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Visual strategies for the control of steering toward a goal

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A B S T R A C T

We have shown that people steer toward a target by aligning their heading with the target when target egocentric direction is not available for steering [24]. Here we examined what visual strategies people use to steer toward a target when target egocentric direction is available for steering. The display simulated a participant walking over a ground plane with a target placed off to one side. The participant's simulated heading in the display was displaced 10° away from the participant's straight ahead. A textured ground display that provided dense global optic flow and an empty ground display that provided nearly no flow were tested. Participants were instructed to use a joystick to control their simulated self-motion in the display to (a) steer toward the target, (b) center the target at their straight ahead, or (c) minimize the target drift on the screen. We found that participants produced similar heading error profiles when they were instructed to steer toward the target or to center the target straight ahead, but not when they were instructed to minimize the target movement on the screen. Furthermore, regardless of the instructions received, final heading errors were about 5° smaller with the textured than with the empty ground display, indicating the effect of optic flow on the control performance. We conclude that when target egocentric direction is available for steering, people do not steer toward the target by canceling its optical drift. Optic flow contributes to steering toward a target even when control could be based on egocentric direction alone.

1. Introduction

Steering or walking toward a target is a task that we frequently experience in our daily life for which vision plays a key role. While the importance of vision in the control of steering or walking has been widely accepted, how exactly vision contributes to such behavior is still controversial. Specifically, there is an on-going debate on the use of the following visual strategies in goal-oriented locomotion control.

1. *Optic flow strategy*. It has long been proposed that humans use information in the projected retinal image motion of the environment generated during self-motion (optic flow) to perceive and control their movement in the world [1]. For example, when we travel on a straight path with no body, head, or eye rotation (pure translation), the flow pattern is radial. The focus of expansion (FOE) in the radial flow pattern indicates our instantaneous direction of travel (i.e., heading), which can be used to control our self-motion in the world. Specifically, to steer toward a target, we can align heading specified by optic flow with the target (Fig. 1a). Previous psychophysical studies have shown that humans can locate the FOE in optic flow to accurately estimate heading (within 1° of visual angle) to support the precise control of locomotion in the world (e.g., [2,3]). Under more complex but natural conditions when traveling on a straight path with eye, head, or body rotation or traveling on a curved path (translation and rotation), the retinal flow pattern is not radial anymore as the rotation shifts the FOE away from the heading direction. Although the added rotation complicates the process of extracting heading from optic flow [1,4], previous studies have shown that when the display provides sufficient optic flow information, observers can still estimate heading within 2° of visual angle to sustain successful steering toward a goal (e.g., [5–11]).
2. *Centering strategy*. In contrast to the optic flow strategy, it has also been proposed that humans can steer/walk toward a target using its egocentric direction with respect to their straight ahead (i.e., their body midline), the primary axis in egocentric space, without relying on information from optic flow [12,13]. In natural circumstances, centering the target straight ahead provides a direct straight line course to the target (Fig. 1b) [13,14].
3. *Canceling target optical drift strategy*. In an early study, Llewellyn [15] noticed that participants tried to steer toward a target by canceling the target drift on the image screen (i.e., the target optical drift). Later, several researchers showed mathematically that to walk or steer to cancel the target optical drift to keep it

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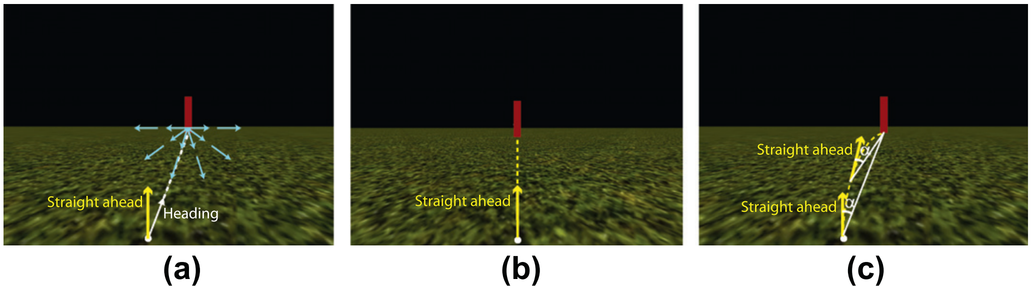

Fig. 1. Illustrations of the visual strategies for the control of steering toward a goal: (a) Align heading specified by optic flow with the target, (b) center the target straight ahead, and (c) cancel the target optical drift to keep it in a fixed direction from the straight ahead (i.e., maintain a constant target bearing angle α with respect to the straight ahead).

in a fixed direction away from the straight ahead results in traveling on equal-angular spirals toward the target (Fig. 1c) [14,16,17]. Rushton and Harris [14] further computationally illustrated that if an observer overcompensates for the target optical drift, e.g., when the target drifts 1° to the right, the observer rotates 2° (100% overcompensation) to the right, the path eventually straightens out as the target egocentric direction converges with heading.

1.1. Previous studies

Under natural situations, heading and the straight ahead coincide, and centering the target straight ahead provides the same straight line course to the target as does the optic flow strategy. To separate the use of target egocentric direction from heading specified by optic flow in the control of walking toward a goal, Rushton et al. [12] had participants wear displacing prism glasses that shifted both the target and the heading specified by optic flow away from their straight ahead. This, nevertheless, left the specified heading with respect to the target unaffected. Thus, if participants relied on the specified heading to walk toward the target, their walking should not be affected by the prism glasses and they would walk on a direct straight path to the target. Rushton et al. found that participants walked on a curved spiral path toward the target, consistent with the idea that participants walked in the target egocentric direction. Due to fact that the prism glasses constantly shifted the target away from participants' straight ahead, this study however could not determine whether participants walked to center the target at their straight ahead or to cancel the target optical drift to keep it in a fixed direction from their straight ahead.

