Experimental Brain Research (2023) 241:67–80
https://doi.org/10.1007/s00221-022-06504-6

RESEARCH ARTICLE

Vertical–horizontal illusory effects with gaze restrictions do not change length estimations using the lower limb

Shijun Yan[1,2,3] · **Matthew A. Yeomans**[1,4] · **Jan M. Hondzinski**[1]

Received: 16 May 2022 / Accepted: 3 November 2022 / Published online: 10 November 2022

Abstract

Gaze direction and use of visual feedback can affect illusory influences over perceptions and manual length size estimates of the vertical−horizontal (V−H) illusion, in which the vertical, bisecting segment of an inverted T (IT) appears longer than the horizontal, bisected segment. We questioned whether V−H illusory influences would also exist for the lower limb. Participants stepped forward in an attempt to make the toe-to-toe distance of their dominant foot equal to a short or long bisecting segment length of a vertically projected IT. Performances under three gaze conditions included: maintaining gaze on the IT intersection throughout a trial for target fixation (TF); viewing the intersection for 4 s then looking down and performing the step for movement fixation (MF); and viewing the intersection for 4 s then maintaining gaze on the remembered location of the intersection and performing the step for remembered target fixation (RTF). Variables included step displacement, peak velocity (PV), and normalized ground reaction force amplitude (GRFampN), as well as time to peak and peak amplitude of the center of pressure (COPtime and COPamp, respectively). Main effects of gaze on PV, GRFampN, COPtime, and COPamp revealed lower values for MF compared to TF and RTF, which did not exist for step displacement. No significant correlations existed between step displacement and other variables across participants. Together, we found evidence to suggest differences between movement planning and movement completion. Exploitation of deceptive visual cues can guide step planning and early step execution, but do not guide final step estimations.

Keywords Sensorimotor control · Illusory perceptions · Closed-loop task · Kinematics · Kinetics

Abbreviations

V–H	Vertical–horizontal
IT	Inverted T
TF	Target fixation
MF	Movement fixation
RTF	Remembered target fixation
PV	Peak velocity
GRFampN	Normalized ground reaction force amplitude
COP	Center of pressure
COPtime	Time to peak amplitude of the center of pressure
COPamp	Peak amplitude of the center of pressure
2D	Two-dimensional
APA	Anticipatory postural adjustment
3D	Three-dimensional
COPx	Onset of center of pressure in *x* direction
peakGRFz	Peak vertical ground reaction force
ANOVA	Analysis of variance
ES	Effect size

Introduction

The ability to utilize illusory influences to alter movement control is of interest because it has potential to positively influence movement in people with motor declines, due to healthy aging, disease, and/or injury. The use of multiple vertical and horizontal segments on the rise and tread components of stairs, respectively, revealed greater vertical toe

---

Communicated by Melvyn A. Goodale.

✉ Jan M. Hondzinski
jhondz1@lsu.edu

[1] School of Kinesiology, Louisiana State University, 1246 Pleasant Hall, Baton Rouge, LA 70803, USA

[2] Legs and Walking Lab, Shirley Ryan AbilityLab, Chicago, IL, USA

[3] Department of Physical Medicine and Rehabilitation, Northwestern University, Chicago, IL, USA

[4] Department of Health and Human Performance, University of Tennessee at Martin, Martin, TN, USA

clearance for ascending one stair (Elliott et al. 2009) or several stairs (Elliott et al. 2009; Foster et al. 2015) than unlined stair components for young adults (Elliott et al. 2009) and elders (Foster et al. 2015). Greater toe clearance when stepping over an obstacle with vertical segments on the front surface compared with clearing an obstacle without the vertical segments (Foster et al. 2016) may limit the low vertical toe clearance associated with falling in older adults (Tinetti et al. 1988; Downton and Andrews 1991). These outcomes provide promise for illusory influences on perceptuomotor control in illuminated environments with eyes open (Elliott et al. 2009; Foster et al. 2015, 2016; Wood et al. 2013) contradicting the perception–action dissociation (Franz et al. 2000; Mendoza et al. 2005) proposed previously (Goodale and Milner 1992). Variations across illusions, experimental procedures, and data analyses explain several inconsistent results of influences of visual illusions on perception and action (Bruno et al. 2008; Kopiske et al. 2017) and explain why data from some studies revealed that visual illusions influence perceptual judgments and movements, differently (Haffenden and Goodale 1998; Westwood et al. 2000; Bartelt and Darling 2002). For example, allowing people to gaze freely can limit illusory influences on upper limb motor control, while restricting people's gaze direction to the configuration or the moving limb can enhance illusory influences on this control (Yan and Hondzinski 2021). Specifically, reduction in movement accuracy accompanied illusions when people looked at the illusion or only their finger than when looking freely during the movement. We reasoned that the use of certain gaze strategies, while gazing at the illusory configuration or the movement, might also enhance illusory influences on length estimations using the lower limb. We use the present study to explore whether such illusion enhancement to step length estimations occurs.

The well-known eye-hand coupling that ensures upper limb movements is less common for the eyes and feet. In a visually guided reaching movement, people usually move the eyes and hand toward a target, coupling the directions of gaze and hand motion. Consider reaching for a book on a shelf, for example. However, people often look ahead when asked to step on objects during walking, rarely watching their exact foot placement (Turano et al. 2001; Zettel et al. 2005). The common use of an eye−foot coordination strategy may affect the step displacement performances according to gaze direction in a different manner than that of the eyes and hand. Interestingly, greater goal-directed inaccuracies accompany hand movements during visuomotor plane decoupling such that people performing horizontal plane movements of the hand while viewing targets on a vertical plane produce greater errors than performing vertical plane movements of the hand (Dalecki et al. 2019). Increased vertical toe clearance for ascending staircases or stepping across a low-height obstacle resulted from the presentation of 2D shapes on a vertical surface to show vertical illusory presentation altered vertical step performances. Whether vertically projected stimuli can influence horizontal stepping movements in the same manner remains unknown. If application of illusory influences on horizontal stepping does alter step displacement, it may assist those with hypokinetic stepping. We use the current study to assess potential illusory influences on step displacement to gain insight into possible mechanisms for control, and if appropriate, to work out experimental design/methods prior to its application to those with neurological declines.

Goal-directed movements can involve the use of premovement planning and online corrections (Woodworth 1899). Visual illusory effects on planning and corrections associated with constant (Wood et al. 2013; Danckert et al. 2002; Franz 2003) and dynamic (Glover and Dixon 2001) models differ from each other as well as from a digit control model in which different parameters of movement rely on different spatial attributes (Smeets et al. 2003). The illusory influence on early and late execution of a movement can remain constant so that the perceptual influence from the beginning to the end of a movement either does (Wood et al. 2013; Franz 2003) or does not (Danckert et al. 2002) exist. In a golf putting task, for instance, visual illusions influenced perceptual judgment, movement planning, and movement execution similarly (Wood et al. 2013). The likeness across perception as well as the action planning and execution for golf putting could easily result from the person's inability to make online corrections after the ball leaves the putter and rolls toward the hole, where online feedback might be useful. In contrast, the perception–action similarities and differences of a dynamic model can depend on the phase of movement. Visual illusions, which affect online control during the motor planning phase and can influence early motor execution, may decay (Glover and Dixon 2001) to result in perception–action differences by movement end. However, using illusory attributes of an object that affect an approach parameter/movement planning, while using nonillusory attributes to affect contact position/movement end, could also explain what appears as perception–action differences across movement phases (Smeets et al. 2003). As indicated previously, participants revealed an increase in toe height during stair ascent yet ended with each foot on a stair (Elliott et al. 2009; Foster et al. 2015) to provide support for potential illusory differences across phases of stair ascent that may or may not exist in forward stepping.

In the case of producing a single step, visual illusions which influence perceptions could influence movement planning and early movement execution yet not the end of movement. Limiting assessment to step displacements alone would not allow for exploration of movement planning, thus, assessments should include variables known for providing insight into movement planning. People often shift body weight, thus, displace the center of pressure (COP), prior to movement during the motor planning phase of a forward step (Mann et al. 1979; Burleigh-Jacobs et al. 1997; Ruget et al. 2008), towards the swing leg along the medial–lateral direction which is known as an anticipatory postural adjustment (APA) and refers to the concept that people adjust their body weight prior to a step initiation (Caderby et al. 2014; Mouchnino et al. 2012; Sun et al. 2015). During movement execution of a forward step, people can greatly alter step length, unlike that of step ascent in which the stairs limit the step length a person can produce. Thus, monitoring variables associated with APAs, which offer insight into motor planning, and variables associated with the kinematics of stepping, which offer insight into movement execution and termination, could help provide greater understanding of visual illusory influences on forward step execution.

