Cautious gait in relation to knowledge and vision of height: is altered visual information the dominant influence?

M. C. A. Tersteeg, Dilwyn E. Marple-Horvat, and Ian D. Loram
Institute for Biomedical Research into Human Movement and Health, Manchester Metropolitan University, Manchester, United Kingdom

Submitted 27 September 2011; accepted in final form 26 February 2012

There are several reasons why height might present a visual stimulus that is disturbing.

Visual information powerfully influences the human sense of upright orientation. In the absence of cutaneous contact with a fixed surface, humans tend to orientate and sway in accordance with environmental visual information even when this conflicts with vestibular sources of information (Allison et al. 2006; Dobie et al. 2003; Kiemel et al. 2006; Oie et al. 2001). It has been repeatedly demonstrated that moving the surroundings while a person attempts to stand stationary results in enhanced postural sway and even loss of balance (Lishman and Lee 1973).

Visual information not only influences stance but also locomotion and possibly has an even stronger effect during locomotion than during stance (Jeka et al. 2009; Logan et al. 2010). Logan and colleagues (2010) showed that the low frequency coupling (gain) between unpredictable visual flow and trunk orientation are very similar during stance and locomotion. This shows that postural control of the trunk (unrelated to the stepping cycle) is similarly weighted to visual information in stance and locomotion. In addition, at the transition from stance to swing phase, thigh angle showed a large response to large field visual stimulation. This implies that the nervous system may upweight its use of vision during swing initiation to aid leg/foot control which would not be required during stance. This shows that just as in stance, visual flow is a potent factor during locomotion.

So when at height, what is the effect of visual information on standing and walking? When standing at height, information obtained through motion parallax will be altered because objects on the distant ground provide reduced angular deviation. Thus, visual resolution of sway will be degraded: this is true whether perception of sway arises from retinal slip or from sensation of eye or head rotations during foveal tracking of objects (Kapoula and Lê 2006). It is well known that increasing viewing distance has the effect of increasing antero-posterior and mediolateral postural oscillation and decreasing postural stability (Bles et al. 1980; Brandt et al. 1986; Kapoula and Lê 2006; Paulus et al. 1984, 1989).

Walking at height will alter the relationship between body motion and optic flow rate. At height, the ground is much further away than during overground walking; therefore, the rate of optic flow would suggest a lower than actual walking speed, which is disturbing. Previous experiments predict this would increase gait progression (Chou et al. 2009; Konczak 1994; Palhous et al. 1990; Prokop et al. 1997). However, the observation that people slow down at height suggests that other

Address for reprint requests and other correspondence: M. C. Tersteeg, Institute for Biomedical Research into Human Movement and Health, Manchester Metropolitan Univ., John Dalton Bldg., Oxford Road, Manchester, M1 5GD, UK (e-mail: m.tersteeg@mmu.ac.uk).
factors, such as lack of visual anchor, may affect gait in the opposite direction to the changed optic flow.

More importantly, disparity in optic flow is likely to be confusing and has been shown to alter gait (Chou et al. 2009). On the walkway at height, in a large proportion of the visual field (the floor), the optic flow is altered and is disparate from the familiar flow from the walkway, walls and ceiling. An everyday example of this disparity would be encountered when walking on a motorized walkway in an airport where people slow down (Young 1999).

These visually driven balance mechanisms suggest that when at height, visual feedback may be disturbing and also less effective. It is possible that removing visual exposure, while retaining knowledge of the fall, may eliminate the observed changes in balance and gait.

Virtual reality experiments have shown that vision of height is a powerful manipulator of sway and movement during standing (Simeonov et al. 2005) and walking (Hsiao et al. 2005). This might be thought to confirm the effect of visual information of height on stance and locomotion. However, the use of a virtual environment does not allow one to discriminate the cause of the observed changes as either 1) the content of the visual information, meaning altered optic flow, reduced angular deviation due to objects that are further away, etc., or 2) the subjective interpretation of the visual information, if a person believed in the virtual reality and thus believes themselves to be at height.