Later studies, using either prism glasses [18–21] or head mounted displays that mimicked the effect of the prism glasses [22,23], found that participants walked on a straighter path when the display contained rich optic flow information, supporting the use of the optic flow strategy. Specifically, Warren et al. [22] displaced heading specified by optic flow 10° away from the participant's actual walking direction in a virtual environment, and found that when the display contained complex 3D structure and dense flow information, participants walked on a nearly straight path to place their heading specified by optic flow on the target.

More recently, Li and Cheng [24] had participants sit in front of a large screen and presented them with displays that simulated their walking over a ground plane. Participants were asked to use a high-precision joystick to control their walking to steer toward a target placed on the ground. Li and Cheng fixed the target egocentric direction and made this cue unavailable for steering to force participants to rely on information from optic flow to perform the task. They found that participants initiated their control response faster when the display contained richer optic flow information, and they steered to align their heading but not their future path specified by optic flow (see [25]) with the target. Furthermore, participants did not steer toward the target by equating the time-to-closure of the target-heading angle with the time-to-passage of the target (tau-equalization, see [26]). These findings provide direct support for the use of heading specified by optic flow in goal-oriented locomotion control when target egocentric direction is unavailable for steering.

1.2. The current study

In the present study, we examined what visual strategy people use to steer toward a target when the egocentric direction cue is available for steering. Specifically, we examined whether people steer to center the target at their straight ahead or to cancel the target optical drift to keep it in a fixed direction from their straight ahead. Furthermore, we examined how optic flow interacts with the use of the centering and the target drift strategies for goal-oriented locomotion control.

In previous walking studies, participants were instructed to walk toward a target, thus their heading was specified by both optic flow and non-visual cues such as the vestibular, proprioceptive, and motor information from the movement of the limbs [27–30]. As participants' heading specified by optic flow was displaced away from their actual walking direction through either prism glasses or head mounted displays, optic flow and non-visual cues

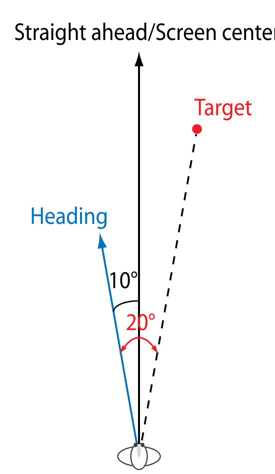

Fig. 2. A bird's eye view of the experimental setup with the target placed at 20° to the right of the initial heading. Participants' simulated gaze direction was aligned with the center of the screen that was calibrated to correspond to their straight ahead, and their simulated heading was displaced 10° to the left of their straight ahead. The target would drift to the left on the screen when participants tried to minimize the target-heading angle, causing the change of the target egocentric direction relative to their straight ahead.

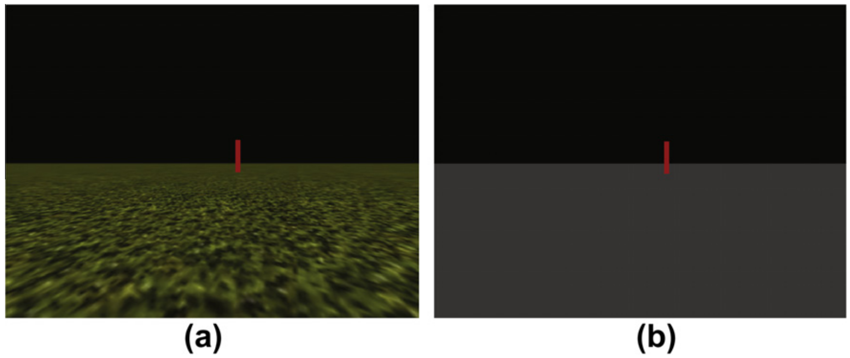

Fig. 3. Illustrations of the two display conditions: (a) A textured ground and (b) an empty ground. The post is at 10° to the right of the center of the display.

were in conflict with each other. It still remains in question how heading specified by non-visual information (i.e., participants' actual walking direction) interacts with the displaced heading specified by optic flow for goal-oriented locomotion control. In the current study, to remove the conflicting non-visual cues and to ensure that participants could only use visual information to perform the task, we had participants sit in front of a large screen with their head stabilized by a chinrest. Participants viewed a display that simulated their walking over a ground plane. Their heading specified by optic flow was displaced 10° away from the center of the screen that was calibrated to correspond to their straight ahead (Fig. 2). At the beginning of each 10 s trial, a target placed at 25 m in distance and 20° away from their initial heading direction appeared, and participants were instructed to use a joystick to control their simulated self-motion to (i) steer toward the target, (ii) center the target straight ahead, or (iii) minimize the target movement on the screen (i.e., cancel the target optical drift). We tested two display conditions, a textured ground (Fig. 3a) and an empty ground (Fig. 3b), to evaluate the control performance of each instruction group with and without global optic flow.

The logic of the study was given as follows. If participants steered toward the target by centering it straight ahead, the performance of the participants who were instructed to center the target should be similar to that of the participants who were instructed to steer toward the target, in which case the heading error of the steady-state control performance should be close to the heading displacement (10°). On the other hand, if participants steered toward the target by canceling its optical drift, the performance of the participants who were instructed to minimize the target movement on the screen should be similar to that of the participants who were instructed to steer toward the target, in which case the heading error should be constant and close to the initial target-heading offset angle (20°) throughout the trial. Furthermore, if optic flow affected the use of the centering or the target drift strategy, given that the textured ground display contained dense global flow while the empty ground display provided nearly no flow except the target expansion, participants in all three instruction groups should display different control performance for these two display conditions.