The use of short-term memory can alter stepping movements according to illusory perceptions when presented in the same plane of movement. Participants standing with eyes open at one end of the Müller−Lyer illusion configured with wings-in stepped or hopped to place their hallux at the other end of the illusory configuration as accurately as possible, while keeping eyes open (closed loop), after closing the eyes and stepping/hopping immediately (open loop), or after closing the eyes and initiating the stepping/hopping after 3 s (open-loop delay) (Glover and Dixon 2004). The toe-to-toe movement distance (step or hop length) differed across conditions so that the smallest illusory effects on lower-limb movement existed in the visual closed-loop condition task. We wonder whether these heightened illusory effects on movement with short-term memory of remembered illusions on a different planar surface (open loop) would also occur when restricting gaze direction of participants.

In this study, we used a forward step length estimation task to determine if participants' step displacements would follow vertical−horizontal (V−H) illusory influences similar to some conditions used for the upper limb manual length estimations used previously (Yan and Hondzinski 2021). The standard V−H illusion is characterized by an inverted "T" (IT), in which people overestimate the vertical segment and/or underestimate the horizontal segment when the two perpendicular segments are physically equal in length (Fig. 1A). Therefore, a movement displacement longer than the actual length of the vertical segment in the presence of the horizontal segment of the IT is expected for illusory influences on movement. Removing configurations just prior to performing the step estimation, thus, use of remembered configurations, allowed us to assess if a short-term memory of the illusion also affected lower limb motor control. The purposes of this study were to determine: (1) whether size estimates of a vertical segment length using step displacements differ when viewing the vertical/bisecting segment of the V−H illusion (see Fig. 1) and a vertical segment without the illusion; (2) whether restricting gaze and visual feedback during movement would influence size estimations of the vertical/bisecting segment length for the V−H illusion using step displacements; and (3) whether restricting gaze and visual feedback during movement would influence performance during motor planning and early phase execution of the step. We hypothesized that individuals' size estimates using step displacements would be greater for the V−H illusion than a single vertical segment without the illusion. We also hypothesized that fixating the eyes on the remembered (and possibly real) center of the illusion during the step would produce stronger illusory effects (greater step displacements) as compared to looking down at the feet or movement space during the step.

Methods

Participants

Twenty healthy college students (6 males and 14 females) who were unfamiliar with visual illusions participated in this experiment. They read and signed the consent form prior to participation in the protocol described below that was approved by the University's Institutional Review Board. Participants with visual acuity 20/25 or better on the Snellen eye chart assessment had no difficulty viewing targets and were right foot dominant as determined by the leg preferred to kick a ball (Zettel et al. 2002) far.

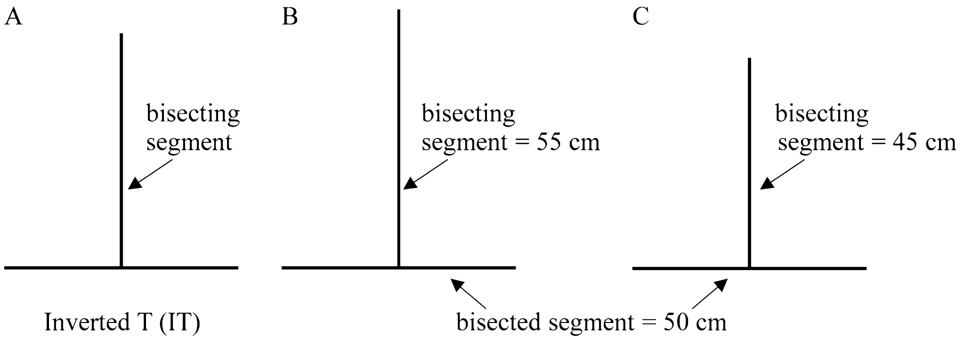

Fig. 1 Inverted T (IT) with vertical and horizontal segments equal in length (**A**). Pictorial descriptions of long **B** and short **C** configurations of IT visual stimuli used in the experiment

Only data from 15 participants (12 females) were used for data analysis (mean age = 21 ± 1.2 years, mean body mass = 75 kg ± 22 kg), which still exceeds our estimated 12 participants from a previous similar study required to obtain a power = 0.80. Three participants did not follow the experiment instructions involving gaze direction, while problems with force plate recordings for two others prompted their removal.

Experimental setup

Figure 2A shows the experimental setup. Participants stood in the start position on a force plate (49.6 × 49.6 × 4.65 cm), surrounded on three sides by a platform of the same height. Chalk outlines of foot position provided the same start position throughout trials. A screen, 311 × 196 cm, used for projecting visual stimuli, was positioned in a frontoparallel plane at a distance of 400 cm. The intersection of the IT configurations or the low end of a vertical segment (no horizontal/bisected segment in Fig. 1B, C) for control trials was projected directly in front of the participants at eye level (average eye level height = 158 ± 9 cm).

The visual stimuli involved the IT configuration with two sizes such that the bisecting segment was 10% longer (55 cm) or shorter (45 cm) than the bisected segment (50 cm) (Fig. 1B, C). Stimuli involved solid black line segments with a projected line width = 1 cm on a white background. In a control trial, a single vertical segment of 55 or 45 cm was presented to participants. The use of two lengths prevented memorization of one movement distance. The visual stimuli were designed and presented to participants using PsychoPy program (Peirce 2007).

Experimental procedure

Barefooted participants stood upright on a force plate with their feet placed a self-selected comfortable distance apart. Remember, chalk outlines of each foot position ensured consistent starting stance across trials. Prior to the experimental trials, investigators instructed participants to stand on the force plate and perform five practice trials of a forward comfortable step with their right dominant leg to get accustomed to procedural cues.

Participants performed a perceptual judgment task prior to the perceptuomotor task for each experimental trial. Protocol was as follows. After stimulus presentation of an IT configuration on the screen, participants viewed the IT intersection and orally responded "equal" when the segments appeared identical in length, "horizontal" when the horizontal segment appeared longer than the vertical segment, and "vertical" when the vertical segment appeared longer than the horizontal segment. Perceptual responses were recorded by hand and via audio in the gaze tracking video recorder (see below). Stimulus presentation lasted for 4 s followed by an audio cue (programmed in advance using PsychoPy), which signaled participants to initiate a comfortably paced, single forward step with their right foot. Duration of 4 s prior to stepping ensured that participants had enough time to make a perceptual judgment and get ready to move. Participants were asked to estimate the bisecting segment length so that their forward step displacement, described as the distance from their start to end position of the right big toe/hallux (Fig. 2B), equaled the length of the vertical bisecting segment of the presented configuration. The foot of the supporting left leg remained in contact with the force plate throughout the step. Participants were asked to make a comfortably paced single forward step and not to adjust foot

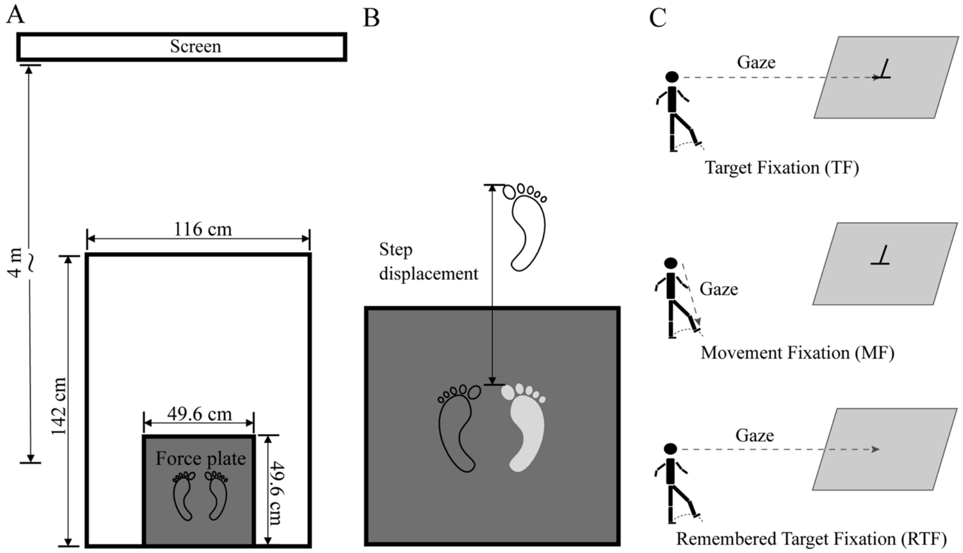

Fig. 2 Experimental setup is pictured. Foot outlines on the force plate (gray square) represent start position. The force plate was surrounded on three sides by a platform of the same height (**A**). A cartoon depicting step displacement is also shown (**B**). Participants completed the stepping task under three gaze conditions: *TF* target fixation, *MF* movement fixation, *RTF* remembered target fixation, (**C**)

placement after the foot touched the ground. Task reminders were given every few trials. After they stepped, an investigator signaled them to move back to the start position and prepare for the next trial using a "relax" command. Participants estimated the length of a single vertical segment with step displacements for control trials.

