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Optic flow and scene structure do not always contribute to the control of human walking

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Abstract

Using displacing prisms to dissociate the influence of optic flow and egocentric direction, previous research (*Current Biology 8* (1998) 1191) showed that people primarily use egocentric direction to control their locomotion on foot, rather than optic flow. When wearing displacing prisms, participants followed the curved path predicted by the use of simple egocentric direction, rather than a straight path, as predicted by the use of optic flow. It has previously been suggested that, in rich visual environments, other visual information including optic flow and static scene structure may influence locomotion in addition to direction. Here we report a study where neither scene structure nor optic flow have any influence on the control of walking. Participants wearing displacing prisms walked along a well-lit corridor (containing rich scene structure and flow) and along the same corridor in darkness (no scene structure or flow). Heading errors were not significantly different between the dark and light conditions. Thus, even under conditions of rich scene structure and high flow when walking in a well-lit corridor, participants follow the same curved paths as when these cues are not available. These results demonstrate that there are conditions under which visual direction is the only useful source of visual information for the control of locomotion. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

One of the major functions of visual perception is to enable us to interact with and move around in our environment. A crucial task for a mobile animal such as ourselves is to be able to walk or run precisely towards (or away from) an object of interest. How do we do this? Over 50 years ago, Gibson made what was then a radical suggestion: that we use optic flow (the pattern of motion flow available at the eye as an observer moves through their environment), rather than object position, to control our direction of locomotion (Gibson (1950)). A large body of experimental and theoretical evidence has built up in support of the optic flow hypothesis (see Lappe, Bremmer, & van den Berg, 1999, for a recent review). Recently, the use of simple egocentric direction (the sum of extra-retinal gaze direction and retinal location) has been offered as an alternative source of visual information (Rushton, Harris, Lloyd, & Wann, 1998).

In the real world, optic flow and egocentric-direction strategies both provide information that can be used to reach a target. When displacing prisms are placed over the eyes during locomotion, the information provided by optic flow and direction-based strategies can be dissociated (Rushton et al., 1998). Displacing prisms shift the image of the world on the retina by an amount corresponding to the power of the prism. The result is that objects that appear to be straight ahead when viewed through the prisms, are actually positioned to one side of the observer's body midline. If observers use a simple egocentric-direction strategy to direct them to the target, then while wearing prisms they will attempt to walk directly towards the image of the target, rather than the target itself. The constant heading error (difference between the direction in which the participant is walking and the actual direction of the target) induced by the prisms will cause them to walk a *curved* path. In contrast, flow-based locomotion strategies should be unaffected by prisms (apart from on the first step, when flow is not available). This is because displacing prisms

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do not change differential properties of the flow field such as the focus of expansion (FoE). Instead, they change the visual direction of the FoE. Thus, the FoE will still coincide with the image of the target to which one wants to walk and if FoE is used to control locomotion, the observer should walk along a *straight* path to the target.

Rushton et al.'s study (1998) was the first to use the prism technique to dissociate egocentric direction from flow. The study has now been replicated and extended by several groups (Rogers & Allison, 1999; Rogers & Dalton, 1999; Wood, Harvey, Young, Beedie, & Wilson, 2000; Harris & Carré, 2001; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). It is now generally agreed that under some circumstances, participants walk a curved path and make heading errors consistent with the use of perceived egocentric direction. The debate now centres around how scene structure and optic flow information influence locomotion *in addition* to simple egocentric direction (Fajen & Warren, 2000; Harris, 2001; Harris & Carré, 2001; Wann & Land, 2001). It has been argued that structure and flow cues could act directly, for example through the use of classic optic flow strategies (Warren et al., 2001) and the use of motion parallax (Harris & Carré, 2001), or indirectly, by influencing the perception of egocentric direction (Rushton & Salvucci, 2001). For example, both static scene structure and changing structure (flow) are known to have an effect on perceived direction (see Rushton & Salvucci, 2001). Such an effect could play a part in the control of locomotion in addition to the possible direct use of flow to guide locomotion.

