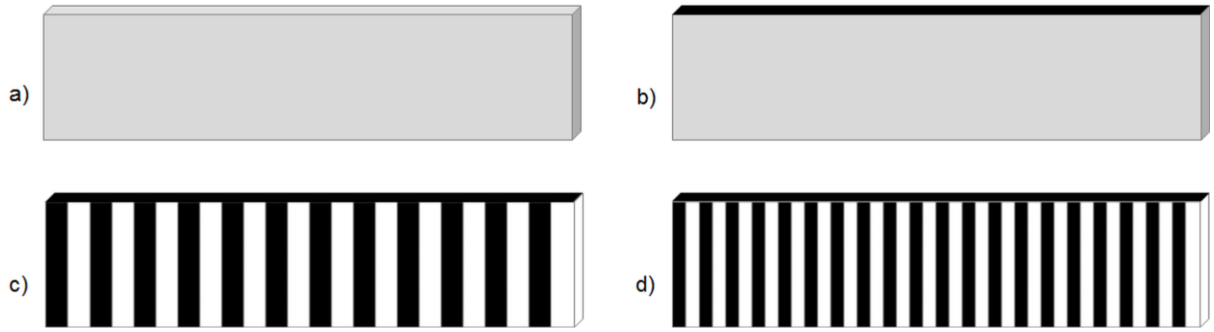

Figure 2. The obstacle appearance conditions. The HV illusions were compared to a plain obstacle (a), and a plain obstacle with a high-contrast black line painted on the top edge of the obstacle (b). The HV illusions were created by vertical black and white stripes at spatial frequencies of 12 (c) or 20 (d) per metre accompanied by a high-contrast black line painted on the top edge of the obstacle to complete the horizontal component of the illusion.

Methods

Participants:

Eleven young adults (mean ± 1 SD: age 27.3 ± 5.1 years; height 169 ± 8 cm; mass 78.0 ± 15.6 kg) provided informed written consent to participate in the study. All participants reported no recent history of falling, no significant vision impairments, and no history of cardiovascular, musculoskeletal, neurological or vestibular disorders that would disrupt their gait. All of the participants had normal vision, with binocular visual acuity better than 0.00 logMAR (log of the minimum angle of resolution, equivalent to Snellen 20/20) and binocular contrast sensitivity better than 1.95 log units on the Pelli-Robson chart. The tenets of the Declaration of Helsinki were observed and the study received institutional ethical approval.

Protocol:

Participants stood facing away from an 8 m walkway, whilst one of three obstacle heights (3, 5 or 7 cm) with one of the four appearances (plain [Figure 2a]; top-edge [Figure 2b]; SF12 [Figure 2c]; SF20 [Figure 2d]) was placed approximately four and a half walking steps away from the participant. Each obstacle was 80 cm wide and 1 cm thick. The three obstacle heights represented the varying heights of the floor-section of double-glazing door frames now often seen in the home (either front, back and/or patio doors). Each obstacle was free-standing and would tip over easily if hit (no hits occurred during the experiment). Participants were instructed to turnaround and walk along the 8 m walkway at a comfortable self-selected speed, stepping over the obstacle with their preferred leading-limb as they went (the preferred leading limb for the first trial was maintained for all subsequent trials). Participants were free to look wherever they chose during each trial. Each obstacle condition at each obstacle height was repeated five times in random order. Due to the repetitive nature of the task participants began each trial from one of three start positions (allocated randomly) that were separated by 5 cm in the direction of travel (Chapman et al. 2010; Foster et al. 2014) to encourage participants to use visual information regarding obstacle height and positioning in the travel path to complete the task.