The aim of this study is to establish whether the disturbing effects of visual exposure can be eliminated by removing all visual information of the height while retaining full knowledge, danger, and risk of the drop. If all disturbances of normal walking are eliminated when sight of the drop is removed, then it is primarily the visual stimulus that causes the adaptations. If the disturbed control of walking is maintained when sight of the drop is eliminated, we can exclude visual information as the primary factor causing changes to the control and pattern of walking. Our hypothesis is that removing visual exposure alone will remove the disturbing effects so that walking at height is indistinguishable from walking at ground level.

**METHODS**

Subjects. Twelve healthy subjects, three female and nine male, aged 34 ± 10 years (means ± SD), voluntarily participated in this study and gave informed, written consent. Ethical approval was obtained from the ethics committee of the Department of Exercise and Sport Science, Manchester Metropolitan University.

Apparatus and measurements. Subjects were asked to perform three different walking tasks at a self-selected walking velocity in random order. In order of increasing postural threat, the tasks were: 1) ground walkway (GW), walking along a 4.8-m long walkway (22 cm wide, walkway height 4.3 cm) at ground level; 2) high walkway with sheets (HWS), walking along a similar walkway 3.5 m off the ground with sheets attached horizontally around the beam to remove visual exposure to the drop; and 3) high walkway (HW), walking along the 3.5-m high walkway without the sheets attached (Fig. 1). Any differences between the visual exposure while retaining knowledge of the drop.

Before the HWS task, subjects watched a demonstration (placing a light weight on the sheets) in which the sheets would come off very easily to make sure that the subject knew that it would provide no support whatsoever. Subjects performed three consecutive trials for each high-beam task and four for the ground-beam task.

The high walkway (a scaffold plank) was attached to the railing of a mezzanine floor and supported by a custom made wooden construction. The visibility of the supporting construction was designed to be minimal when standing on the walkway, and the design was rigid to eliminate instability as a source of fear. The walkway stopped halfway in the building and had as such an open end. Sheets (240 cm × 700 cm) could be attached to the sides of the walkway with velcro. The sides of the sheets distant from the walkway were attached with strings to each of the far and side walls: this provided a level surface that fully obscured the view of the drop in all directions (sides and end of walkway). The ground walkway was positioned on the mezzanine floor to minimize the difference in ceiling height between the ground and high walkway (difference was less than 1 m). Subjects wore a full body safety harness and climbing helmet during all walking tasks. While walking on the high walkway, they were attached to a safety system, in case of a fall. Subjects were not allowed to test the safety system, in case of a fall. Subjects were not allowed to test the safety system.

During walking on the high walkway, they were attached to a safety system, in case of a fall. Subjects were not allowed to test the safety system. While walking on the high walkway, they were attached to a safety system, in case of a fall. Subjects were not allowed to test the safety system.

Data analysis. In this study, we present the analysis of the walk to the end of the walkway of the first trial of each task. Data analysis was performed in Matlab 7.4 (The Mathworks). Marker data were filtered using a fourth-order bidirectional, zero lag, low-pass Butterworth filter with cut-off frequency 5 Hz. Heel strike and toe-off were determined to calculate stride length, stride time, and double support.
phase (DSP) as percentage of the gait cycle duration. Heel strike was determined by a peak in the downward velocity of the toe marker, and toe-off was determined by the maximum upward velocity of the heel marker (Pijnappels et al. 2001). All strides in a trial were entered in the analysis and averaged over the trial. Walking velocity was calculated from the two back markers on the harness from the first until the last right heel strike. Prior to the start of the experiment, a standing trial was conducted in which subjects were asked to stand as still as possible. This trial was used to obtain a baseline level for GSC. GSC levels for each trial were calculated by dividing the signal by the baseline and taking the average over all strides. For one subject, the GSC could not be obtained due to technical difficulties and was excluded from the GSC analysis. One subject was unable to walk to the end of the walkway. For this subject, only the strides made were included. Coefficient of variation (CoV) was calculated for all measures as an indication of variability.

Statistical analysis. SPSS 16.0 (SPSS) was used for statistical analysis. To see whether gait pattern and GSC differed between the tasks, a linear mixed model with the factor task (GW, HWS, and HW) was performed separately for GSC, DSP, velocity, stride length, and stride time as dependent variables. The chosen error structure for the model was compound symmetry. If a significant effect for task was observed, a pairwise comparison of the estimated marginal means was used to see which tasks differed from each other. A Bonferroni correction to adjust for multiple comparisons was used for these tasks.