There is evidence suggesting such an indirect use of flow or scene structure. Wood et al. (2000) found less curved paths (hence smaller heading errors) for a 'rich cue' scene containing ground markings, surrounding buildings and a wide field of view, than for a 'reduced cue' scene with a grass ground plane but narrow field of view. Harris and Carré (2001) found less curved paths when participants reduced their viewing height by crawling, rather than walking. But paths were not less curved when participants directed their gaze down to include foreground flow. Warren et al. (2001) also observed reductions in path curvature by increasing the amount of scene structure and optic flow in a virtual environment. They modelled their data as a weighted interaction between simple egocentric direction and optic flow, but did not consider the indirect contributions of static scene structure and flow.

In this experiment, we compared the paths taken by prism wearing participants in two natural world conditions, one with no flow or scene structure and one with rich structure and flow. This is the first study where path deviations during walking have been measured in a corridor, which has rich scene structure and optic flow right across the visual field. Surprisingly, the expected difference in the curvature of paths for the two conditions was not found. Our findings cannot be incorporated easily into theories that assume a simple combination of flow and egocentric direction.

2. Methods

Participants wore a pair of displacing prisms (of side 3.5 cm, field of view 60°) mounted in a set of thin-rimmed spectacle frames. Two pairs of spectacles were used, one with the prisms displacing the world by 14° to the right, the other by 14° to the left (prism displacement was measured using a digital camera to record prism-induced position shifts. Measured shifts were in agreement with displacement calculated from the power of the prisms).

We measured participant's trajectories as they walked towards a luminous target at a natural pace along a corridor under full lighting (light condition), or in the dark (dark condition), see Fig. 1. The floor was clearly patterned with irregularly textured linoleum; walls were of simple breeze-block construction, painted and textured with each separate block easily visible; the ceiling

Fig. 1. (a) A participant walks towards the target (bottom centre of image, suspended from ceiling by string) in the control condition (no prisms worn). (b) A condition with a participant wearing right-deflecting wedge prisms (14 degrees deflection) and attempting to walk towards the target. Notice that her trajectory is well to one side of the target.

was covered in square polystyrene tiles, easily visible. Compared with previous real world studies which used outdoor settings or large rooms (Rushton et al., 1998; Wood et al., 2000; Harris & Carré, 2001; Rogers & Allison, 1999; Rogers & Dalton, 1999), walking in a corridor provides additional flow and static scene structure from the walls and ceiling. In the dark, structure and flow will be absent as all the observer sees is the luminous target.

Eight naïve participants walked along a well-lit corridor towards a luminous target. The target was a small toy human figure, 6 cm high × 4 cm wide, suspended from the ceiling by thin string, and located at about waist height. In the dark, the only visible part of the target was a flat luminous star shape (approximately 4×4 cm^2) attached to the front of the figure.

On each walk, participants started from a slightly different point 4–7 m from the target, randomly varied from trial to trial. For each of the two conditions (light/dark) they walked two trajectories in three prism conditions: (i) no prisms, (ii) left-deflecting prisms, or (iii) right-deflecting prisms. Participants were split into two groups. One group performed trials in the light first, the other in the dark first. No significant differences in performance were found between groups, so all data presented here are pooled. Walking speed was self-paced. Participants were simply asked to walk towards the target. Across all participants and trials, the mean speed for light conditions was slightly faster (0.87 m/s, $\sigma = 0.16$ m/s) than for dark conditions (0.76 m/s, $\sigma = 0.17$ m/s).