Data collection and analysis:

A 10-camera motion capture system (Vicon MX, Oxford, UK) was used to capture foot kinematic data (at 100 Hz) as participants walked up to and over the obstacle. Two clusters of three reflective markers (0.7 cm in diameter) placed in a triangular arrangement, were attached to the forefoot and rearfoot portion of each shoe. A digitizing wand (C-Motion, Germantown, MD, USA) was used to determine the anterior- and posterior-inferior tip of each shoe (toe- and heel-tips, respectively) relative to the clusters (De Asha and Buckley 2015), which during locomotion are the parts of the foot closest to the ground and/or ground-based obstacles. Two reflective markers (1.4 cm diameter) were positioned at each end of the top of each obstacle to provide three-dimensional co-ordinates of the obstacle position and height in the travel path. Marker trajectories were labelled and gap filled within Vicon Nexus (Vicon, Oxford, UK) and the resultant C3D files were uploaded to Visual 3D (C-Motion, Germantown, MD, USA) for further analysis. Marker trajectories were smoothed with a 4th order 6 Hz Butterworth low-pass digital filter.

The following dependent variables were determined in visual 3D (Figure 3):

Penultimate and final foot placement (prior to the obstacle): The penultimate foot placement was the horizontal distance between the toe-tip of the leading-limb and the obstacle (figure 3a), and final foot placement was between the trailing-limb toe-tip and the obstacle (figure 3b).

Lead toe clearance and heel clearance: The vertical distance between the toe- and heel-tips of the leading-limb (first limb to pass over the obstacle) and the top of the obstacle as each respective marker passed over the obstacle (figure 3c and 3d, respectively).

Lead-foot placement after the obstacle: the horizontal distance between the heel-tip of the leading-limb and the obstacle for the foot placement immediately after crossing the obstacle (figure 3e).

Trail toe clearance: The vertical distance between the toe-tip of the trailing-limb (second limb to pass over the obstacle) and the top of the obstacle as it passed over the obstacle (figure 3f).

Values for each parameter were calculated as the average across the five repeats. The standard deviation across the five repetitions was used to determine the within-subject variability for each dependent variable.

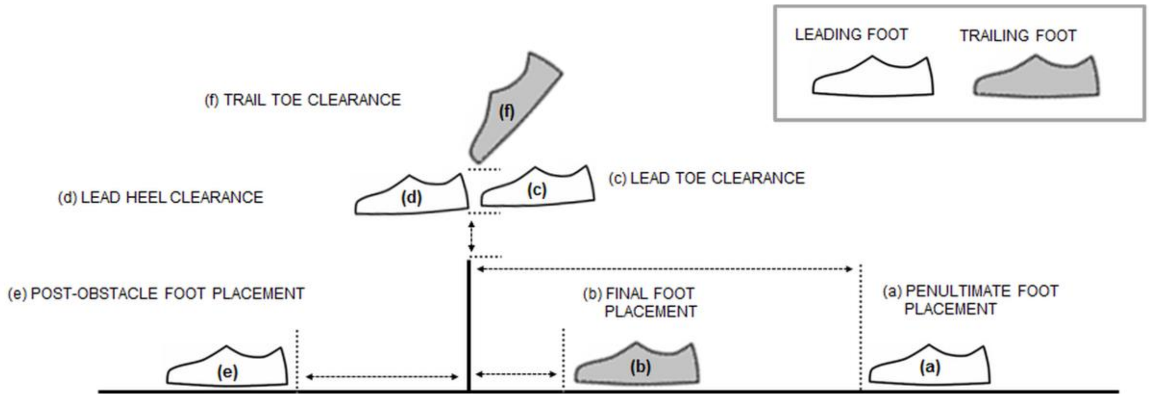

Figure 3. Schematic illustrating the foot placement and clearance parameters that were determined during obstacle negotiation (parameters a-f).

Statistical analysis:

Data were analysed using a 2-way repeated measure analysis of variance (ANOVA, Statsoft, Statistica, USA) with obstacle appearance (plain, top-edge, SF12, SF20) and obstacle height (3 cm, 5 cm, 7cm) as repeated factors. Post-hoc analyses were carried out using Tukey's HSD test and the level of significance was set at $p<0.05$.

Results

Table 1 presents the mean (±1 SD) foot clearances and foot placements for each obstacle appearance condition across all three obstacle heights (combined average of 3, 5 and 7 cm).