2. Methods

2.1. Participants

Twenty-three students and staff (all naïve as to the specific goals of the study; 7 males, 16 females) between the age of 19 and 38 at the University of Hong Kong participated in the experiment. All had normal or corrected-to-normal vision and provided informed consent in accordance with guidelines from the University of Hong Kong Human Research Ethics Committee. The participants were randomly assigned to three groups with different steering instructions. As a result, nine (7 females, 2 males) were instructed to steer toward the target, seven (6 females, 1 males) were instructed to steer to center the target straight ahead, and seven (3 females, 4 males) were instructed to steer to minimize the target movement on the screen. One participant (female) who was instructed to steer toward the target reported that she was not able to perform the task as required and was thus excluded from the data analysis.

2.2. Visual stimuli and experimental setup

The display simulated a participant walking over a ground plane (depth range: 1.41–100 m) at the fast walking pace of 2 m/s in an ideal scenario with no bounce or sway of the head. At the beginning of a trial, a red post target (1.3°W × 6.9°H) was placed at 25 m in distance and 20° away from the participant's initial heading. Participants were asked to use a high-precision joystick (B&G Systems, FlyBox) to control their simulated self-motion to steer toward the target, to center the target straight ahead, or to minimize the target movement on the screen. Participants' simulated/virtual gaze direction (i.e., the "camera" in the computer program for the display) was aligned with the center of the screen that was calibrated to correspond to their straight ahead, and their simulated heading was displaced 10° away from their straight ahead (i.e., the screen center). Given that the initial heading and the target direction were set to be on the opposite sides relative to the straight ahead, to steer to center the target straight ahead would cause a 10° under-steering heading error (Fig. 2). The control dynamics of the joystick was similar to that of the steering wheel of a car, i.e., the displacement of the joystick was proportional to path curvature. The joystick displacement was sampled at 60 Hz (i.e., every frame of the display). Its values ranged from −1 to 1, corresponding to peak path rotation rates of ±20°/s.

Two types of displays were tested: (1) a textured ground in which the ground plane was mapped with a multi-scale green texture with a power spectrum of $1/f$ (maximum luminance contrast +99%, Fig. 3a), and (2) an empty ground in which the ground plane was filled with solid gray color[1] (Fig. 3b). The luminance of the gray empty ground was equated to the average luminance of the textured ground. The textured ground display provided dense global flow, and the empty ground display provided nearly no flow except the target expansion. The background sky was black in the two display conditions.

The visual stimuli were generated on a Dell Precision Workstation 670n with an NVIDIA Quadro FX 1800 graphics card at 60 Hz,

[1] For interpretation of color in Fig. 4, the reader is referred to the web version of this article.

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and were rear-projected on a large screen (110°H × 94°V) with an Epson EMP-9300 LCD projector (native resolution: 1400 × 1050 pixels, refresh rate: 60 Hz). The screen edges were covered with black cloth to minimize their visibility. Participants sat on a high chair at 0.56 m away from the center of the screen and viewed the display monocularly with their dominant eye from a chin rest. Before the experiment started, participants' cyclopean eye (i.e., their straight ahead) was calibrated to be aligned with the center of the screen.

2.3. Procedure

Participants were randomly assigned to three instruction groups. On each trial, participants in the first instruction group were asked to imagine that they were walking over a ground plane and their task was to use the joystick to control their walking to steer toward the red post. In contrast, participants in the second instruction group were instructed to steer to place the red post at their straight ahead and keep it there throughout the trial, and participants in the third instruction group were instructed to steer to minimize the movement of the red post on the screen throughout the trial, i.e., to make the red post stay as much in the same position on the screen as possible. Given that the joystick controlled path curvature, participants in the second and third groups were informed that leftward movement of the joystick would effect rightward movement of the target on the screen and vice versa. The first frame was displayed until participants pulled the trigger to start each 10 s trial. Participants could freely move their eyes when viewing the displays. The time series of the participant's position in the virtual world and the joystick displacement were recorded for further analysis.

The experiment was composed of two blocks for the two display conditions. Each block contained 30 randomized trials (15 trials × 2 target directions) for each display condition. The testing order of the two blocks was counterbalanced between participants. Before the experiment started, participants received 12 randomized practice trials (3 trials × 2 target directions × 2 display types) to make sure that they understood the instructions and were familiar with the joystick control dynamics. No feedback was given during the practice or the data collection trials. The experiment lasted less than 30 min.

3. Results

To evaluate whether participants used heading specified by optic flow or target egocentric direction to steer toward the target, we computed the time series of heading error (i.e., the target-heading angle) from the recorded time series of the participant's position in the virtual world. Given the mirror-image performance for the left and right target direction conditions as indicated by the recorded time series of the participant's position (Fig. 4), we collapsed the performance data across the two target directions such that positive heading errors indicate under-steering and negative heading errors indicate over-steering.

Fig. 5a plots the predicted heading error profiles assuming that participants steered to (i) align their heading specified by optic flow with the target, (ii) center the target straight ahead, and (iii) minimize the target movement on the screen, respectively. Specifically, heading error would start at the initial target offset angle of 20°. If participants used the optic flow strategy and steered to align their heading specified by optic flow with the target, heading error would quickly converge to zero. In contrast, as the display was generated in such a way that participants' straight ahead was in between their initial heading and the target direction (Fig. 2), if participants steered to center the target straight ahead, they would under-steer which results in a positive heading error equal to the heading displacement (10°) for the steady state control. Lastly, if participants steered to minimize the target movement on the screen and keep it in a fixed direction away from their straight ahead, heading error would remain constant and close to the initial target-heading offset angle (20°) throughout the trial. Note that steering to center the target at the straight ahead or to minimize the target movement on the screen entails continual adjustments of the joystick to maintain the required target-heading angle.