It was essential to avoid the possibility that participants might adapt to the prisms over the course of several trials, which could cause them to walk straighter paths than expected. The following procedure was designed to minimise this problem. Before donning the prism glasses, participants were asked to close their eyes, turn their back on the target, then put on the glasses, turn back towards the target (aided by the experimenter), open their eyes and walk towards the target. The same procedure was followed in the dark condition except that the lights were turned off just before the observer closed their eyes to put on the prism glasses, and turned on again as soon as the glasses were removed on arrival at the target. Thus participants had a clear view of the lit corridor before and after they walked in the dark. After each trial, participants removed the prisms glasses and were instructed to look around and walk around for a few minutes before the next trial began. The three prism conditions (right deflect, left deflect, no prism) were each run twice in random order.

Walking paths were measured using a digital video camera (running at 5 Hz) located near the target. A small battery-powered low intensity light was attached to the participant at waist level to provide a constant reference point on the body for subsequent video analysis. Knowing the position of the camera, the height of the waist mounted light, and the corridor dimensions (10 m long, 1.7 m wide, 2.4 m high), it was possible to calculate the 3-D position of the reference light in every video frame from its location in the 2-D image. Reference light positions were recorded for each frame of the movie sequence, and thus we were able to reproduce the path walked (as an x-position across the corridor, and z-position along it) by each participant during each trial. This method assumes that the reference light has a constant height. In fact, as a participant walks, the reference light bobs up and down (about 1–4 cm depending on an individual's gait). Assuming an error of 4 cm, we calculated the associated z-position errors as being roughly 4 cm, smaller than our estimated measurement errors (20 cm for z-position, 9 cm for x-position).

The raw 3-D position data were smoothed with a square filter (window size of three video frames). Heading error was calculated (difference between the direction the participant walked in and the direction of the target) for each video frame along each path. We wanted to plot mean heading errors across all participants for the three prism conditions. In each individual trial, the distance walked was slightly different and participants walked at slightly different speeds, and thus took slightly different times to reach the target (mean time in the light was 6.9 s, in the dark, 5.9 s). It was therefore necessary to normalise the data before averaging. The data for each trajectory was split into seven equal sized time sections, and mean heading errors calculated for each. Data from the first and last intervals were not analysed as we wanted to avoid using regions of the trajectory where participants were not walking at a constant speed. When we refer the 'interval' in Fig. 3, we are referring to these normalised time intervals.

3. Results

Participants walked towards the luminous target wearing left-, right-deflecting or no prisms. Sample paths for one participant are shown in Fig. 2. These paths were fairly typical, although no single path, for any participant or any condition, was exactly the same. The paths walked for the dark (a) and light (b) conditions are very similar. If anything, it appears in this example that the participant's path curves slightly less in the dark than in the light (the opposite of what would be predicted if flow were involved in the guidance of locomotion in the light condition). These results concur with those found in a preliminary study where dark and light conditions were compared for locomotion through a large room (Rogers & Allison, 1999).

To quantify the data more carefully, we considered how heading error varied over the course of the path. The simple egocentric-direction strategy predicts that

