Visual exteroceptive information provided during obstacle crossing did not modify the lower limb trajectory

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Abstract:
The roles of visual exteroception (information regarding environmental characteristics) and exproprioception (the relation of body segments to the environment) during gait adaptation are not fully understood. The purpose of this study was to determine how visual exteroception regarding obstacle characteristics provided during obstacle crossing modified foot elevation and placement with and without lower limb-obstacle visual exproprioception (manipulated with goggles). Visual exteroceptive information was provided by an obstacle cue – a second obstacle identical to the obstacle that was stepped over —– which was visible during crossing. Ten subjects walked over obstacles under four visual conditions: full vision with no obstacle height cue, full vision with an obstacle height cue, goggles with no obstacle height cue and goggles with an obstacle height cue. Obstacle heights were 2, 10, 20 and 30 cm. The presence of goggles increased horizontal distance (distance between foot and obstacle at foot placement), toe clearance and toe clearance variability. The presence of the obstacle height cue did not alter horizontal distance, toe clearance or toe clearance variability. These observations strengthen the argument that it is the visual exproprioceptive information, not visual exteroceptive information, that is used on-line to fine tune the lower limb trajectory during obstacle avoidance.
Keywords: Visual information; Visual exteroception; Visual exproprioception; Obstacle avoidance; Gait; Gait adaptations; Locomotion

Article:
Environmental visual cues and cues of one's self in relation to the environment are used for the planning and control of human movement [1,3]. Visual information during obstacle crossing can be used in a feedforward or on-line manner [5]. Feedforward refers to the use of visual information that was viewed before obstacle crossing, while on-line refers to the use of visual information available during obstacle crossing. A robust finding during obstacle avoidance is that the view of the lower limb as it crosses an obstacle is an important factor in controlling the lower limb trajectory [5,9]. Information of the body relative to the environment is termed visual exproprioception, which is distinguished from visual exteroception, information of environmental characteristics, such as height or color of an obstacle [3]. Researchers have manipulated visual exproprioception with the use of goggles (termed visual interference) that act as blinders to remove vision of the lower limbs, and this manipulation resulted in increased horizontal distance (the horizontal distance of the foot relative to the obstacle), toe clearance (vertical distance between the toe and obstacle when toe is over the obstacle) [5,9] and toe clearance variability [9]. The increased toe clearance variability may reflect the absence of fine-tuning when visual sensory information is not available [5,7]. For example, if it is true that the trajectory is modified during swing as a function of visual information, the absence of visual information will result in a more variable response.

A series of studies have demonstrated the effect of visual information on toe clearance measures. When crossing with the trail limb the obstacle is behind the subject, so visual input regarding the obstacle and the limb is unavailable, and toe clearance variability of the trail limb is higher than the lead limb [7]. Similarly, when vision of the lead limb and obstacle is obstructed two steps prior to crossing, toe clearance variability also increases [5]. Lead limb elevation, but not trail limb elevation, decreased when full vision was restored during obstacle crossing [4] and sudden changes in obstacle height were accommodated by increased limb elevation [8]. With this rich set of experiments, it is clear that lead limb elevation is controlled by visual information. However, it is not clear if the control is dependent on seeing just the obstacle or if it is the relationship of the lower limb relative to the obstacle which provides the on-line control [7].