Participants performed the stepping perceptuomotor task under 3 gaze and visual feedback conditions, referred to as gaze conditions throughout the manuscript (Fig. 2C). In the first condition, participants maintained gaze on the segment intersection of the IT and performed the step (Target fixation—TF). In the second condition, participants looked down after hearing the auditory cue and performed the step. In this condition, they were allowed to look at their foot or the step area only (Movement fixation—MF). In the third condition, the visual stimulus disappeared at the time of the audio cue and participants maintained gaze on the remembered intersection of the IT and performed the step (Remembered target fixation—RTF). For control trials, participants maintained gaze on the lower end of the single vertical segment, then looked down and performed the step after the audio cue. Thus, the only restrictions for gaze in control trials during movement involved not looking back at the vertical segment.

Participants always performed the control trials last to prevent influence of previous experience on experimental performances and memorization of movement distances. The order of 3 gaze conditions (TF, MF, and RTF) was randomized prior to data collection for each participant. Table 1 shows the distribution of 70 experimental trials. Participants were given rest between gaze conditions, allowed to rest between each 2 minute data collection period, and finished the experiment within 80 min.

Data collection and processing

A 60 Hz binocular mobile eye tracker (SMI, Teltow, Germany) was used to check whether participants followed task instructions for each gaze condition. We deleted and repeated trials when participants had obvious deviations in gaze by checking the point of gaze on the viewing field video while conducting the experiment. We ensured proper fixation of gaze prior to and during the step (when appropriate) for each experimental and control trial during inspection of offline recorded viewing field video using B-Gaze software (SMI, Teltow, Germany) and a frame-by-frame analysis. For example, in TF, we removed the trials when participants looked anywhere besides the segment intersection (e.g., foot, floor, up, etc.) before or during a step. Trials with incorrect gaze deviations were removed and not included in analyses. We removed three participants with incorrect gaze deviations for greater than 40% of trials in any condition. Data analyses involved the use of 90% of trials for the 15 participants.

Table 1 A summary of the number of trials

Configurations	Target fixation (TF)	Movement fixation (MF)	Remembered target fixation (RTF)	Control
Long	10	10	10	5
Short	10	10	10	5

Perceptual judgments

Perceptual responses were documented by hand and recorded on the video of the mobile eye tracker and checked using B-Gaze software. We counted the number of experimental trials that the participants reported as vertical, equal, or horizontal. Dividing these numbers by total trial number within a gaze condition and size gave us the percentage for correct and incorrect responses. Responses according to the V−H illusion only existed for the short configuration; thus, analyses of illusory responses were limited to the short configuration trials. For this configuration, the percentage of vertical and equal responses combined determined illusory responses.

Stepping task

A 2 cm diameter reflective marker was placed on the hallux and the heel of the right foot. Marker movements were recorded at 250 Hz using a 4-camera Qualisys system (Qualisys Medical AB, SE). The 3D coordinate data of each marker were lowpass filtered using a Butterworth second order filter with a 13 Hz cutoff frequency similar to elsewhere (Sinclair et al. 2017; Sinclair and Stainton 2019). Toe tangential velocity represented the differentiation of the hallux marker position data with respect to time. Start and end of the movement were determined when toe velocity was maintained below 5% of peak velocity for $\geq$ 100 ms before and after movement, respectively, similar to other reports (Yan and Hondzinski 2021). Step displacement represented the distance between start and end locations of the hallux marker in the horizontal plane. The maximum velocity of the hallux marker between movement start and end was used to determine peak velocity (PV) of stepping to offer insight into temporal aspects of the stepping movement (see Fig. 3).

A mobile AMTI force plate was synchronized with the Qualisys system to record forces during stepping movement at 250 Hz (AMTI Watertown, MA, USA). Ground reaction force in the vertical (GRFz) direction and center of pressure (COP) in the x (medio-lateral) direction, provided from specialized software (AMTI Balance Clinic, Watertown, MA, USA), were filtered using a Butterworth

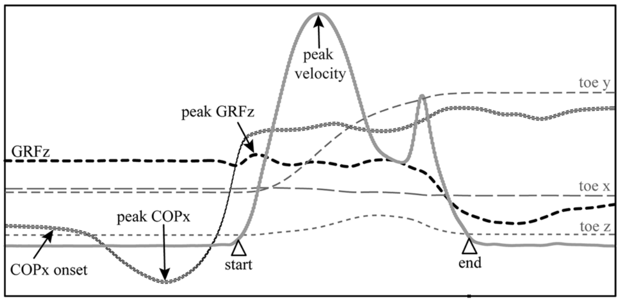

Fig. 3 Data represent center of pressure in the medial–lateral direction (COPx), *x*-, *y*-, and *z* position of the toe marker, velocity of the toe marker (solid gray line), and vertical ground reaction force (GRFz) of the stepping foot for one trial. Arrows from left to right represent the onset of COPx, peak COPx, the time of peakGRFz, and the time of peak step velocity. Triangles represent the start and end of stepping movement at 5% of peak velocity

fourth order filter with 13 Hz cutoff frequency (Koltermann et al. 2018) and are presented in Fig. 3. We identified the time and amplitude of APAs associated with each step to help explain the motor planning phase of stepping (Mann et al. 1979; Burleigh-Jacobs et al. 1997; Ruget et al. 2008) using the following procedures. The onset of COP in *x* direction (COPx) was determined as the time that the COPx exceeded 1 mm (Azuma et al. 2007). APA duration (COPtime) was determined as the time difference between the peak COPx toward the swing leg and onset of COPx (Russo and Vannozzi 2021). APA amplitude (COPamp) was determined as the spatial difference between COPx at peak and onset (Russo and Vannozzi 2021). When preparing to step, people concurrently increase their medial–lateral COP and vertical ground reaction force of their swing leg to transfer their weight (center of mass—COM) toward the stance leg with the aim of maintaining balance (Halliday et al. 1998; McIlroy and Maki 1999). Thus, the peak vertical (*z* direction) ground reaction force (peakGRFz) was determined between the peak COPx and ≤ 20 ms after the PV. The peak ground reaction force amplitude was determined as the force difference between peakGRFz and GRFz just prior to onset of COPx normalized by GRFz (GRFampN).

Statistical analyses

Mean step displacement was determined for each gaze condition, configuration size, and participant. Other variables of interest included mean COPamp, mean COPtime, mean GRFampN, and mean PV for each gaze condition, configuration size, and participant, as well as an illusory percentage for each gaze condition and participant. The Shapiro–Wilk *W* test was used to assess existence of normal distributions. The data were log transformed for violations of normality. Mauchly's test statistic assessed violations of sphericity. Greenhouse–Geisser corrections were used for violations. The effects of configuration size (long, short) and gaze condition (TF, MF, and RTF) on mean variables were analyzed with repeated measures ANOVAs (Tukey's post hoc tests). The effect size (ES), corresponding to partial eta squared, provided insight into the strength of relationships for significant outcomes. ES strength was considered small ≤ 0.25, large ≥ 0.40, or medium between 0.25 and 0.40 (Cohen 1969). Owing to the smaller number of trials in the control condition, comparisons between the control trial and each gaze condition for each configuration size and variable were made using dependent *t* tests and included Bonferroni corrections for multiple comparisons. We determined whether significant associations existed between step displacement and COPamp, COPtime, GRFampN, and PV across and within participants using Spearman's correlations. Alpha level was 0.05 for all analyses, unless corrected.