Fig. 5b–d plot the time series of the heading error performance data averaged across participants for the three instruction groups. The solid lines represent the heading error data averaged over 30 trials in each display condition, and the dashed lines represent the data averaged over the first trial of the two (left and right) initial target directions in each display condition. Below we analyze the control performance of each instruction group in detail.

3.1. Steering to minimize the target movement

For participants who were instructed to steer to minimize the target movement, the heading error profile for the empty ground display shows that heading error starts at the initial target-heading angle (20°) and stays relatively constant at that value (within ±3°), then starts to increase at about 7 s. The increase of heading error near the end of the trial indicates that participants had difficulty in minimizing the target movement to keep it at a fixed position on the screen when they got close to the target, which is natural given the rapid outward acceleration of the target at close distance and the limits of steering with the joystick. For the textured ground display, heading error slowly gets smaller (mean <5° at 6–7 s), then starts to increase at about 7 s (Fig. 5b). This shows that adding optic flow information to the scene affected participants' control performance. Nevertheless, the heading error profiles for both the empty and the textured ground display conditions are consistent with the fact that participants followed the instructions and steered to minimize the target movement on the screen.

3.2. Steering to center the target and steering toward the target

For both the group of participants who were instructed to steer to center the target and the group that was instructed to steered toward the target, heading error started at 20° and then got smaller with time, reaching steady-state performance at 6–7 s (Fig. 5c and d). As the width of the target at 6–7 s is 2.72°, the about 12° under-steering final heading error observed for the empty ground display shows that participants could accurately steer to center the target at their straight ahead, consistent with the predicted heading error profile for centering the target shown in Fig. 5a. However, for the textured ground display, heading error near the end of the trial is smaller than 10° although not close to zero. This again shows that adding optic flow information to the scene affected participants' control performance.

To systematically compare the control performance of the three instruction groups for the two display conditions, we analyzed the accuracy of the control response, indicated by the final heading error averaged across the last 1 s of the trial. Fig. 6 plots the mean final heading error averaged across 30 trials against display condition for each participant for the three instruction groups. A 3 (instruction group) × 2 (display condition) mix-designed ANOVA on the final heading errors revealed that both the main effects of instruction group and display condition were significant ($F(2,19) = 14.34$, $p < 0.001$ and $F(1,19) = 33.15$, $p < 0.0001$, respectively), but not their interaction effect ($F(2,19) = 0.77$, $p = 0.48$). Tukey HSD tests showed that across the two display conditions, the mean final heading error for the minimizing-the-target-movement

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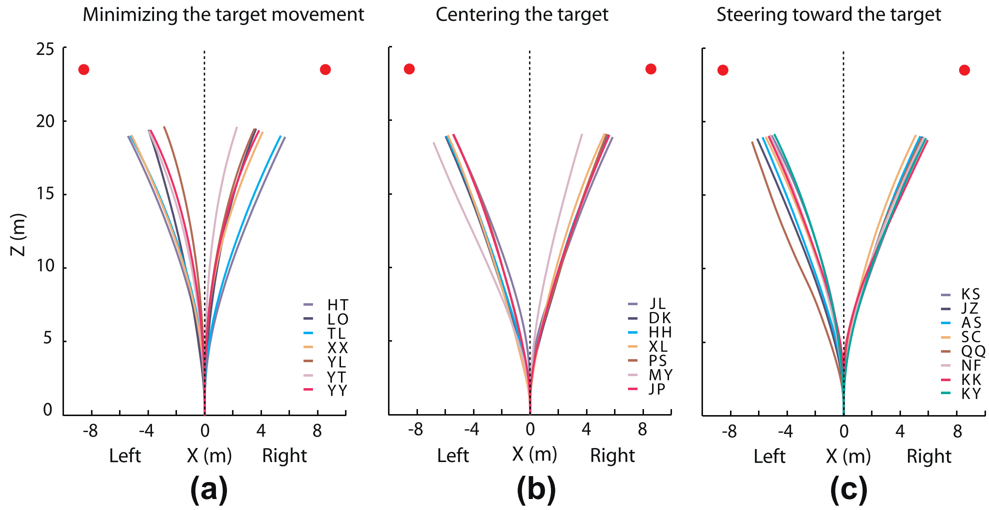

Fig. 4. The recorded time series of each participant's position averaged over 15 trials with the textured ground display for (a) the minimizing-the-target-movement, (b) the centering-the-target, and (c) the steering-toward-the-target instruction groups. The red dot indicates the target.