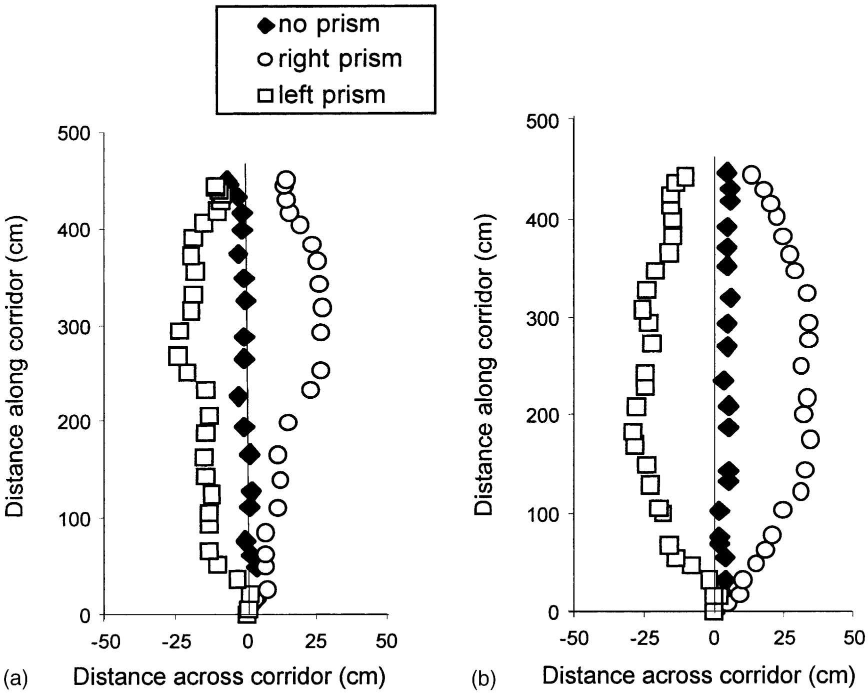

Fig. 2. Graphs show individual sample trajectories for a single participant in the dark (a) and when the corridor was lit (b), for left-deflecting prisms (□), no prisms (◆) and right-deflecting prisms (○).

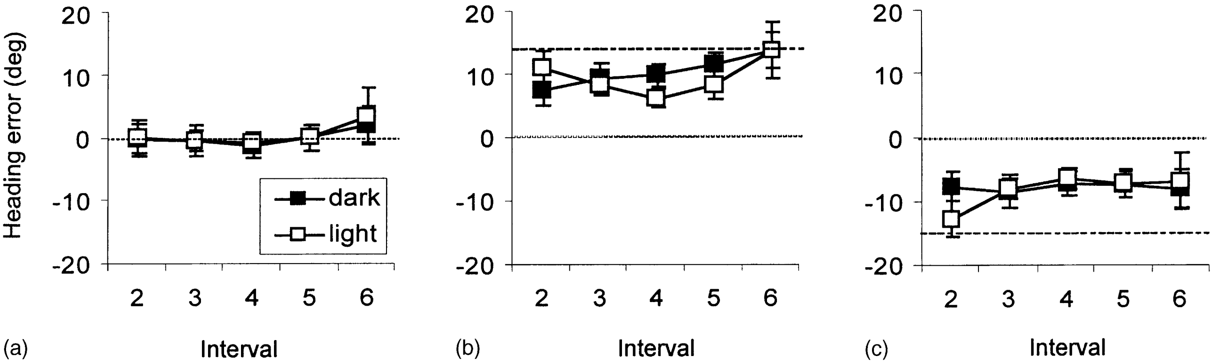

Fig. 3. The graphs show mean heading error as the trials progressed, as a function of normalised time interval (see Section 2). Negative error represents a drift to the right, positive to the left. We plot pooled data from eight participants (error bars are standard errors). Results for the light condition are shown by open symbols, dark condition by filled symbols. (a) Heading errors for the control condition where no prism were worn. (b) Heading errors with left-deflecting prisms. (c) Heading errors with right-deflecting prisms. Dashed lines show prediction of the simple egocentric-direction strategy.

there should be a constant heading error, equal to the prism displacement. The use of optic flow would predict that the heading error should reduce as the trial progresses. Plots of mean heading error for eight participants over the course of the trials are shown in Fig. 3. Fig. 3a shows mean heading errors for the conditions when participants did not wear prisms (open symbols for light condition, filled for dark condition). As expected, the errors were very close to zero (observers walk a straight line path). When observers wore left-deflecting prisms (Fig. 3b) heading error was almost constant over the majority of the trial, although below that predicted by the power of the prisms (dashed line). For right-deflecting prisms (Fig. 3c), heading error was in the opposite direction, as expected, but again, less than that predicted by the power of the prisms. Note that there was very little difference between the heading errors in the light and dark conditions in any of these plots, and that the error did not reduce during the duration of the trial.