Results

Perceptual judgments

We recorded perceptual responses prior to a step to assess the V−H illusory influences on perceptual judgments for the short configuration. Table 2 shows the associated perceptual judgment response percentages for the three gaze conditions. Fourteen out of fifteen participants always perceived longer bisecting segment and/or equal bisecting and bisected segments when presented with a short bisecting segment. Only one person reported "horizontal" on a few trials. Illusory responses for most participants in this study were 100% for each gaze condition to confirm strong V−H illusory effects on perceptual judgments.

Table 2 Perceptual judgment response percentages for the short configuration

Target fixation (TF)			Movement fixation (MF)			Remembered target fixation (RTF)		
Vertical	Equal	Horizontal	Vertical	Equal	Horizontal	Vertical	Equal	Horizontal
56%	40%	**4%**	57%	41%	**2%**	57%	39%	**4%**

Bold numbers: Percent of correct responses

Stepping task

Mean step displacement for each participant is shown for each gaze condition and the control condition (Fig. 4). These data show that mean step displacement varied across participants within each gaze condition and the control condition. Review of individual participant's data revealed varying trends across these conditions.

To explore whether length estimations of the V−H illusion using stepping movements would differ for different sizes among gaze directions, we analyzed effects of configuration size and gaze condition on variables of interest.

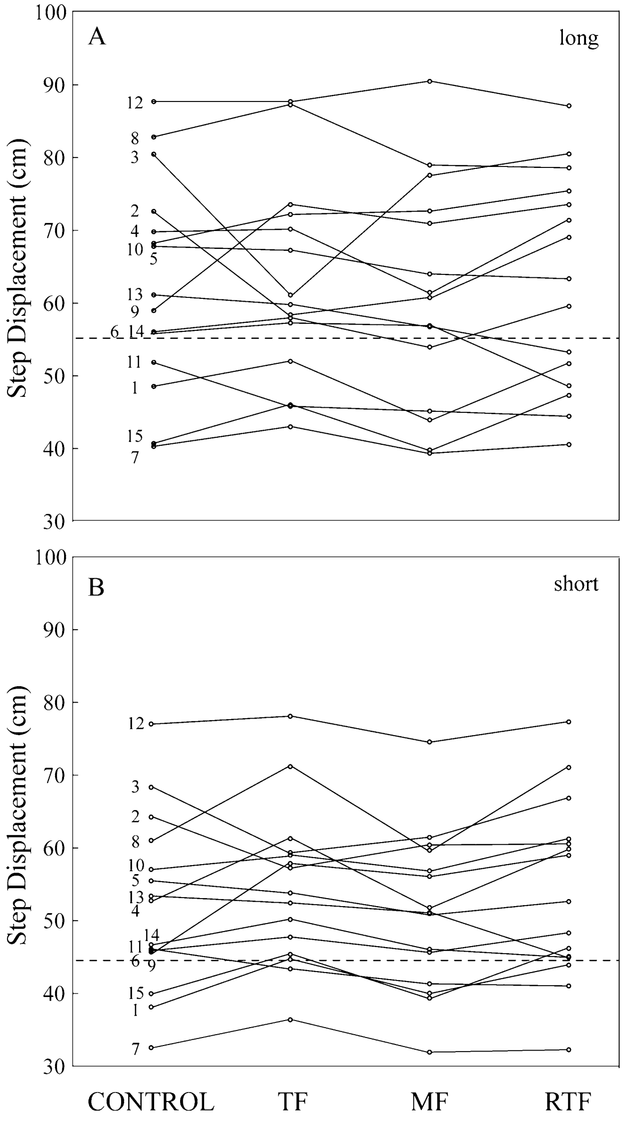

Fig. 4 Mean step displacement is shown for each participant (identified by number) for each gaze condition (*TF* target fixation, *MF* movement fixation, *RTF* remembered target fixation) and the control condition. The horizontal dashed lines stand for the actual length of the vertical segment on the projector screen for long **A**, 55 cm, and short **B**, 45 cm sizes

Significant results for mean step displacement, mean PV, and mean GRFampN were found. A significant main effect of configuration size on step displacement indicated that participants displaced their foot more when presented with long (62.2 ± 3.7 cm) than short (53.2 ± 2.9 cm) configurations ($F(1,14) = 61.90$, $p < 0.001$, ES = 0.82) revealing that participants adjusted step displacement according to size and overestimated lengths on average by about 7.5 cm. Significant main effects of configuration size ($F(1,14) = 59.17$, $p < 0.001$, ES = 0.81, Fig. 5A) and gaze condition ($F(2,28) = 33.26$, $p < 0.001$, ES = 0.70, Fig. 5B) on PV were also observed. Participants used less PV for short than long configurations and less PV in MF condition than RTF and TF conditions. Similarly, the results revealed significant main effects of configuration size ($F(1,14) = 10.60$, $p = 0.006$, ES = 0.43, Fig. 5C) and gaze condition ($F(1.44, 20.08) = 17.49$, $p < 0.001$, ES = 0.56, Fig. 5D) on GRFampN to indicate that participants exerted the greatest vertical forces for the long configuration and in TF and RTF conditions. Moreover, results of t tests indicated no significant differences between gaze conditions and control conditions for step displacement. Although similarities existed between MF and control trials for PV and GRFampN ($p > 0.05$), mean PV and GRFampN for control trials were significantly smaller than those for TF and RTF ($p < 0.005$).

To determine whether size of the configuration or gaze restrictions influenced participant's abilities to plan a movement, we examined the main effects of configuration size and gaze condition on APA-related variables: COPtime and COPamp. The results showed a significant main effect of gaze condition on COPtime ($F(1.43,20.08) = 4.20$, $p = 0.024$, ES = 0.23) and COPamp ($F(2,28) = 25.09$, $p < 0.001$, ES = 0.64), indicating that participants spent longer time to reach the peak COPx and produced a greater COPx amplitude (Fig. 6A) in TF and RTF conditions than MF condition. The significant interaction of configuration size x gaze condition for COPtime ($F(2,28) = 3.84$, $p = 0.030$, ES = 0.22) revealed that the shorter COPtime observed for MF condition only existed for the short configuration (Fig. 6B). Significant differences also existed between control trial COPamp and COPamp of TF and RTF gaze conditions ($p < 0.005$), revealing similarities in COPamp values for control trials and the MF condition once again. In contrast, COPtime values for control trials did not significantly differ from TF, RTF, or MF.

To assess whether step displacement associated with temporal aspects of movement and variables of motor planning, we correlated PV, GRFampN, COPtime, and COPamp with step displacement for each configuration. Significant positive correlations were observed between step displacement and PV in the three gaze conditions and control condition for each configuration size across participants (Fig. 7). These results indicated that participants