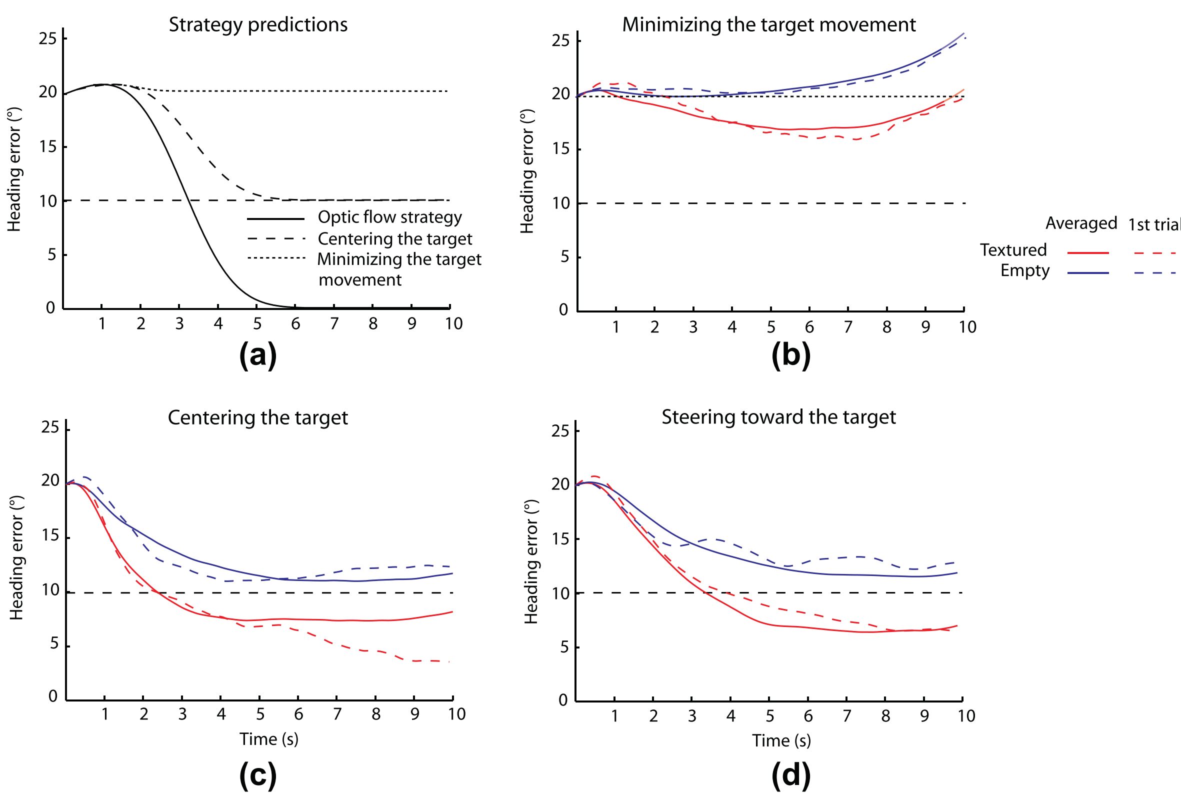

Fig. 5. (a) The predicted heading error profiles for the three steering strategies, and the time series of heading error performance data averaged across participants for the two display conditions for (b) the minimizing-the-target-movement, (c) the centering-the-target, and (d) the steering-toward-the-target instruction groups. The solid lines in (b), (c), and (d) represent the heading error data averaged over 30 trials in each display condition, and the dashed lines represent the heading error data averaged over the first trial of the two (left and right) initial target directions in each display condition. The dotted line at 20° indicates the initial heading error, and the dashed line at 10° indicates the heading error for perfectly centering the target at the straight ahead.

instruction group (21.42°) was significantly larger than those for the centering-the-target (9.67°, $p < 0.001$) and the steering-toward-the-target instruction groups (9.54°, $p < 0.001$), and the latter two were not significantly different from each other ($p = 0.999$). This shows that when target egocentric direction was available for steering, participants did not steer toward the target by canceling the target optical drift to keep it in a fixed direction away from their straight ahead.

3.3. Effect of optic flow on the control of steering

To examine the effect of optic flow on the control performance for the three instruction groups, we computed the reduction of the final heading error as flow was added by subtracting the final heading error for the textured ground display from that for the empty ground display. Fig. 7 plots the mean final heading error reduction averaged across participants for each instruction group.

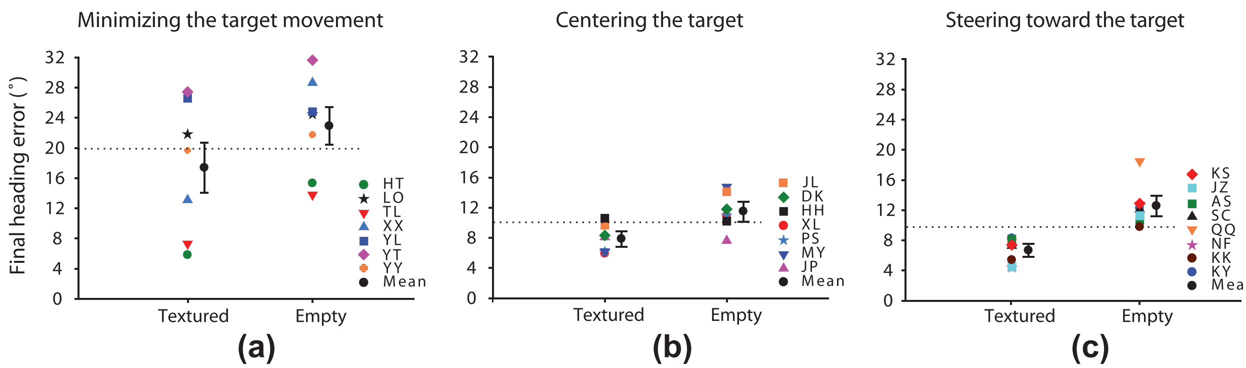

Fig. 6. Mean final heading error averaged across 30 trials for each participant along with the mean averaged across participants against display condition for (a) the minimizing-the-target-movement, (b) the centering-the-target, and (c) the steering-toward-the-target instruction groups. Error bars are SEs across seven participants in (a) and (b), and across eight participants in (c). The dotted line at 20° in (a) indicates the heading error for perfectly minimizing the target movement on the screen, and the dotted line at 10° in (b) and (c) indicates the heading error for perfectly centering the target at the straight ahead.