To see if GSC could be seen as an independent variable compared with the kinematic measures, a principal component analysis was conducted on the variables GSC, DSP, velocity, stride length, and stride time, without a rotation structure. Following this analysis, Pearson's correlations were calculated between GSC and each of the kinematic measures to see the extent to which physiological arousal and voluntary motor control were coupled. For all tests, a significance level of $P < 0.05$ was used.

RESULTS

Modifications to walking in response to knowledge and vision of the drop. Figure 2 shows how subjects modified their gait and GSC when faced with three levels of postural threat. These levels of postural threat were walking on the walkway at ground level, walking at height with knowledge of the drop but vision of the drop removed, and walking at height with both knowledge and vision of the drop. Figure 2A shows that on average physiological arousal increased significantly with each increase in postural threat [$F(2,20) = 22.3, P < 0.01$], increasing due to knowledge of the drop with 38% ($P < 0.01$) and with a further significant increase when visual information of the drop was present to levels 64% higher than on the ground ($P = 0.04$). In all kinematic measures (Fig. 2, B–E), there was a significant change in walking when comparing the three walking tasks [DSP: $F(2,22) = 10.1, P < 0.01$, velocity: $F(2,22) = 13.3, P < 0.01$, stride length: $F(2,22) = 7.77, P < 0.01$ and stride time: $F(2,22) = 4.33, P = 0.03$]. All gait measures were significantly different between the task at height with visual information and the task on the ground (HW vs. GW). When vision of the drop was removed (HWS vs. HW), there was no significant change in gait measures [DSP: $P = 0.58$, velocity: $P = 0.65$, stride length: $P = 0.63$, and stride time: $P = 1.00$]; however, those measures were all closer to that observed at ground level.

The sizes of the observed gait changes were substantial. The percentage of time spent in DSP more than doubled (from 17% to 40% of the gait cycle) when subjects walked at height compared with ground level (HW vs. GW) ($P < 0.01$). Also, subjects walked more slowly at height (0.61 ms$^{-1}$ vs. 0.95 ms$^{-1}$, HW vs. GW, $P < 0.01$). The change in velocity (HW vs. GW) was caused by both a decrease in stride length and an increase in stride time ($P < 0.01$ and $P = 0.04$, respectively). When visual information was removed (HWS vs. HW), DSP was on average reduced to 32% and velocity increased to 0.70 ms$^{-1}$. These changes were not significant at $P = 0.05$ level. Knowledge and vision of being at height therefore powerfully modified walking. The reduction in modification seen when...
visual exposure was removed was by comparison weaker than the modification made when both knowledge and vision were present.

Figure 2 also shows that variation increases with postural threat. For instance, for velocity, the CoV at ground level was 0.33; this increased to 0.54 on the high walkway without visual information and to 0.70 for walking on the high walkway with both knowledge and vision of the drop present. This indicates that subjects respond differently to the three tasks, especially in the high walkway tasks.

**Association between physiological arousal and kinematics.**

Two components were included in the principal component analysis in combination explaining 90.5% of the variance. Component 1 explained 76.2% of the variance, and component 2 explained 14.2%. Items that cluster on the same components suggest that component 1 represents mainly kinematics, with a moderate contribution from GSC; and component 2 represents mainly arousal with a minor contribution from kinematics (Fig. 3A). This shows that GSC is partially different from but largely related to the kinematic measures.

The correlation analysis revealed that an increase in GSC was associated with an increase in DSP ($r = 0.54, P < 0.01$, Fig. 3B). The figure shows that with an increase in GSC, the variation in DSP becomes larger, similar to what we observed with the CoV. Furthermore, velocity, stride length, and stride time also correlate significantly with GSC and showed similar graphs, an increase in variability with an increase in GSC ($r = -0.52, P < 0.01; r = -0.46, P < 0.01; r = 0.35, P < 0.05$, respectively) (Fig. 3C). So, an increase in GSC was associated with a change in kinematic measure that is towards a more cautious gait pattern.