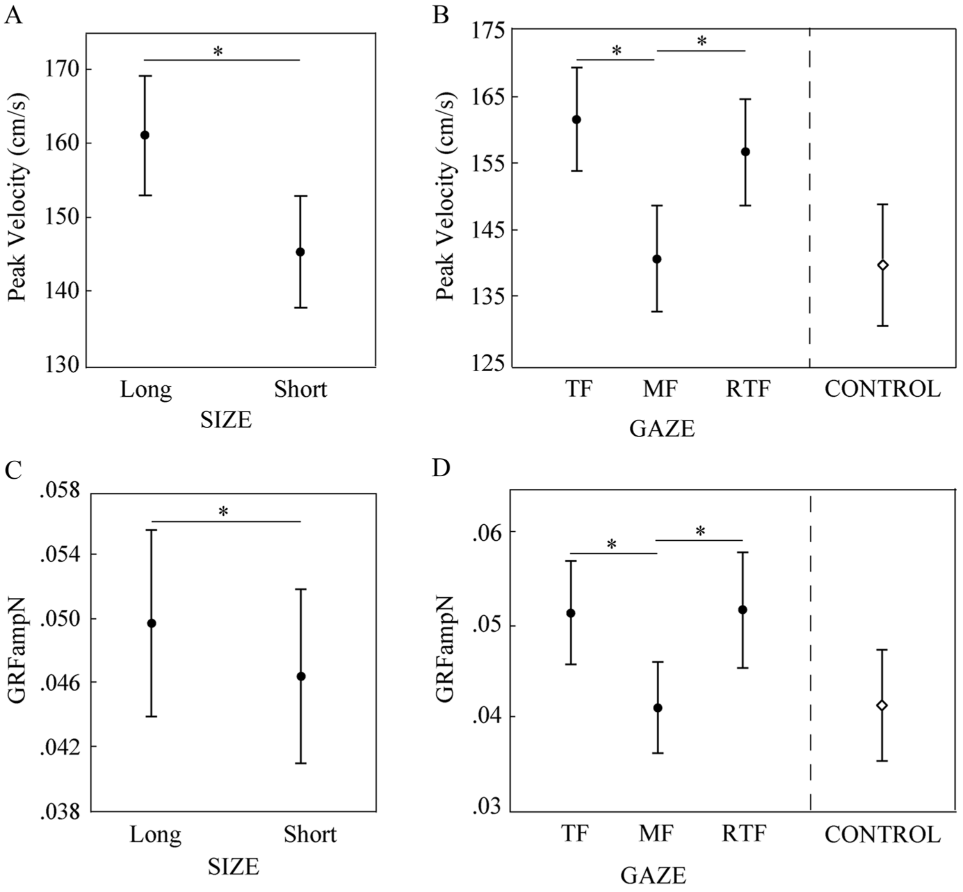

Fig. 5 Main effects of size (long, short) and/or gaze condition (*TF* target fixation, *MF* movement fixation, *RTF* remembered target fixation) on peak velocity **A** and **B**, and normalized ground reaction force amplitude—GRFampN **C** and **D** are shown. Data represent means (solid circles) ± 1 standard error. Data of control trials (open diamonds) are also shown. Asterisks indicate a difference between means of two conditions

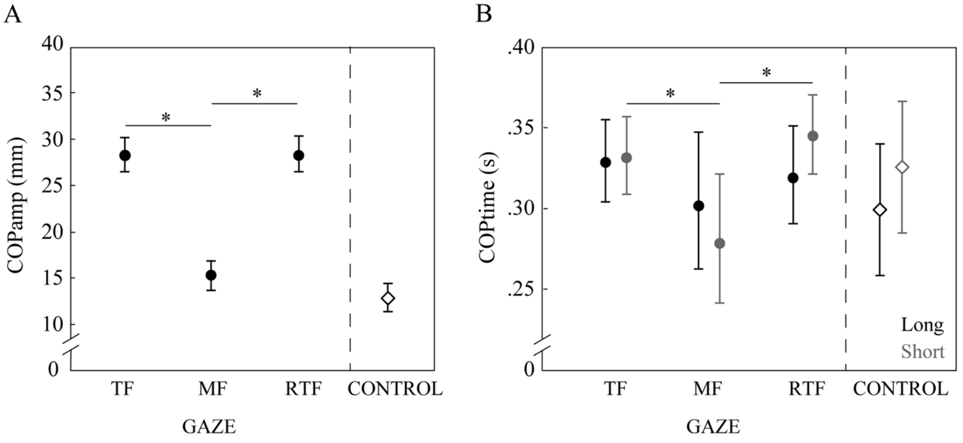

Fig. 6 Main effect of gaze condition (*TF* target fixation, *MF* movement fixation, *RTF* remembered target fixation) on anticipatory postural adjustment amplitude—COPamp (**A**) and the interaction of configuration size (long, short) x gaze condition on anticipatory postural adjustment time—COPtime (**B**). Data represent means (solid circles) ± 1 standard error. Data of control trials (open diamonds) are also shown

who achieved greater PV displaced the foot more regardless of gaze direction and configuration size. Within subject correlations of PV and step displacement only revealed significant correlations for 6 participants or less for each configuration size and gaze condition pairing (1 for long TF, 5 for long MF, 3 for long RTF, 5 for short TF, 6 for short MF, 5 for short RTF) to indicate few associations between step displacement and PV within a person. With few significant within subject correlations between step displacement and GRFampN (4/90), COPtime (6/90), and COPamp (4/90), and no significant across participant correlations ($p > 0.05$) we determined that these variables did not correlate uniformly with step displacement across or within participants. These results suggest no associations of APAs and vertical ground reaction forces with step displacement in our participants.

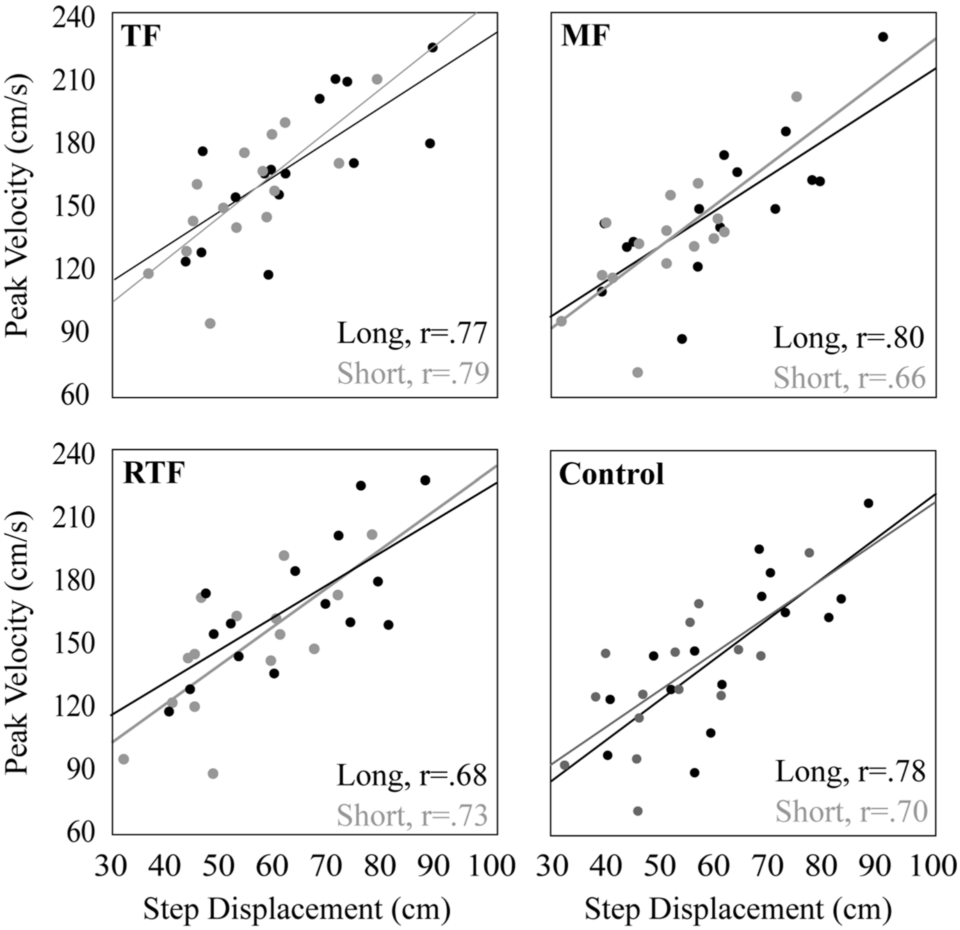

Fig. 7 Significant positive correlations existed between peak velocity (PV) and step displacement for long (black) and short (gray) configurations in each gaze condition (*TF* target fixation, *MF* movement fixation, *RTF* remembered target fixation, and Control). Each data point represents the mean PV plotted against mean step displacement for one participant in the given condition. Black and gray lines represent a linear fit to the corresponding data for long and short configurations, respectively

Discussion

The primary aim of this study was to determine whether size estimates using stepping movements would be influenced by the V−H illusion according to gaze direction restrictions and use of visual feedback. We first discuss the effects of V−H illusory influences on perceptual judgments in the context of the existing literature. Then, we discuss the effects of configuration size and gaze condition on step displacement and other variables associated with stepping and include discussion on the relationship between the illusory influences on perception and performance. Discussions include the application of our findings to the relationship between perception and action and how our results contribute to visuomotor control for the lower extremity.