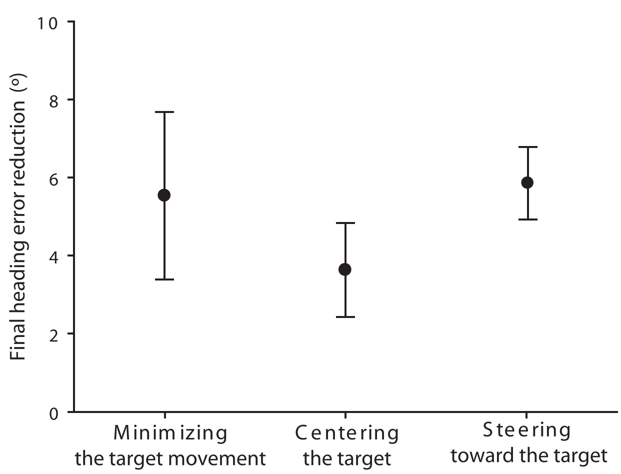

Fig. 7. Mean heading error reduction for the three instruction groups. Error bars are SEs across seven participants for the minimizing-the-target-movement and the centering-the-target instruction groups, and across eight participants for the steering-toward-the-target instruction group.

A one-way ANOVA showed that the main effect of instruction group was not significant ($F(2,19) = 0.77$, $p = 0.48$). Separate t-tests revealed that for all three instruction groups, the mean final heading error reduction was significantly different from zero ($p < 0.05$). These results indicate that optic flow similarly affected the control performance for all three instruction groups. On average, the dense global flow field provided by the textured ground display led to a reduction of the final heading error by 5.24°.

4. Discussion

The current study was designed to find out whether, when target egocentric direction is available, participants steer toward a goal by centering the target straight ahead or by canceling the target optical drift to keep it in a fixed direction from their straight ahead. Furthermore, the current study examined how optic flow interacts with the use of the target egocentric direction cue for the control of steering toward a goal. Below we discuss how the findings from the current study address these issues.

4.1. Use of target egocentric direction

The distinct heading error profile of participants who were instructed to steer to minimize the target movement shows that although computationally possible [14,16,17], people do not steer toward the target by simply canceling the target optical drift to keep it in a fixed egocentric direction from their straight ahead. Instead, the similar heading error profiles for the participants who were instructed to steer to center the target straight ahead and those who were instructed to steer toward the target suggest that when target egocentric direction is available for steering, people steer to center the target at their straight ahead. As the experimental setup in previous walking studies, which used either displacing prism glasses [12,18,19,21,31] or head mounted displays [20,22,23,32], did not allow to assess whether participants walked to center the target straight ahead or to cancel the target optical drift, the current study for the first time showed that when people use target egocentric direction for goal-oriented locomotion control, they prefer steering or walking to center the target at their straight ahead.

We then performed detailed analysis of the target optical drift strategy and found that when the observer's straight ahead is fixed relative to the world (i.e., the observer has a fixed body orientation and is not rotating) during traveling, the observer can walk toward the target by directly canceling the target optical drift (Fig. 8, upper panel) as previously shown by the computational models [14,16,17]. In contrast, when the observer's straight ahead is not fixed relative to the world (e.g., the observer rotates to align the body orientation with heading) during traveling, the observer rotation affects the angular velocity of the target drift (Fig. 8, lower panel). In this case, the observer needs to take self-rotation into account when canceling the target optical drift (see also [33]). Otherwise, walking to cancel the target optical drift would not allow the observer to reach the target (Fig. 8, lower panel). Theoretically, given the available retinal and extra-retinal information generated during self-rotation, observers should be able to accurately estimate their body rotation. However, Cheng and Li [34] showed that observers could not accurately estimate self-rotation from retinal information alone when the rotation rate is low (1.5°/s). This indicates the limitation of the canceling target optical drift strategy for locomotion control. In comparison, to steer to center the target straight ahead and keep it there provides a direct straight line course to the target that does not depend on the perception of self-rotation, and is thus a robust strategy for the control of locomotion toward a goal.

4.2. Effect of optic flow

For all three instruction groups, the final heading error for the textured ground display that provides dense global flow is on average about 5° smaller than that for the empty ground display. The