Rietdyk and Rhea [9] further examined the role of visual exproprioception by removing exproprioception of the lower limb relative to the obstacle (visual interference provided by goggles), but provided exproprioception of the head relative to the obstacle position through the use of position cues. The obstacle position cues (2m tall) were placed on each side of the obstacle and were visible while wearing the goggles. The subject lost direct view of the obstacle about two steps prior to the obstacle in the visual interference condition, but the position cues provided indirect information of the obstacle's location. The presence of the position cues returned lead and trail horizontal distances to values that were not significantly different from full vision conditions, but had limited effects on toe clearance. The authors suggested that visual information of the head relative to the obstacle allowed subjects to estimate the relative distance to the obstacle to regulate foot placement. These findings are consistent with suggestions made by Rietdyk et al. [10] that increased visual structure provided by a platform, as opposed to an obstacle, may have compensated for the effects of occluded lower limb-obstacle exproprioception. When stepping up onto a platform, visual interference due to carrying a box did not modify the swing limb trajectory [10]. That is, with visual interference the leading edge of the platform and the entire obstacle would not be visible during approach, starting at about two steps prior to the obstacle. However, a portion of the 3.7 m long platform was visible beyond the visual interference boundary, which may have allowed subjects to estimate the location of the leading edge, and may have counteracted the effects of the visual interference. By increasing visual exproprioceptive information using a platform or position references, the results of these studies support the idea that increased visual structure, which provides indirect information regarding the obstacle location, can compensate for loss of lower limb-obstacle exproprioception.

Mohagheghi et al. [4] argued that successful obstacle avoidance is dependent on two pieces of information, updated distance to the obstacle and obstacle height. Our previous study [9] highlighted the effect of updated distance provided as exproprioceptive information, and this paper will explore obstacle height information provided as exteroceptive information. It is clear that visual exteroceptive information is used in a feed-forward manner to control the swing limb (e.g. [5,7,4]). This implies that the obstacle height must be retained in memory once it is no longer visible, and this may account for increased toe clearance variability when visual input is unavailable [5,7]. In parallel, memory-guided reaching (i.e. without on-line vision) is more variable and less accurate than reaching with vision (e.g. [2]). Although there is evidence for the use of visual exteroceptive information in a feed-forward manner [5,7,4], it is unknown if this information can be used on-line during obstacle avoidance in gait.

As noted earlier, lead toe clearance was not influenced by providing updated distance of the eyes/head to the obstacle in the absence of lower limb-obstacle exproprioception [9]. It is not surprising that updated information regarding the distance between the head and the obstacle altered the horizontal distance of the foot, but had less effect on the vertical variables, such as toe clearance, which are dependent on obstacle height information. To differentiate between the height information which is exproprioceptive in nature (the height of the lower limb relative to the obstacle height) and exteroceptive in nature (simply the height of the obstacle) we removed the lower limb-obstacle exproprioceptive information and added exteroceptive information that was visible as the subject crossed the obstacle. Lower limb-obstacle exproprioceptive information was removed with the use of basketball goggles that occluded vision of the lower limbs and the environment immediately in front of the subject [5,9]. To increase visual exteroceptive information two identical obstacles were used: One was placed across the walkway (which the subject stepped over) and the second obstacle was placed parallel and to the side of the walkway (Fig. 1); the second obstacle was visible during crossing and would provide on-line exteroceptive information regarding obstacle characteristics. Since the characteristic most relevant to toe clearance is obstacle height, the second obstacle has been termed the obstacle height cue. To focus on the exteroceptive effects, obstacle position cues (2 m tall, placed on each side of the obstacle) were included in all conditions, to provide head-obstacle exproprioceptive distance information [9]. A decrease in toe clearance and/or toe clearance variability when the height cue is present will provide evidence that visual exteroceptive information available in an on-line manner modifies control of the lower limb during gait adaptation.

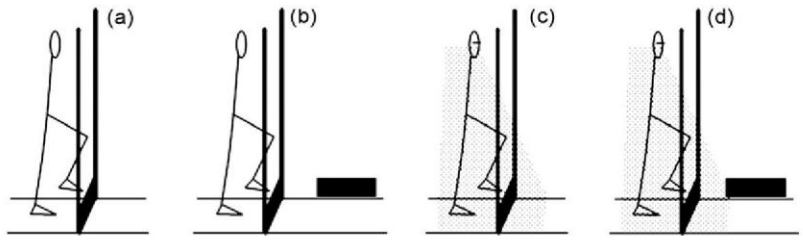

Fig. 1. Diagram of the four visual conditions. Full vision (a), full vision with height cue (provided by identical obstacle placed parallel to the walkway) (b), visual interference (c), and visual interference with height cue (d). The shaded areas in (c) and (d) represent the area of visual obstruction due to the goggles.