Perceptual judgments

In the present study, participants perceived a longer bisecting segment length than the length of the bisected segment of the V−H illusion even when presented with the short configuration, in which the bisecting segment was actually shorter than the bisected segment. Thus, participants in the present study revealed V−H illusory influences on perception similar to others, who revealed the greatest influences for a bisected, IT configuration (Finger and Spelt 1947; Wolfe et al. 2005; Gavilán et al. 2017). Restricting gaze fixation on the intersection of the bisecting and bisected segments of the IT V−H illusion produced high percentages of illusory responses on perceptual judgments (Table 2) probably because gaze restrictions on the illusion elicit robust effects on perceptual judgments (Chouinard et al. 2017; Yan and Hondzinski 2021).

Length estimations

Length estimations via step displacements by our participants changed according to the size of the V−H illusion. The configuration size effect on step displacement, which revealed longer step displacements for the long compared to short configurations, indicates that participants can alter segment length estimations relative to the length of the bisecting segment of the V−H illusion. Although these results do not address the purposes of this study, they at least demonstrate that participants tried to follow task instructions as self-reported.

The insignificant gaze condition effect on step displacement contradicted the posed hypothesis that size estimates using step displacements would be more biased by the V−H illusion in TF, MF, and RTF conditions compared to control trials. Irrespective of the consistent relative size estimations, length estimations varied greatly across participants for control trials and gaze conditions (see Fig. 4) to reveal inaccurate length estimations of vertically oriented segments using the lower limb displacements. These findings are not consistent with a previous report showing biased movement distances during open-loop stepping/hopping according to the Müller−Lyer illusion (Glover and Dixon 2004) or average manual displacements according to the V−H illusion with gaze direction restricted (Yan and Hondzinski 2021).

One obvious potential explanation for the nonsignificant results is linked to the perception–action dissociation, in which the action, in this case of step displacement, differs from perceptual judgments (Goodale and Milner 1992; Haffenden and Goodale 1998). However, we also consider another explanation, which links to the plane of stimulus presentation relative to the plane of movement. People actually altered step displacement according to the Müller–Lyer illusion (a line segment with inward or outward facing arrows) when stepping without vision occurred after viewing illusion presentation on the stepping surface (Glover and Dixon 2004). People also produced greater vertical toe clearance while ascending stairs (Elliott et al. 2009; Foster et al. 2015) or stepping over obstacles (Foster et al. 2016) when presented with multiple vertical segments on the vertical surface of stair or obstacle, respectively. In these cases, the plane of step displacement and plane of visual presentation coincided. In contrast, people in the present study viewed vertically oriented stimuli and performed step displacements on the horizontal surface of the ground. These outcomes may correspond to the fact that goal-directed hand movement accuracy on a horizontal surface differs from the accuracy of goal-directed hand movements on vertical surfaces, the surface of visual stimulus presentation (Dalecki et al. 2019). These authors suggest that the increased cognitive effort required for plane dissociation of stimulus presentation and movement can explain accuracy decreases. According to this reasoning, the general biases matching illusory influences to movement may exist for conditions when movement displacements align with the direction of stimulus presentation, requiring less cognitive processing. Illusory influences on lower limb movement may only occur when the stimulus and movement displacement are parallel in direction in the same plane or at least in parallel planes. Future studies are warranted to test these hypotheses.

We also consider the possibility of motor adaptation across trials within our participants to explain the nonsignificant step displacement findings across experiment conditions. Previously, researchers showed an existence of locomotor adaptation in toe elevation when stepping over obstacles with repeated exposure to illusory stimuli placed on the rise of the obstacles (Rhea et al. 2010). Increased toe clearance observed early in clearing obstacles with illusory stimuli disappeared with practice. After receiving corrective feedback about the greater toe clearance, people in that study likely reoptimized their performances during the learning process (Bütefisch et al. 2000) and altered their toe clearance accordingly. Since participants in our study did not receive corrective feedback, we expected no need for correction of unknown errors. Review of the data support this supposition, as we noticed only 3 of 90 significant negative correlations between trial number and step displacement for experimental conditions. With no evidence of motor adaptation across trials, we now consider other aspects of the movement.

Anticipatory postural adjustments

APA variables, COPtime and COPamp, can help explain the motor planning phase of stepping (Mann et al. 1979; Burleigh-Jacobs et al. 1997; Ruget et al. 2008). Increases in APA durations often accompany worse balance (Remelius et al. 2008; Ruhe et al. 2011). For example, people with Parkinson's disease, known for imbalance, are less capable of generating a fast COP displacement (Burleigh-Jacobs et al. 1997; Palmisano et al. 2020). The greater COPtime, thus APA durations, in TF and RTF conditions compared to MF and controls, especially for the short configuration (see Fig. 6B), indicated greater illusory influence over participants motor planning in these conditions. The greater illusory influence on motor planning in TF and RTF likely results from gaze direction effects on body orientation (Hondzinski and Kwon 2009) and step direction (Hondzinski and Cui 2006). This possibility is further supported by the fact that gaze direction influences on step direction do not affect step amplitude (Hondzinski and Cui 2006), similar to results in the present study. Relatively small COP amplitudes prior to the step initiation occur in people with neurological impairments, such as multiple sclerosis (Remelius et al. 2008), Parkinson's disease (Gantchev et al. 1996; Halliday et al. 1998; Morris et al. 2001; Martin et al. 2002; Mancini et al. 2009; Palmisano et al. 2020), and people with low back pain (Ruhe et al. 2011) to suggest alterations in movement planning that differ from healthy controls. Although participants in the present study were not neurologically impaired, they did produce smaller COPamp in MF condition compared to TF and RTF conditions. With no significant differences from control trials, we reasoned that task requirements of estimating bisecting segment lengths when able to view the lower limb right before and during stepping differed from planning in the TF and RTF conditions, in which viewing was restricted away from the movement. Furthermore and unlike other research (Zettel et al. 2002), greater APAs did not accompany greater step displacement in this study. It appears logical to conclude that APAs used for estimating segment lengths through a forward step in the current study, would differ from APAs used when people switched from a cognitive task involving backward counting by 3 s to stepping over a suddenly appearing obstacle used previously (Zettel et al. 2002).

Propulsive forces and peak velocity

Peak velocity of the stepping movement was influenced by configuration size and gaze condition. ANOVA and correlation results revealed that the greater peak velocities associated with faster movements for long configurations surpassed the smaller peak velocities for short configurations and corresponded to step displacement. With very long step lengths by a few participants, we considered the possibility that some participants stepped fast to help maintain balance rather than actually estimating step length as requested. Nevertheless, since each participant expressed they possessed the ability to complete the task, it seems apparent that these results support evidence revealing that greater peak velocities often coincide with larger movement excursions (Bahill et al. 1975; Newell et al. 1984; Pfann et al. 2001). Of greater interest in the present study is the evidence which revealed that smaller peak velocities existed for MF compared to TF and RTF conditions, yet did not change significantly for step displacements. The inability to view the limb and target during movement in TF and RTF, which can impair movement accuracy (Beaubaton and Hay 1986), likely created less certainty during task preparation. The faster stepping when confidence is low during movement planning, may be linked to greater balance control (Sun et al. 2015). COPtime results across gaze conditions support this low balance confidence possibility in TF and RTF conditions. The fact that we observed the smallest peak velocity and COPtime in the MF condition would suggest the potential for use of greater visual feedback (Khan and Franks 2000) for stepping and balance control (Baratto et al. 2002), and possibly, a false sense of length estimation accuracy.

Results for normalized peak vertical ground reaction force mimicked those for peak velocity to suggest an association between the two. Participants produced greater vertical ground reaction force for long configurations and longer step displacements compared to the shorter counterparts similar to elsewhere (Frederick and Hagy 1986). Our findings also compare similarly to hand movements in which greater grasping force (Jackson and Shaw 2000) and lifting force (Brenner and Smeets 1996) accompanied large-sized objects; thus, larger hand apertures. Similar to PV results, gaze condition effects on normalized peak vertical ground reaction force amplitude did not exist for step displacement. However, unlike results for PV, correlative relationships with step displacement also did not exist for normalized peak vertical ground reaction force amplitude. We use the discussion in the next section to address these seemingly contradicting outcomes.