To test for a significant difference between the conditions, we used a repeated measures ANOVA with the mean unsigned heading error across the whole trial as a factor and participant as a random factor. There was no significant difference found between the light and dark conditions ($F_{1,7} = 0.03$, $p = 0.869$). It has been suggested that observers may use the direction strategy at the beginning of a trial and are then influenced by flow as the trial progresses (Warren et al., 2001; Harris & Carré, 2001). We therefore considered the data separately for time blocks 2 and 6. Using the mean unsigned heading error for time block 2 as a factor, there was almost a significant difference between conditions ($F_{1,7} = 5.17$, $p = 0.057$), but there were *larger* heading errors in the light condition than the dark condition (the opposite of what would be expected if flow and structure influenced trajectories in the light). Crucially, using the mean unsigned heading error for time block 6 as a factor, there was no significant difference between the two conditions ($F_{1,7} = 0.97$, $p = 0.357$). This suggests that there is no influence of the availability of optic flow or scene structure on the size of the heading error when participants walk along a corridor.

4. Discussion

The simple egocentric-direction strategy relies on target position and, in its simplest form, is not affected by the motion or 3-D structure of other objects in the environment. Here we obtained data consistent with this simple strategy. Observers followed the same curved paths for a condition where the only visual information was egocentric direction, as for a condition containing rich scene structure information and optic flow. Our data therefore suggest that these additional sources of information are not being used in the control of walking along a corridor. These results stand in contrast to the three other studies that have varied scene structure and optic flow (Wood et al., 2000; Harris & Carré, 2001; Warren et al., 2001), which found that paths became less curved under certain conditions as more scene structure and flow were introduced. Why are our results different from those of other studies? Currently, we have no definitive answer to this question. But we are able to comment on some key aspects of the currently published data and how it relates to that presented here.

4.1. Why are heading errors less than the prism deflection would predict?

When participants wear prisms, the heading errors we found, although almost constant across the trial, are about 65% of what would be expected based on the angular deflection of the prisms, for both the light and dark conditions. If optic flow or scene structure were responsible for the reduced heading error (as suggested by Warren et al. (2001)), then we would expect no such reduction for the dark condition. A referee suggested that the target itself might provide useful flow information. We think this is unlikely, for the following reasons. First, the only thing visible in both the light and dark conditions was the luminous star on the front of the target (4×4 cm^2). The star itself was flat, and thus provided no useful local motion parallax information as a participant approached. Neither could motion parallax between target and background be used, as the background was not visible in the dark condition.

Second, changes in the target's projected shape could in principle be a cue to the direction of self-motion. However, such changes were very small. Consider the change in projected shape of the star when viewed from one side, rather than from straight ahead. The new projected shape will be slightly narrower than the original shape, so that the side nearer to an observer is slightly wider than the side further away. There will also be a slight difference in relative heights between right and left sides of the retinal projection. We calculated the size differences that would occur when the participant's position was furthest left (or right) of centre (typically 40 cm when the participant was 2.5 m from the target (see Fig. 2)). The relative width difference was calculated to be 4 s of arc (0.25% of the width) and the relative height difference also about 4 s of arc (0.25% of the height). These values are well below typical thresholds for a similar task, just discriminible changes in aspect ratio are never better than 1.6% (Regan & Hamstra, 1992).

Interestingly, all the other published studies have also found heading errors lower than that predicted by the power of the prisms. Rushton et al. (1998), using an outdoor scene and prism glasses with a deflection of 16°, found errors around 85% of the prism deflection. Wood et al. (2000) found errors around 90% of prism deflection for their reduced cue condition, and Harris and Carré (2001) found that their observers largest heading errors were around 70% of the prism deflection they used. Further, in an experiment using a virtual reality set-up to simulate a prism deflection, Warren et al. (2001) also found predicted deflections at the start of their trials (before optic flow could have any effect) to be around 90% of that predicted. We currently do not have a good idea of why these effects are of different magnitude in different studies. Whatever these effects are caused by, they appear in all the experiments, and it is thus quite possible that they are not directly related to the issue of flow and structure. For example, similar effects are seen in experiments on perceived visual direction when wearing prisms, when observers do not move (hence there is no flow). Rock, Goldberg, and Mack (1966) showed an 'immediate correction' effect for observers indicating direction whilst wearing prisms. Errors in perceived direction, even on an observers first attempt at pointing to a target, were less than predicted by the power of the prisms. However, Rock's study did not find an immediate correction effect when a single object was viewed in the dark (but see Rushton (2001), who found an immediate correction effect in both the light and the dark).