Foot clearances and placements:

Penultimate and final foot placement were unaffected by appearance ($p>0.31$) and height ($p>0.44$) but each was affected by a significant interaction between terms (Penultimate: $F(6,60)=4.3$,$p= 0.001$, Final: $F(6,60)=2.6$, $p=0.02$); however, post-hoc analyses of the interactions indicated no meaningful differences across appearance and height conditions. Obstacle appearance had a significant effect on lead toe clearance ($F(3,30)=15.0$, $p<0.001$) and heel clearance ($F(3,30)=9.4$, $p<0.001$); lead clearance was significantly lower over the obstacle for the plain condition in comparison to the top-edge (by 4.8%, $p=0.03$), SF12 (by 8.6%, $p<0.001$) and SF20 (by 10.5%, $p<0.001$), and was significantly higher for the SF20 condition compared to the top-edge condition ($p=0.01$). Lead heel clearance was significantly higher over the obstacle for SF12 and SF20 (both by 14%) in comparison to the plain ($p<0.001$) and top-edge condition ($p\leq0.03$). Obstacle height had no significant effect on lead toe clearance ($p=0.59$) and heel clearance ($p=0.92$).

Post-obstacle foot placement was unaffected by obstacle appearance ($p=0.99$) but was significantly affected by obstacle height ($F(2,18)=4.5$, $p=0.03$) and there was a significant interaction between terms ($F(6,54)=2.9$, $p=0.01$). Foot placement increased with obstacle height, so that placement was significantly greater between heights 3 cm and 7 cm (but not between 3 cm and 5 cm, or 5 cm and 7 cm). Post-hoc analyses (of the interaction) indicated no meaningful differences across appearance and height conditions.

Trail toe clearance was significantly affected by obstacle appearance (F(3,30)=4.6, p=0.01); toe clearance was significantly lower over the obstacle for the plain condition in comparison to SF12 (by 8.6%, p=0.04) and SF20 (by 11.1%, p=0.01). Trail toe clearance was not significantly affected by obstacle height (p=0.48)

There were no significant differences in within-subject variability for obstacle appearance and obstacle height for any of the outcome parameters analysed (penultimate/final foot placement, lead toe clearance, heel clearance, post-obstacle foot placement and trail toe clearance).

Table 1. Effects of obstacle appearance: mean and 1 SD for lead and trail foot clearance, and foot placement across the three obstacle heights (3, 5 and 7 cm combined average).

	Mean (± 1 SD)			
	Plain	**Top-edge**	**SF12**	**SF20**
Lead Toe Clearance (cm)	10.5 ± 2.8	11.0 ± 3.1*	11.4 ± 2.9*	11.6 ± 3.1*
Lead Heel Clearance (cm)	5.7 ± 2.2	5.9 ± 2.5	6.5 ± 2.4*	6.5 ± 2.2*
Trail Toe Clearance (cm)	8.1 ± 3.3	8.5 ± 3.2	8.8 ± 3.4*	9.0 ± 3.4*
Penultimate Foot Placement (cm)	101.2 ± 12.9	100.6 ± 13.2	100.7 ± 12.7	100.4 ± 13.0
Final Foot Placement (cm)	24.1 ± 6.5	24.2 ± 6.8	24.3 ± 6.6	24.1 ± 6.7
Post-obstacle Foot Placement (cm)	26.7 ± 4.0	26.7 ± 5.0	26.8 ± 4.9	26.9 ± 5.3

* indicates a significant difference ($p<0.05$) from the plain condition (control).