The purpose of this study was to determine how visual exteroceptive information regarding obstacle height provided during obstacle crossing modified foot placement and foot elevation in the absence of lower limb-obstacle exproprioceptive information. Specifically, this study extended previous studies by maintaining constant exproprioceptive information, but manipulating the availability of on-line exteroceptive information. The main two hypotheses were: (1) loss of lower limb-obstacle exproprioception would increase toe clearance and toe clearance variability and (2) increased visual exteroceptive information regarding obstacle height would decrease toe clearance and toe clearance variability. While we did not expect that obstacle height information would alter foot placement, we wanted to confirm our previous findings regarding lower limb-obstacle exproprioception and foot placement, which led to the following hypotheses: (3) loss of foot-obstacle exproprioception would not alter horizontal distance of either limb as head-obstacle exproprioception was provided by position cues and (4) increased visual exteroceptive information regarding obstacle height would not alter foot placement.

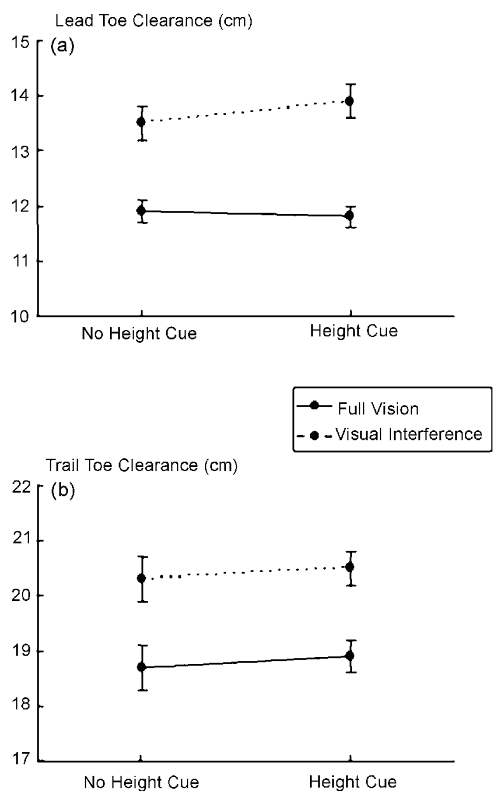

Fig. 2. Lead (a) and trail (b) toe clearance as a function of height cue and visual interference.

This study was approved by the local Institutional Review Board. Six male and four female subjects (age 21.0 ± 3.2 years; mass 82.1 ± 17.3 kg; height 1.75 ± 0.11 m) gave informed consent to participate in this study. All subjects self-reported they were free of any ailments that would disrupt normal gait, including any known neurological disorders. All of the subjects had normal or corrected-to-normal vision. Two infra-red emitting diodes (IREDs) were placed on the head. Four IREDs were placed on the lateral side of the subjects' right toe and heel and the medial side of the subjects' left toe and heel. One IRED was placed on the obstacle. Position data were collected at 120 Hz with two Optotrak 3020 sensors (Northern Digital Inc., Waterloo, ON, Canada).