4.2. Is visual direction information favoured because prisms distort flow?

It has been suggested that small distortions caused by wearing prisms can adversely affect flow and thus favour the visual direction cue by making the optic flow cue less salient (Warren et al., 2001). Displacing prisms do inevitably distort the image. Fig. 4 show a pair of photographs of the corridor in which our experiment took place, one of which was taken through a rightwards deflecting displacing prism. When wearing the prisms, there was no noticeable chromatic aberration and participants did not report any loss in optical quality. The photograph shows that there is geometric distortion. In particular, vertical lines in the scene are obviously curved by the prism. These effects are, however, minor compared with the large displacement the prisms provide. Could these distortions cause the visual system to reject flow information in favour of visual direction? A recent study suggests that this is unlikely. Large, deliberate, distortions to an optic flow field, using a fish-eye lens, cause only very small errors in circular heading perception (Kim, Fajen, & Turvey, 2000). These authors were not aiming to compare flow with other sources of visual information, but their study does illustrate that a hugely distorting prism does not affect the use of optic flow for gauging heading direction. Finally, a preliminary study has recently found no difference in the shape of paths when the world was displaced using prisms, or using mirror glasses, which do not generate the same geometrical distortions (Rogers, 2000).

Warren et al. (2001) found smaller heading errors when participants wore distorting prisms inside their head mounted display, than when displacement of the scene was achieved through a virtual reality manipulation. They interpreted the data as revealing the effects of prism distortion. However, there could be explanations for this result that are unrelated to prism distortion. For example, Warren et al. did not report the field of view of the prisms and whether field of view was different with and without prism glasses. Wood et al. (2000) found that a 30° field of view resulted in a reduction of heading error, when compared with a much wider field of view, and they commented that this might be caused by a reduction in scene structure as well as a possible reduction of optic flow. Further, Harris and Carré (2001) found that heading errors could be reduced by altering the flow and structure in the scene. They suggested that the reduction in heading error could be due to changes in scene structure, optic flow or motion parallax, and that it was not possible in theirs, or other studies, to distinguish between these possibilities.

4.3. The influence of scene conditions and experimental procedure

It seems likely that differences in the particulars of scene conditions and procedure may account for the different results found in different studies. All studies used different scene conditions, sometimes outdoors (Rushton et al., 1998; Wood et al., 2000), sometimes in a large room (Harris & Carré, 2001), or a virtual room (Warren et al., 2001). No study apart from the one presented here used a corridor, which has obvious symmetrical scene structure. In the corridor, there were