Motor planning versus motor execution

We found evidence to support the use of V−H illusion influences on perceptual judgments in our participants in each of the gaze conditions. This is not surprising considering that viewing stimuli were the same for perceptual judgments across gaze conditions. We also found that allowing people to look down during movement (MF) produced similar results to control trials, regardless of the use of different stimuli and greater gaze restrictions set for MF. Looking down during movement in MF also resulted in different anticipatory postural adjustments, peak velocity, vertical ground reaction forces, yet similar length estimations using step displacements compared to restricting gaze away from movements (TF and RTF). Asking participants to look at the real or remembered intersection of the V−H illusion during the movement altered the planning of the step and early step execution through approximately the first half of the movement (see results of APA measures and PV) but not the final performance (step displacement). These findings support the use of a dynamic model in which illusory effects on movement can change over time (Glover and Dixon 2001) or the digit control model in which different parameters of movement rely on different spatial attributes (Smeets et al. 2003) with gaze directed away from movement. Results also support the use of a constant model in which no illusory influences existed on movement planning or execution (Danckert et al. 2002) with gaze direction toward movement to suggest gaze direction can influence illusory effects over movement control. Although our data do not support consistent illusory influences on step displacement performances, this may be linked to the poor performance of length estimations, thus greater errors using step displacements that occur with separate planes of stimulus presentation and movement (Dalecki et al. 2019).

Implications and future studies

The use of the V−H illusion may be developed into motor learning interventions to improve walking abilities in neurological populations in future studies. Walking speed is a critical clinical measurement of mobility (Saunders et al. 2020). Although step displacements remained the same, the results that revealed alterations in motor planning (APAs) and early step execution (PV) provided promising improvements in step initiation which may result in a faster walking speed. Future studies could include individuals with impaired walking ability to determine whether the methods, similar to those applied here, would generalize to other populations that may benefit from these alterations.

Conclusion

We found evidence that directing gaze toward movement after viewing an inverted *T* eliminated V−H illusory influences over movement planning and execution of length estimations using forward step displacements. We concluded that exploitation of simple deceptive visual cues in a vertical plane which may guide movement planning and early movement execution does not guide the termination of horizontal plane stepping movements according to the V−H illusory influences.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Azuma T, Ito T, Yamashita N (2007) Effects of changing the initial horizontal location of the center of mass on the anticipatory postural adjustments and task performance associated with step initiation. Gait Posture 26:526–531. https://doi.org/10.1016/j.gaitpost.2006.11.203

Bahill AT, Clark MR, Stark L (1975) The main sequence, a tool for studying human eye movements. Math Biosci 24:191–204. https://doi.org/10.1016/0025-5564(75)90075-9

Baratto L, Morasso PG, Re C, Spada G (2002) A new look at posturographic analysis in the clinical context: sway-density versus other parameterization techniques. Mot Control. https://doi.org/10.1123/mcj.6.3.246

Bartelt R, Darling WG (2002) Opposite effects on perception and action induced by the Ponzo illusion. Exp Brain Res 146:433–440. https://doi.org/10.1007/s00221-002-1198-2

Beaubaton D, Hay L (1986) Contribution of visual information to feedforward and feedback processes in rapid pointing movements. Hum Mov Sci 5:19–34. https://doi.org/10.1016/0167-9457(86)90003-5

Brenner E, Smeets JB (1996) Size illusion influences how we lift but not how we grasp an object. Exp Brain Res 111:473–476. https://doi.org/10.1007/BF00228737

Bruno N, Bernardis P, Gentilucci M (2008) Visually guided pointing, the Muller-Lyer illusion, and the functional interpretation of the dorsal-ventral split: conclusions from 33 independent studies. Neurosci Biobehav Rev 32:423–437. https://doi.org/10.1016/j.neubiorev.2007.08.006

Burleigh-Jacobs A, Horak FB, Nutt JG, Obeso JA (1997) Step initiation in Parkinson's disease: influence of levodopa and external sensory triggers. Mov Disord 12:206–215. https://doi.org/10.1002/mds.870120211

Bütefisch CM, Davis BC, Wise SP, Sawaki L, Kopylev L, Classen J, Cohen LG (2000) Mechanisms of use-dependent plasticity in the human motor cortex. Proc Natl Acad Sci 97(7):3661–3665. https://doi.org/10.1073/pnas.97.7.3661

Caderby T, Yiou E, Peyrot N, Begon M, Dalleau G (2014) Influence of gait speed on the control of mediolateral dynamic stability during gait initiation. J Biomech 47(2):417–423. https://doi.org/10.1016/j.jbiomech.2013.11.011

Chouinard PA, Peel HJ, Landry O (2017) Eye-tracking reveals that the strength of the vertical-horizontal illusion increases as the retinal image becomes more stable with fixation. Front Hum Neurosci 11:143–143. https://doi.org/10.3389/fnhum.2017.00143

Cohen J (1969) Statistical power analysis for the behavioural sciences. Academic Press, New York

Dalecki M, Gorbet DJ, Sergio LE (2019) Development of rule-based eye-hand-decoupling in children and adolescents. Child Neuropsychol 25:1098–1115. https://doi.org/10.1080/09297049.2019.1578342

Danckert JA, Sharif N, Haffenden AM, Schiff KC, Goodale MA (2002) A temporal analysis of grasping in the Ebbinghaus illusion: planning versus online control. Exp Brain Res 144(2):275–280. https://doi.org/10.1007/s00221-002-1073-1

Downton JH, Andrews K (1991) Prevalence, characteristics and factors associated with falls among the elderly living at home. Aging Clin Exp Res 3:219–228. https://doi.org/10.1007/BF03324009

Elliott DB, Vale A, Whitaker D, Buckley JG (2009) Does my step look big in this? A visual illusion leads to safer stepping behaviour. PLoS ONE 4:e4577–e4577. https://doi.org/10.1371/journal.pone.0004577

Finger FW, Spelt DK (1947) The illustration of the horizontal-vertical illusion. J Exp Psychol 37:243–250. https://doi.org/10.1037/h0055605

Foster RJ, Whitaker D, Scally AJ, Buckley JG, Elliott DB (2015) What you see is what you step: the horizontal-vertical illusion increases toe clearance in older adults during stair ascent. Invest Ophthalmol vis Sci 56:2950–3295. https://doi.org/10.1167/iovs.14-16018

Foster RJ, Buckley JG, Whitaker D, Elliott DB (2016) The addition of stripes (a version of the 'horizontal-vertical illusion') increases foot clearance when crossing low-height obstacles. Ergonomics 59:884–889. https://doi.org/10.1080/00140139.2015.1105304

Franz VH (2003) Planning versus online control: dynamic illusion effects in grasping? Spat vis 16:211–223. https://doi.org/10.1163/156856803322467491

Franz VH, Gegenfurtner KR, Bülthoff HH, Fahle M (2000) Grasping visual illusions: no evidence for a dissociation between perception and action. Psychol Sci 11:20–25. https://doi.org/10.1111/1467-9280.00209

Frederick EC, Hagy JL (1986) Factors affecting peak vertical ground reaction forces in running. J Appl Biomech 2:41–49. https://doi.org/10.1123/ijsb.2.1.41

Gantchev N, Viallet F, Aurenty R, Massion J (1996) Impairment of posturo-kinetic co-ordination during initiation of forward oriented stepping movements in parkinsonian patients. Electroencephalogr Clin Neurophysiol 101:110–120. https://doi.org/10.1016/0924-980X(95)00253-H

Gavilán JM, Rivera D, Guasch M, Demestre J, García-Albea JE (2017) Exploring the effects of visual frame and matching direction on the vertical-horizontal illusion. Perception 46:1339–1355. https://doi.org/10.1177/0301006617724979

Glover SR, Dixon P (2001) Dynamic illusion effects in a reaching task: evidence for separate visual representations in the planning and control of reaching. J Exp Psychol Hum Percept Perform 27:560–572. https://doi.org/10.1037/0096-1523.27.3.560

Glover S, Dixon P (2004) A step and a hop on the Müller-Lyer: illusion effects on lower-limb movements. Exp Brain Res 154:504–512. https://doi.org/10.1007/s00221-003-1687-y

Goodale MA, Milner AD (1992) Separate visual pathways for perception and action. Trends Neurosci 15:20–25. https://doi.org/10.1016/0166-2236(92)90344-8

Haffenden AM, Goodale MA (1998) The effect of pictorial illusion on prehension and perception. J Cogn Neurosci 10:122–136. https://doi.org/10.1162/089892998563824