**DISCUSSION**

In this study the following main results were obtained: 1) Height produced substantial, significant changes in physiological arousal and gait (Fig. 2, GW vs. HW). 2) Removing vision of the drop, while retaining danger and knowledge of the risk, did not change the walking pattern in response to height (Fig. 2, HWS vs. HW). Therefore, visual information is rejected as the dominant disturbing influence. Knowledge of postural threat was the more powerful factor driving the changes. 3) Between GSC and kinematic locomotor changes, GSC was more strongly related to the availability of visual information of the drop.

The disturbing effect of visual information when walking at height. Visual information does indeed contribute to autonomic response to height. Our results showed a significant reduction in GSC when visual information of the drop was removed when walking at height (Fig. 2, HWS v HW). Since subjects retained knowledge of the danger and risk, and only visual information was altered, this confirms that visual information, associated with the drop, contributes to the elevated physiological arousal. This finding is consistent with those postural control studies that found that closing the eyes significantly mitigated the disturbing effect of standing on an edge with eyes open (Carpenter et al. 1999, 2001; Sibley et al. 2007).

However, altered visual information was not the main stimulus causing disturbed arousal and locomotion (Fig. 2). In the intermediate task (HWS), the surrounding sheets removed all sight of the drop and provided the same viewing distance and optic flow as the floor when walking at ground level. Since the cautious gait and elevated arousal observed at height (HW) was still present in this task, it can be concluded that altered optic flow or angular deviation of objects due to viewing distance are

---

**Fig. 3.** Physiological arousal is associated with the gait pattern. The principal component analysis shows that GSC is largely related to the kinematic measures (component 1) but that GSC is also partially reflecting a factor barely associated with the kinematic measures (component 2) (A). B and C illustrate that an increase in GSC is correlated with a more cautious gait pattern. V, velocity; SL, stride length; ST, stride time.
not the stimulus that causes these changes (Fig. 2). In fact, comparing walking at height with (HW) and without (HWS) visual information of the drop, there was no significant difference in any gait measures, and the difference in arousal was small (Fig. 2, HWS vs. HW). Thus we reject the altered visual environment as the main cause of altered gait. Knowledge of danger and risk, i.e., cognition, was the main stimulus to modify walking.

The disturbing effect of knowledge when walking at height. This result leads us to consider an explanation from nonvisual factors, which could challenge motor control when at walking at height. The consequences of a fall are different between the tasks; the consequences of a fall or step off the walkway are much more severe at height compared with the walking task at ground level. As such, the task at height creates a different control problem than the task at ground level, one where a tighter control might be preferred.

The perception of these consequences, of the danger of the task, is subjective and individual. This would depend on a complex interaction of factors including familiarity/prior experience. This is reflected in the observed increase in variation with an increase in postural threat (Figs. 2 and 3). Perception of danger stimulates powerful neurophysiological mechanisms, which outputs include a release of stress hormones (Mason 1968), increased reflex excitability (Davis 1992), and behavioral responses such as freezing (Blanchard and Blanchard 1988; Davis 1992). The cautious gait and increased physiological arousal observed in response to knowledge of postural threat, even in the absence of visual input, are very naturally interpreted as responses of the “danger system” rather than responses of the balance system to altered visual input.

The functional significance of the response to postural threat. Survival may be best served by avoiding height. However, circumstances, including survival and performance, may require progression at height. Do the observed responses reflect the actual demands of controlling balance and movement at height? The reduction in velocity and increase in DSP are not improving the progression along the walkway. The increase in DSP could be more indicative of unwillingness to expose oneself to the more demanding single support phase than aiding progression. Regarding energy demand, the adaptations could be judged as less economical. The output pathway of the amygdala is considered to be responsible for both autonomic and behavioral responses following perception of danger (Blanchard and Blanchard 1988; LeDoux et al. 1988; LeDoux 1993). For example, adrenaline is known to alter muscle properties (Roatta and Farina 2010), decreasing twitch time and increasing the probability of tremor (Marsden and Meadows 1970). Therefore, if circumstances require progression at height, it seems questionable whether the observed gait adaptations are reflective of the demands of the task and even if these adaptations are helpful.