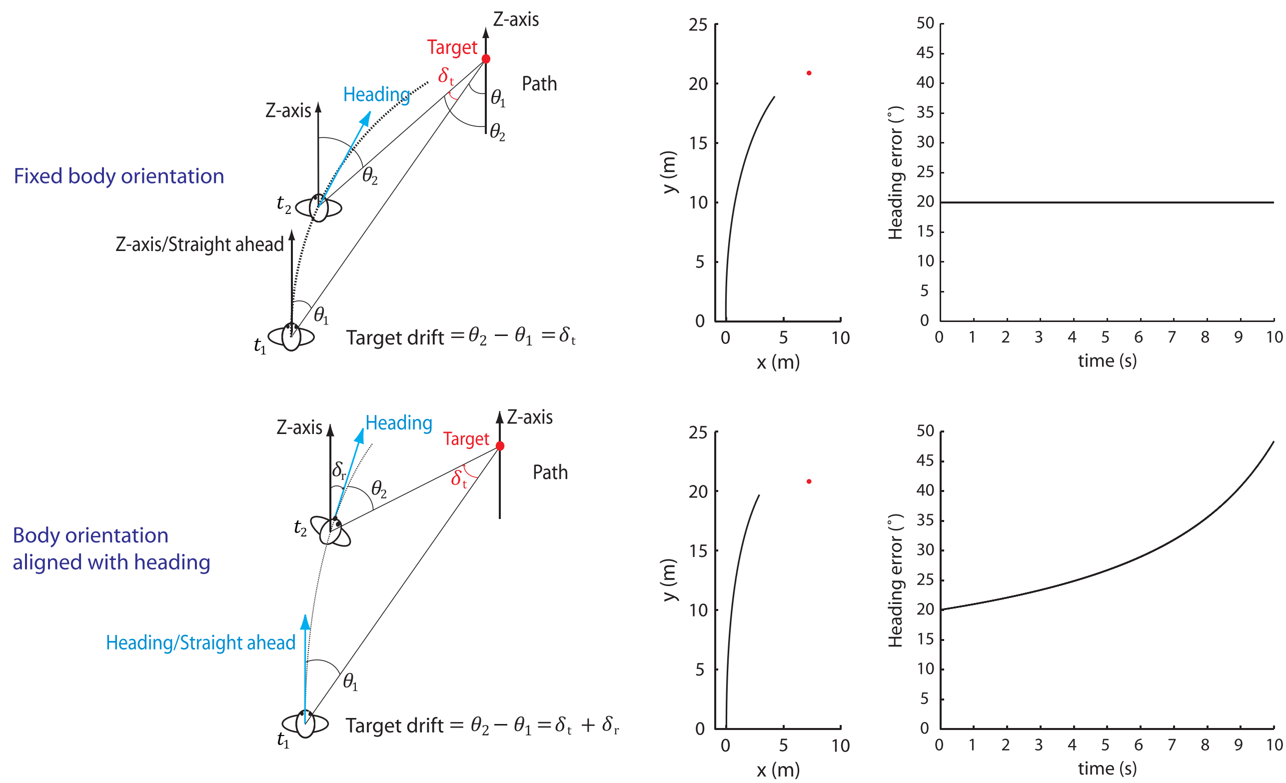

Fig. 8. The bird's eye views showing two scenarios of traveling toward a target by canceling the target optical drift along with the computational simulations of the path traveled and the heading error profile. The observer's body orientation (i.e., the straight ahead) is fixed along the *Z*-axis in the world in the upper panel, and is aligned with heading thus rotates in the world (δ_r) in the lower panel. The target is at 25 m away from the start position and 20° to the right of the initial heading. The simulated traveling speed is at 2 m/s.

similar effect of optic flow on control performance across the three instruction groups shows that even when the target egocentric direction cue was available for steering, optic flow still had an effect on their control performance.

The reduction of the heading error as global flow is added with the textured ground display is consistent with the use of heading specified by optic flow for the control of steering. In fact, the smaller than 10° but larger than zero final heading errors observed for both the steering-toward-the-target and the centering-the-target instruction groups with the textured ground display (Fig. 6b and c) are consistent with the previous findings showing that participants used both heading and target egocentric direction for the control of walking toward a goal [18–23], with the final heading error determined by a weighted average of the use of these two cues (e.g., [22,35]).

In most cases of traveling in the world, one's straight ahead is aligned with one's instantaneous direction of travel (i.e., heading). Rushton and Salvucci [36] proposed that when heading specified by optic flow does not coincide with one's straight head, one's perceived straight ahead can shift toward the displaced heading specified by optic flow. As a consequence, the effect of optic flow on the locomotion control observed in the current study and in many previous walking studies could also be indirect through affecting the perceived target egocentric direction. The empirical evidence that supports this argument includes the studies showing that after walking for an extended period of time in a structured environment with prism glasses that displaced heading specified by optic flow away from the straight ahead, the perceived straight ahead shifted in the direction of the heading displacement (e.g., [37–39]). Recently, Herlihey and Rushton [31] had participants wearing displacing prism glasses walk toward a goal for a relatively short period of time and found that reducing the amount of optic flow also reduced the amount of shift of the perceived straight ahead. All these findings support the claim that optic flow plays an important role in driving the recalibration of the perceived straight ahead and thus affecting the perceived target egocentric direction for goal-oriented locomotion control.

The effect of optic flow on the control of steering toward a goal observed in the current study is in conflict with what was reported by Saunders and Durgin [32]. They found that global optic flow provided by a textured ground had a rather small effect on the control of walking toward a target attached to the ground. Their findings are also in conflict with previous walking studies that reported a large effect of optic flow on the control of walking toward a goal using a similar head mounted display setup (e.g., [20,22,23]). We surmise that their different findings could be due to the following reasons. First, unlike the textured ground used in the current study and in previous walking studies, the textured ground used by Saunders and Durgin is composed of hexagons that fade out quickly with distance, thus providing weak global flow. Accordingly, the weak but still significant effect of optic flow observed in their study is likely due to the smaller amount of flow in their display. Second, Saunders and Durgin used a dual task paradigm in which walking toward the target was a secondary task in their study. This might have further reduced participants' reliance on the weak global flow in their display due to insufficient attention to the walking task. The dual task paradigm also added noise to participants' walking data which was revealed by the reported large variability in the end point of walking across trials.

5. Conclusions

In this study, we examined whether, when target egocentric direction is available for steering, people steer toward a target by

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centering the target straight ahead or by canceling the target optical drift to keep it in a fixed direction from their straight ahead. We also examined how optic flow interacts with the use of the centering and the target drift strategies by testing a textured ground display that provides dense global flow and an empty ground display that provides nearly no flow. Three groups of participants were instructed to use a joystick to control their simulated walking to (i) steer toward the target, (ii) center the target straight ahead, or (iii) minimize the target movement on the screen, respectively. The heading error profiles showed that when using target egocentric direction for steering, participants steered to center the target straight ahead. Further computational analysis showed that the target drift strategy works well when the observer's straight ahead is fixed in the world during traveling (such as walking like a crab). Across all three instruction groups, final heading errors are about 5° smaller with the textured than with the empty ground display, showing the effect of optic flow on control performance even when participants were explicitly instructed to use target egocentric direction for steering. Further research is needed to examine the extent to which the effect of optic flow on goal-oriented locomotion control is due to the change of the perceived target egocentric direction caused by the recalibration of the perceived straight ahead.