Independent variables were vision type (full vision or visual inference), obstacle height cues (present or not), and obstacle height (2, 10, 20, or 30 cm). A total of 128 trials were recorded (2 vision × 2 height cue × 4 obstacle height × 8 trials each). Subjects were instructed to walk down an 8-m walkway, step over the obstacle placed in the middle, and continue to the end of the walkway. Visual interference was provided by basketball goggles which occluded vision of the lower limbs and anything approximately two steps in front of the subject. All conditions included position cues (PVC tubing, 6 cm in diameter and 2 m tall, painted black to increase contrast) placed next to the obstacle (Fig. 1). The obstacle height cue was a second obstacle identical to the obstacle in the path. The obstacle height cue was placed parallel to the walkway, on the left side of the walkway, and 2 m ahead of the obstacle that was to be crossed (Fig. 1). Obstacles were composed of masonite, 90 cm wide by 0.5 cm deep, painted black to increase contrast and designed to tip when contacted to reduce the chance of a fall. The subjects were told that the obstacle on the left side of the walkway was identical in height to the obstacle they were walking over. The height cue gave the subjects a continual reference of obstacle height, even though they could not see the obstacle they were crossing as they approached it, thus providing on-line visual exteroceptive information during obstacle crossing. The dependent variables were lead and trail horizontal distance and toe clearance, and the variability of these measures, and head pitch angle and head medial-lateral motion. Horizontal distance was the distance between the toe diodes and the obstacle at foot placement. Toe clearance was the vertical distance between the toe diode and the top of the obstacle as the foot crossed the obstacle. The range of head pitch angle and head medial-lateral motion were determined from lead toe-off to the point in time when the lead foot crossed the obstacle.

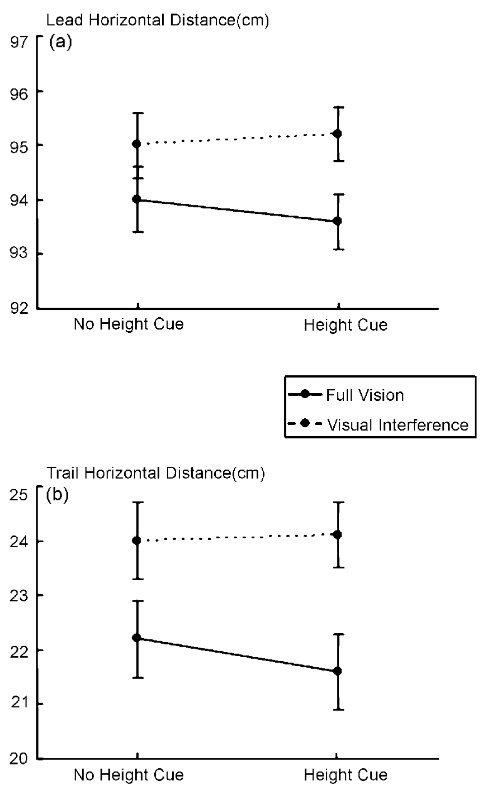

Fig. 3. Lead (a) and trail (b) horizontal distance as a function of height cue and visual interference.

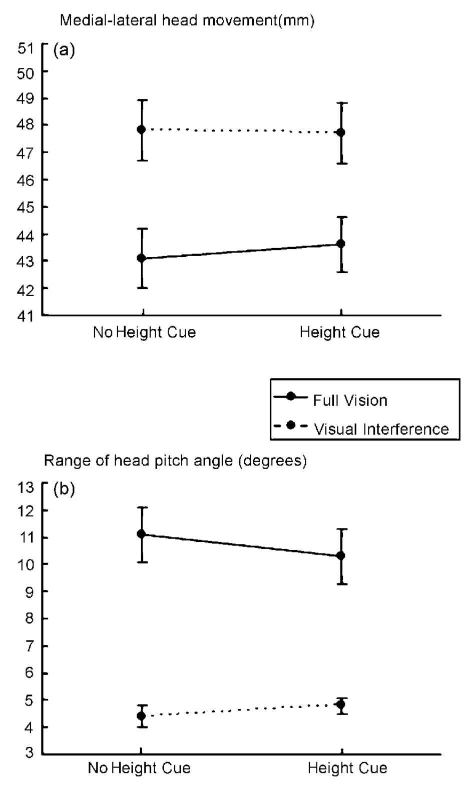

Fig. 4. Range of motion for medial-lateral head movement (a) and head pitch angle (b).