Whatever their prior experience, there are consequences of falling from height. Subjects’ intentional set must reflect their response to the risk. Literature shows that subjects move their center of mass away from the edge even at the cost of increased muscle activity and joint stiffness during cliff experiments (Adkin et al. 2000, 2002; Carpenter et al. 1999, 2001; Davis et al. 2009; Sibley et al. 2007). The intention is apparently to place the whole body center of mass as far from the edge as possible. It is possible that a similar strategy is used while walking on along the walkway, limiting lateral movement of the center of mass to the edges of the walkway. A change in strategy, a difference in priority, could lead to changes in the gait pattern. Further research to the coordination pattern and center of mass trajectory is necessary to answer these questions.

Resolution of results with other authors. Previous studies have used walkways of different height and width. Delbeare et al. (2009) used a 60-cm-high and 120-cm-wide walkway, while Brown et al. (2002) used a height of 60 cm in combination with two widths, 60 cm and 15 cm, and Caetano et al. (2009) used a 140- or 19-cm-wide surface on the floor and a 19-cm-wide surface 10 cm off the floor. In agreement with our findings, these authors found a decrease in velocity and stride length, and an increase in double support, indicating that a more cautious gait pattern is generally adopted when postural threat is increased. The differences between ground level and the elevated situation were less than we found. For instance, the decrease in velocity between the floor and elevated task in previous studies were 0.06 ms⁻¹ (Brown et al. 2002) and 0.18 ms⁻¹ (Delbeare et al. 2009), while we observed a decrease in velocity of 0.43 ms⁻¹. The difference between our study and those of Delbeare et al. (2009) and Caetano et al. (2009) is most likely explained by the difference in subject groups. Our subjects were healthy young adults, whereas the others measured elderly subjects and Parkinson’s patients. Brown et al. (2002) measured both young and older adults and found differences for both, but they used a 15-cm width, which is greater constraint in foot placement, and which possibly could explain the differences. Also, the height used in this study was moderate. It is possible that a greater height is necessary to induce postural threat great enough to observe gait changes to the magnitude we observed in young healthy adults.

Experimental clarifications. The average walking velocity on the ground walkway was 0.96 ms⁻¹, which is slower than values found in the literature for normal overground walking, 1.73 ms⁻¹ (Perry 1992). This slower velocity may be due to the 22-cm width of the walkway, which constrains foot placement. Brown et al. (2002) showed that velocity decreased when walkway width was reduced from 60 to 15 cm. Since this constraint was equal in all tasks, it could not explain any differences between the tasks at the height of 3.5 m. Furthermore, due to the nature of the task, walking at height, subjects wore a full body safety harness. Since the harness had straps between the legs, it might also have influenced the walking pattern. However, this harness was worn during all tasks so it could not explain differences between the tasks.

In theory, there are four experimental combinations with the factors height and vision each containing two levels: 1) height and no visual information of the drop; 2) height and vision of the drop; 3) ground and no visual information of a drop; 4) ground and vision of the drop. We did not investigate the fourth combination where visual information of the drop is present without being at height, as would be possible using a virtual environment. Studies using virtual reality show the powerful effect of the visual stimulus in absence of danger (Hsiao et al. 2005; Simeonov et al. 2005). But as already stated in the introduction, a virtual environment cannot discriminate between changes caused by either 1) influences on the balance system or 2) via the subjective interpretation of the visual
information (cognitive processes). Therefore, the fourth condition would not answer the question posed in this study.

Conclusions. Removing visual exposure did not significantly change the cautious gait pattern and produced a small, significant reduction in physiological arousal. We conclude that, in response to postural threat induced by height, higher level cognitive mechanisms rather than visually driven balance mechanisms were the dominant cause of cautious gait and elevated physiological arousal in response to postural threat.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of Dan Jones (Dept. of Interdisciplinary Studies, Manchester Metropolitan Univ.) for help with providing a practical and safe environment for walking at height. Thomas Finbow for assistance on data collections and technical support, and John Howell and Tom McKee for equipment construction and technical assistance. We also thank all anonymous subjects for their enthusiasm and time in carrying out these experiments.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS


REFERENCES