Halliday SE, Winter DA, Frank JS, Patla AE, Prince F (1998) The initiation of gait in young, elderly, and Parkinson's disease subjects. Gait Posture 8:8–14. https://doi.org/10.1016/S0966-6362(98)00020-4

Hondzinski JM, Cui Y (2006) Allocentric cues do not always improve whole body reaching performance. Exp Brain Res 174:60–73. https://doi.org/10.1016/j.neulet.2005.11.071

Hondzinski JM, Kwon TY (2009) Pointing control using a moving base of support. Exp Brain Res 197(1):81–90. https://doi.org/10.1007/s00221-009-1893-3

Jackson SR, Shaw A (2000) The Ponzo illusion affects grip-force but not grip-aperture scaling during prehension movements. J Exp Psychol Hum Percept Perform 26:418–423. https://doi.org/10.1037/0096-1523.26.1.418

Khan MA, Franks IM (2000) The effect of practice on component submovements is dependent on the availability of visual feedback. J Mot Behav 32:227–240. https://doi.org/10.1080/00222890009601374

Koltermann JJ, Gerber M, Beck H, Beck M (2018) Validation of various filters and sampling parameters for a COP analysis. Technologies (2227–7080) 6:56. https://doi.org/10.3390/technologies6020056

Kopiske KK, Bruno N, Hesse C, Schenk T, Franz VH (2017) Do visual illusions affect grasping? Considerable progress in a scientific debate. a reply to Whitwell & Goodale, 2016. Cortex 88:210–215. https://doi.org/10.1016/j.cortex.2016.10.012

Mancini M, Zampieri C, Carlson-Kuhta P, Chiari L, Horak FB (2009) Anticipatory postural adjustments prior to step initiation are hypometric in untreated Parkinson's disease: an accelerometer-based approach. Eur J Neurol 16:1028–1034. https://doi.org/10.1111/j.1468-1331.2009.02641.x

Mann RA, Hagy JL, White V, Liddell D (1979) The initiation of gait. J Bone Joint Surg Am 61:232–239

Martin M, Shinberg M, Kuchibhatla M, Ray L, Carollo JJ, Schenkman ML (2002) Gait initiation in community-dwelling adults with parkinson disease: comparison with older and younger adults without the disease. Physical Therapy 82:566–577. https://doi.org/10.1093/ptj/82.6.566

McIlroy WE, Maki BE (1999) The control of lateral stability during rapid stepping reactions evoked by antero-posterior perturbation: does anticipatory control play a role? Gait Posture 9(3):190–198. https://doi.org/10.1016/s0966-6362(99)00013-2

Mendoza J, Hansen S, Glazebrook CM, Keetch KM, Elliott D (2005) Visual illusions affect both movement planning and on-line control: a multiple cue position on bias and goal-directed action. Hum Mov Sci 24:760–773. https://doi.org/10.1016/j.humov.2005.09.002

Morris ME, Huxham F, McGinley J, Dodd K, Iansek R (2001) The biomechanics and motor control of gait in Parkinson disease. Clin Biomech 16:459–470. https://doi.org/10.1016/S0268-0033(01)00035-3

Mouchnino L, Robert G, Ruget H, Blouin J, Simoneau M (2012) Online control of anticipated postural adjustments in step initiation: evidence from behavioral and computational approaches. Gait Posture 35(4):616–620. https://doi.org/10.1016/j.gaitpost.2011.12.009

Newell KM, Hancock PA, Robertson RN (1984) A note on the speed–amplitude function in movement control. J Mot Behav 16:460–468. https://doi.org/10.1080/00222895.1984.10735332

Palmisano C, Brandt G, Vissani M et al (2020) Gait initiation in Parkinson's disease: impact of dopamine depletion and initial stance condition. Front Bioeng Biotechnol 8:137–137. https://doi.org/10.3389/fbioe.2020.00137

Peirce JW (2007) PsychoPy—psychophysics software in python. J Neurosci Methods 162:8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Pfann KD, Buchman AS, Comella CL, Corcos DM (2001) Control of movement distance in Parkinson's disease. Mov Disord 16:1048–1065. https://doi.org/10.1002/mds.1220

Remelius JG, Hamill J, Kent-Braun J, Van Emmerik REA (2008) Gait initiation in multiple sclerosis. Mot Control 12:93–108. https://doi.org/10.1123/mcj.12.2.93

Rhea CK, Rietdyk S, Haddad JM (2010) Locomotor adaptation versus perceptual adaptation when stepping over an obstacle with a height illusion. PLoS ONE 5(7):e11544. https://doi.org/10.1371/journal.pone.0011544

Ruget H, Blouin J, Teasdale N, Mouchnino L (2008) Can prepared anticipatory postural adjustments be updated by proprioception? Neuroscience 155:640–648. https://doi.org/10.1016/j.neuroscience.2008.06.021

Ruhe A, Fejer R, Walker B (2011) Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature. Eur Spine J 20:358–368. https://doi.org/10.1007/s00586-010-1543-2

Russo Y, Vannozzi G (2021) Anticipatory postural adjustments in forward and backward single stepping: task variability and effects of footwear. J Biomech 122:110442. https://doi.org/10.1016/j.jbiomech.2021.110442

Saunders DH, Sanderson M, Hayes S, Johnson L, Kramer S, Carter DD, Jarvis H, Brazzelli M, Mead GE (2020) Physical fitness training for stroke patients. Cochrane Database Syst Rev 3(3):CD003316. https://doi.org/10.1002/14651858.CD003316.pub7

Sinclair J, Stainton P (2019) Effects of medial and lateral wedged orthoses on knee and ankle joint loading in female runners. Kinesiology 51:189–197

Sinclair J, Bottoms L, Taylor PJ, Mahmood K (2017) Effects of shoes on kinetics and kinematics of the squash forward lunge in male players. Kinesiology 49:178–184. https://doi.org/10.26582/k.49.2.9

Smeets JB, Glover S, Brenner E (2003) Modeling the time-dependent effect of the Ebbinghaus illusion on grasping. Spat vis 16:311–324

Sun R, Guerra R, Shea JB (2015) The posterior shift anticipatory postural adjustment in choice reaction step initiation. Gait Posture 41:894–898. https://doi.org/10.1016/j.gaitpost.2015.03.010

Tinetti ME, Speechley M, Ginter SF (1988) Risk factors for falls among elderly persons living in the community. N Engl J Med 319:1701–1707. https://doi.org/10.1056/nejm198812293192604

Turano KA, Geruschat DR, Baker FH, Stahl JW, Shapiro MD (2001) Direction of gaze while walking a simple route: persons with normal vision and persons with retinitis pigmentosa. Optom vis Sci 78:667–675. https://doi.org/10.1097/00006324-200109000-00012

Westwood DA, Chapman CD, Roy EA (2000) Pantomimed actions may be controlled by the ventral visual stream. Exp Brain Res 130:545–548. https://doi.org/10.1007/s002219900287

Wolfe U, Maloney LT, Tam M (2005) Distortions of perceived length in the frontoparallel plane: tests of perspective theories. Percept Psychophys 67:967–979. https://doi.org/10.3758/BF03193624

Wood G, Vine SJ, Wilson MR (2013) The impact of visual illusions on perception, action planning, and motor performance. Atten Percept Psychophys 75(5):830–834. https://doi.org/10.3758/s13414-013-0489-y

Woodworth RS (1899) Accuracy of voluntary movement. Psychol Rev: Monogr Suppl 3(3):i–114. https://doi.org/10.1037/h0092992

Yan S, Hondzinski JM (2021) Gaze direction changes the vertical-horizontal illusory effects on manual length estimations. J Mot Behav 53:92–104. https://doi.org/10.1080/00222895.2020.1732286

Zettel JL, McIlroy WE, Maki BE (2002) Environmental constraints on foot trajectory reveal the capacity for modulation of anticipatory postural adjustments during rapid triggered stepping reactions. Exp Brain Res 146:38–47. https://doi.org/10.1007/s00221-002-1150-5

Zettel JL, Holbeche A, McIlroy WE, Maki BE (2005) Redirection of gaze and switching of attention during rapid stepping reactions evoked by unpredictable postural perturbation. Exp Brain Res 165:392–401. https://doi.org/10.1007/s00221-005-2310-1