The interaction effect needed to support *both* hypotheses one and two (goggles would increase clearance variables and the height cue would decrease the clearance variables while wearing goggles) was not significant for lead or trail toe clearance (goggles by height cue, $p > 0.22$, Fig. 2) or clearance variability ($p > 0.61$). The main effect of vision (hypothesis one) was significant for lead and trail toe clearance ($p < 0.01$, Fig. 2), and lead toe clearance variability ($p < 0.01$, no goggles 2.3 ± 1.1 cm; goggles 2.9 ± 1.5 cm) but not trail toe clearance variability ($p = 0.29$, no goggles 3.5 ± 1.5 cm; goggles 3.7 ± 1.8 cm). The main effect of height cue (hypothesis two) was not significant for the lead and trail toe clearance ($p > 0.49$, Fig. 2) or lead and trail clearance variability ($p > 0.71$). Therefore, we accepted hypothesis one, but rejected hypothesis two. The toe clearance variability was significantly smaller for the lead limb compared to the trail limb ($p < 0.01$, lead limb 2.6 ± 1.3 cm; trail limb 3.6 ± 1.6 cm).

Visual interference caused a significant increase in lead and trail horizontal distance ($p < 0.01$, Fig. 3) with no change in horizontal distance variability of either limb ($p > 0.34$). Because of the changes in mean horizontal distances we rejected hypothesis three, that the loss of lower limb-obstacle exproprioception would not alter horizontal distance of either limb as head-obstacle exproprioception was provided by position cues. The height cue had no effect on lead or trail horizontal distance ($p > 0.34$, Fig. 3) or horizontal distance variability of either limb ($p > 0.36$), therefore we accepted the fourth hypothesis that increased visual exteroceptive information regarding obstacle height would not alter foot placement.

Seven of the ten subjects contacted an obstacle one or two times (total of eight contacts or 0.6% of all trials). The range of medial-lateral head movement was not influenced by the presence of the height cue for any interaction (cue by goggles by obstacle height, $p = 0.62$; cue by height, $p = 0.08$; cue by goggles, $p = 0.80$, Fig. 4a) or main effect ($p > 0.84$). An interaction of vision type by height cue for head pitch range was found ($p = 0.02$, Fig. 4b), however, post hoc analyses revealed that height cue did not significantly affect head pitch range whether the subject was wearing goggles or not; other interactions were not statistically significant ($p > 0.28$).

Recent research has examined the roles of visual exteroception and exproprioception during obstacle avoidance. Visual exproprioceptive information is used to estimate self-position around the obstacle in an on-line manner [5,9,4,6], whether the subject directly observes their foot relative to the obstacle, or infers the foot position relative to the obstacle, based on head-obstacle exproprioceptive information provided by position cues [9]. Visual exteroceptive information is used as the trail limb crosses the obstacle—both the trail limb and obstacle are out of sight during crossing, and the subject must rely on memory of the obstacle height to control limb elevation in a feedforward manner [7]. Similarly, when vision is obstructed during lead limb crossing, the subject must rely on the visual exteroceptive information [5].

A robust observation in gait adaptation studies is that visual interference causes an increase in toe clearance (e.g. [5,9,4]); these findings are consistent with the current study. We also observed an increase in lead toe clearance variability with visual interference, consistent with Patla [5], and increased toe clearance variability of the trail limb compared to the lead limb, consistent with Patla et al. [7]. The increased variability may reflect the absence of fine-tuning when visual sensory information is not available; the sensory information may be either exteroceptive – regarding obstacle characteristics – or exproprioceptive – regarding limb posture and/or limb-obstacle distances. When the second obstacle was visible, subjects had access to on-line information regarding the obstacle characteristics, but this information did not affect toe clearance or toe clearance variability of the lead or trail foot. This strengthens the argument that it is the visual exproprioceptive information that is used on-line to fine tune the lower limb trajectory [5,6].