Discussion

The increases in foot clearance in the present study in response to the presence of the HV illusion support previous research regarding how the HV illusion affects foot clearance when negotiating raised surfaces or stairs (Elliott et al. 2009). In absolute terms the average increase in foot clearance due to the presence of the illusion was ~1.0 cm which could be considered relatively small. However dangerous levels of foot clearance are reported at less than 0.5 cm, particularly so in older adults (Hamel et al. 2005; Foster et al. 2014) which would suggest small increases in foot clearance can help to improve safety by reducing the risk of tripping. Lead toe clearance was also significantly increased by 0.5 cm (~5%) for the top-edge condition in comparison to the plain condition (Table 1), suggesting that the presence of a high-contrast black line painted on the top edge of the obstacle (Figure 2b) improved the obstacle visibility or at least the feature used to determine its height. This finding contrasts with our previous report which indicated minimal difference in toe clearance when ascending a plain-appearance raised surface in comparison to a raised surface with a high-contrast horizontal stripe painted on the tread-edge (Foster et al. 2015). This may be due to differences, between studies, in participant age (~20-year-olds versus ~70-year-olds) or experiment task (stepping over a low-height obstacle versus stepping onto a raised surface or series of steps). However, a significant increase in lead toe clearance of 1cm or ~10% for the horizontal-vertical illusion (i.e. an additional 0.5 cm or doubling of the effect in comparison to the top-edge condition) suggests the illusion has greater potential to reduce the risk of tripping over obstacles than the presence of just a high-contrast black strip alone. Although heel clearance also increased significantly in response to the HV illusion, the values indicated the heel was much closer to the top of the obstacle across all appearance conditions in comparison to the toe-tip (Table 1). This agrees with previous research that reported a reduction in heel/rearfoot clearance in comparison to lead toe clearance over low-height obstacles (Loverro, Mueske, and Hamel 2013). Clearance of the heel, rather than just toe clearance (as measured in many studies), is therefore an important outcome measure when considering trip prevention when negotiating obstacles (Loverro, Mueske, and Hamel 2013). Participants also demonstrated an increase in trail toe clearance in response to the HV illusion, suggesting that the visual input received during the approach to the obstacle was used to plan foot clearances for both limbs: note that the HV illusion increased both trail toe clearance and lead toe clearance by similar magnitudes (Table 1).

The presence of the HV illusion on the obstacle had no significant effect on foot placement before or after the obstacle, suggesting the illusion did not disrupt determining the exact location of the obstacle in the travel path, only its height. This finding is consistent with our previous study which determined that penultimate and final foot placement were not affected by the HV illusion when ascending a raised surface or stairs (Foster et al. 2015), and would seem to suggest that the illusion had no impact on forward planning of foot placement, only foot clearance. This emphasises that the illusion had no detrimental effects on locomotion.

In the present study, the HV illusion was created by superimposing black and white vertical stripes onto the face of the obstacle. Such a high-contrast pattern would be easy to see, even in those with reduced contrast sensitivity and any use of the illusion in real world conditions should attempt to keep the contrast of the stripes high. The close similarities in foot clearance and placement measures elicited by both spatial frequencies (see table 1) suggests that either could be recommended for use on low-height obstacles, though a lower spatial frequency may be more visible to older adults with visual impairment who have reduced contrast sensitivity at higher frequencies. Cosmetic reasons might prevent use of the illusion from being popular in the home environment, but its use may be particularly warranted on low-height obstacles in public areas or workplaces where trips might frequently occur.

A limitation of the study is that it recruited only young adults. However our previous research reported that the HV illusion led to an increase in toe clearance in older adults whilst negotiating a raised surface or stairs, thus we expect that the results presented here would be reproduced by older adults carrying out the same task, although average toe clearance values (across all conditions) may be slightly reduced (McFadyen and Prince 2002; Kovacs 2005; Galna et al. 2009). Although the current lab-based study clearly demonstrates an increase in heel and toe clearance without detrimental effects to locomotion, further determination of how foot clearance changes over low-height obstacles such as the floor-section of door frames in real-world scenarios, where the thickness of the door frame may be greater or less than 1 cm, is required to fully determine the illusions efficacy as a means to reduce trip risk/improve safety. However, although the thickness of door frames in real-world scenarios may vary it is the perceived size of the face of the oncoming obstacle that appears to drive the increase in toe and heel clearance. For example, an earlier report showed that toe clearance varied depending on the illusion superimposed on the tread and riser and whether the illusion made the step look taller or smaller (Elliott et al. 2009).

Findings from the present study suggest that the HV illusion superimposed onto the floor-section of double-glazing door frames should increase foot clearance when individuals cross over/through such obstacles when entering or exiting the home environment. As double glazing door frames are ever-present in home environments, superimposing high-contrast black and white vertical stripes on each face (riser) of the door frame could improve safety within the home. The high contrast of the obstacle top-edge may also help stepping accuracy, particularly under blurred conditions such as with multifocal wear (Black, Kimlin, and Wood 2014).

Conflict of interest declaration

There are no conflicts of interest in this work.

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