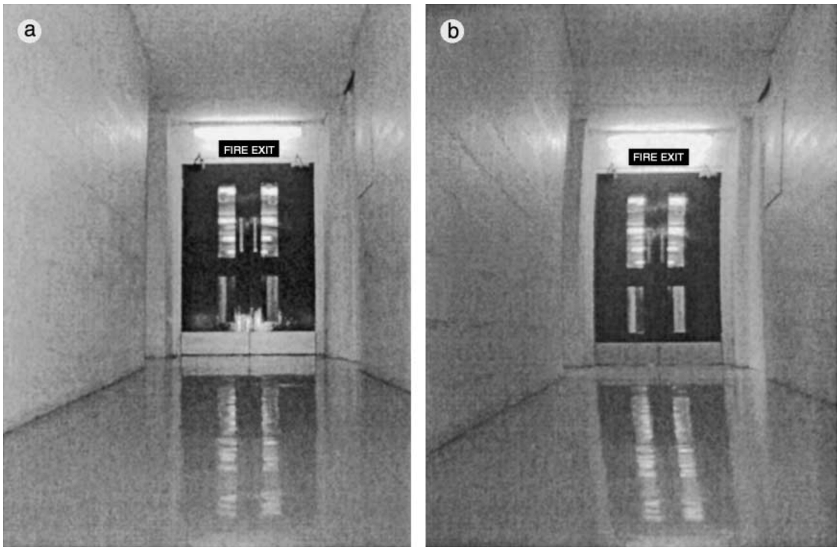

Fig. 4. (a) A photograph of the corridor in which the experiment took place (participants walked away from the doors, towards the camera). (b) A photograph showing the distorting effects of the displacing prism. Although the distortion is slight, vertical lines are clearly curved by the prism.

no stand-alone objects visible and thus there was very little opportunity for the use of motion parallax or alignment information, which have been suggested as potentially important cues in other studies (Wood et al., 2000; Harris & Carré, 2001; Rogers & Allison, 1999). Use of such cues in other studies could be an explanation for why our participants did not show reduced heading errors in the light compared with the dark. More detailed studies that attempt to directly study the use of alignment cues and motion parallax are now required to tests these ideas explicitly.

The differences in procedures used for testing in different studies could also play a part in the widely different results found. In this study we used two trials per condition, and between every trial we insisted that participants walk around without wearing prism glasses. This procedure was used to avoid the possibility (or at least reduce it as much as possible) that participants adapt to the prisms. A large literature shows that adaptation to displacing prisms can occur rapidly. For example, in a reaching task, if a participant is asked to reach to a target repeatedly, whilst wearing prisms, the error in reaching to target location is reduced to half its initial value after only 3–5 trials (e.g. see Redding & Wallace, 1996; Norris, Greger, Martin, & Thach, 2001). Such rapid adaptation has also been seen recently for a throwing task (Fernandez-Riaz, Hall, Vergara, & Diaz, 2000) and importantly, in a preliminary study on locomotion wearing prisms, when curved walking paths became 50% less curved after only 5 min of wearing prisms (Rogers & Dalton, 1999). This is thus a very important issue in the context of locomotion studies. If participants adapted to the prisms over the course of a trial, or over several trials, then heading errors would be reduced, not because participants were using flow, but simply because prism adaptation has reduced the perceived direction error. It is possible that prism adaptation might be occurring in some of the other published experiments. Indeed, it is interesting that here we find no decrease in heading error as trials proceed. In studies such as Warren et al.'s (2001), the description of the procedure suggests that prisms may have been worn over an extended period. The data shows a steady decline in heading error across the course of the trials (data are averaged across many trials so it is not possible to see trial to trial differences in performance). This decline in heading error was interpreted by the authors as being due to the use of optic flow, but could also be explained by participants adapting to the prisms. Thus, studies aiming to explore interactions between visual direction and other cues, including flow, should be designed so that trials are not run in blocks with participants continually wearing prisms with a particular deflection. Rather, adaptation must be avoided by ensuring that participants recover from the possible effects of adaptation between each individual trial. It would be very interesting to design studies to deliberately explore adaptation to separate the possible contributions to the reduction in heading error due to adaptation and flow.

5. Conclusions

In summary, our results provide an important exception to the previously published studies showing that although visual direction appears to dominate for the control of locomotion on foot, increasing scene structure and flow can reduce its influence. Although structure and flow can affect locomotion, we have shown that there are circumstances when they do not. A fruitful way to go forward with this research will be to try and establish what the useful cues are for locomotion, and how reliable they are. It will then be possible to apply models using weighted combinations of different cues to determine when each of the cues are used, and which is the most important. We currently do not know enough about the strength and reliability of the different individual cues for locomotion to make firm statements about which cues contribute most to the control of locomotion in the real world.

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