The second obstacle provided exteroceptive information about the obstacle's characteristics, but not location, and did not affect the horizontal distance in this study—as predicted. In the current study, loss of lower limb-obstacle exproprioception increased the horizontal distance of both limbs, despite the presence of head-obstacle exproprioception provided by position cues. This is in contrast to our previous study [9], which found that presence of position cues decreased lead horizontal distance by 1.5 cm and trail horizontal distance by 2.0 cm, to values not different from the full vision without position cues condition. It should be noted that a full vision without position cues condition was not observed in the current study (all conditions had a position cue in place). Also, in Rietdyk and Rhea [9], presence of position cues with full vision resulted in a small, statistically non-significant decrease in horizontal position for both limbs. To determine the extent of the differences between the two studies, we compared the changes in horizontal distance in the two conditions observed in both studies (full vision with position cues versus goggles with position cues): the difference across the two conditions for lead horizontal distance was 0.4 cm and 1.0 cm (for Rietdyk and Rhea [9] and the current study, respectively); trail horizontal distance difference was 1.3 cm and 1.8 cm (for Rietdyk and Rhea [9] and the current study, respectively). These two studies demonstrate similar changes, but the changes were larger and significantly different in the current study. Therefore, future studies concerning the effect of head-obstacle exproprioception should include a condition of full vision without head-obstacle exproprioception (position cues) to fully understand the contributions of both head-obstacle and lower limb-obstacle exproprioceptive sources of information. When both studies are considered together, the previous study [9] provided evidence that head-obstacle exproprioception provided an important source of information to update the estimated distance between the subject and the obstacle; it is also clear from the current study that the lower limb-obstacle exproprioception contributed to changes in foot placement even when head-obstacle exproprioception was available.

The findings of this study are limited by several factors. First, the nature of this research results in the examination of behavioral changes when different types of visual information are available. When a change in behavior is observed, then it is argued that the visual information is relevant to the task, even if it can't be proven that subjects paid attention to the cues. For example, Mohagheghi et al. [4] manipulated when subjects could visually observe the obstacle, and concluded that only lead limb elevation was influenced by the availability of on-line visual information during obstacle crossing. Rietdyk and Rhea [9] demonstrated that obstacle position cues regarding obstacle location affected subject's behavior even though there is no evidence that the subjects looked at the position cues. However, interpretation is more difficult when a null finding is observed. In the current paper, although the height cue information was available, subjects either did not pay attention to it or the information provided was not relevant for the task. In support of the idea that attention was not given to the second obstacle, the range of head motion did not change with the presence of the height cue (Fig. 4), indicating that the subjects did not have the second obstacle in their central visual field during crossing. However, visual exproprioceptive information from the peripheral visual field altered the lower limb trajectory [5] and we expect that visual exteroceptive information in the peripheral visual field would also be used. Also, head movement is not required as evidence of scanning, as the eyes may move within the head.

A second limitation involves perception of the similarity of the two obstacles. The obstacles were placed at different positions and in different orientations, so subjects may have perceived them as different despite being informed they were identical. While people regularly step over obstacles in their normal routines, the presence of two identical obstacles does not occur normally, so the information may have been ignored. Therefore, due to the above two limitations, the null finding observed here does not prove that visual exteroceptive information cannot be used in an on-line manner, but rather demonstrates that the exteroceptive information provided in the form of a second obstacle was not used in an on-line fashion. However, we believe that the null finding is relevant as it is consistent with the existing literature that highlights the importance of on-line visual exproprioceptive information (e.g. [5,9,7,4,8,6]).

Another limitation is the effect of head motion on the lower limb trajectories. If the subjects were indeed scanning the second obstacle with head movements as they crossed the obstacle, the perturbation could affect the outcome. However, no changes in head movement were observed across height cues (Fig. 4a and b).

In summary, when visual information of obstacle characteristics (exteroception) was provided in the absence of lower limb-obstacle exproprioception, no changes in toe clearance or foot placement were observed. These findings support the argument that visual exproprioceptive information is used on-line to fine tune the lower limb trajectory during obstacle avoidance, while visual exteroceptive information may be limited to feedforward control.

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