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References

[1] J.J. Gibson, The Perception of the Visual World, Houghton Mifflin, Boston, 1950.
[2] W.H. Warren, M.W. Morris, M. Kalish, Perception of translational heading from optical flow, J. Exp. Psychol. Hum. Percept. Perform. 14 (1988) 646–660.
[3] J.A. Crowell, M.S. Banks, Perceiving heading with different retinal regions and types of optic flow, Percept. Psychophys. 53 (1993) 325–337.
[4] D. Regan, K.I. Beverly, How do we avoid confounding the direction we are looking and the direction we are moving?, Science 215 (1982) 194–196
[5] W.H. Warren, D.J. Hannon, Direction of self-motion is perceived from optical flow, Nature 336 (1988) 162–163.
[6] A. Grigo, M. Lappe, Dynamical use of different sources of information in heading judgments from retinal flow, J. Opt. Soc. Am. A: Opt. Image Sci. Vis. 16 (1999) 2079–2091.
[7] L. Li, B.T. Sweet, L.S. Stone, Humans can perceive heading without visual path information, J. Vis. 6 (2006) 874–881.
[8] L. Li, J. Chen, X. Peng, Influence of visual path information on human heading perception during rotation, J. Vis. 9 (3) (2009) 1–14 (article no. 29).
[9] L.S. Stone, J.A. Perrone, Human heading estimation during visually simulated curvilinear motion, Vision. Res. 37 (1997) 573–590.
[10] L. Li, W.H. Warren, Perception of heading during rotation: sufficiency of dense motion parallax and reference objects, Vision. Res. 40 (2000) 3873–3894.
[11] L. Li, W.H. Warren, Retinal flow is sufficient for steering during observer rotation, Psychol. Sci. 13 (2002) 485–491.
[12] S.K. Rushton, J.M. Harris, M.R. Lloyd, J.P. Wann, Guidance of locomotion on foot uses perceived target location rather than optic flow, Curr. Biol. 8 (1998) 1191–1194.
[13] W.H. Warren, Visually controlled locomotion and orientation, Ecol. Psychol. 10 (1998) 157–346.
[14] S.K. Rushton, J.M. Harris, The utility of not changing direction and the visual guidance of locomotion, in: V. Lucia, S.A. Beardsley, S.K. Rushton (Eds.), Optic Flow and Beyond, Kluwer Academic Publishers, Dordrecht, 2004, pp. 363–381.
[15] Llewellyn, Visual guidance of locomotion, J. Exp. Psychol. 91 (1971) 245–261.
[16] D.N. Lee, Guiding movement by coupling taus, Ecol. Psychol. 10 (1998) 221–250.
[17] S.K. Rushton, J. Wen, R.S. Allison, Egocentric direction and the visual guidance of robot locomotion: background, theory, and implementation, in: H.H. Bulthoff, S.-W. Lee, T.A. Poggio, C. Wallraven (Eds.), Biologically motivated Computer Vision: Lecture notes in Computer Science, Springer, London, 2002, pp. 576–591.
[18] M.G. Harris, G. Carré, Is optic flow used to guide walking while wearing a displacing prism?, Perception 30 (2001) 811–818
[19] B.J. Rogers, C. Dalton, The role of (I) perceived direction and (II) optic flow in the control of locomotion and for estimating the point of Impact, Invest. Ophthalmol. Vis. Sci. 40 (1999) s4036.
[20] K.A. Turano, D. Yu, L. Hao, J.C. Hicks, Optic-flow and egocentric-direction strategies in walking: central vs peripheral visual field, Vision. Res. 45 (2005) 3117–3132.
[21] R.M. Wood, M.A. Harvey, C.E. Young, A. Beedie, T. Wilson, Weighting to go with the flow?, Curr Biol. 10 (2000) R545–R546.
[22] W.H. Warren, B.A. Kay, W.D. Zosh, A.P. Duchon, S. Sahuc, Optic flow is used to control human walking, Nat. Neurosci. 4 (2001) 213–216.
[23] H. Bruggeman, W. Zosh, W.H. Warren, Optic flow drives human visuo-locomotor adaptation, Curr. Biol. 17 (2007) 2035–2040.
[24] L. Li, J.C. Cheng, Heading but not path or the tau-equalization strategy is used in the visual control of steering toward a goal, J. Vis. 11 (12) (2011) 1–12 (article no. 20).
[25] J. Wann, M. Land, Steering with or without the flow: is the retrieval of heading necessary?, Trends Cogn Sci. 4 (2000) 319–324.
[26] B.R. Fajen, Steering toward a goal by equalizing taus, J. Exp. Psychol. Hum. Percept. Perform. 27 (2001) 953–968.
[27] L. Telford, I.P. Howard, M. Ohmi, Heading judgments during active and passive self-motion, Exp. Brain Res. 104 (1995) 502–510.
[28] Y. Gu, D.E. Angelaki, G.C. Deangelis, Neural correlates of multisensory cue integration in macaque MSTd, Nat. Neurosci. 11 (2008) 1201–1210.
[29] J.S. Butler, S.T. Smith, J.L. Campos, H.H. Bülthoff, Bayesian integration of visual and vestibular signals for heading, J. Vis. 10 (11) (2010) 1–13 (article no. 23).
[30] K.N. de Winkel, J. Weesie, P.J. Werkhoven, E.L. Groen, Integration of visual and inertial cues in perceived heading of self-motion, J. Vis. 10 (12) (2010) 1–10 (article no. 1).
[31] T.A. Herlihey, S.K. Rushton, The role of discrepant retinal motion during walking in the realignment of egocentric space, J. Vis. 12 (3) (2012) 1–11 (article no. 4).
[32] J.A. Saunders, F.H. Durgin, Adaptation to conflicting visual and physical heading directions during walking, J. Vis. 11 (3) (2011) 1–10 (article no. 15).
[33] B.R. Fajen, W.H. Warren, Behavioral dynamics of intercepting a moving target, Exp. Brain Res. 180 (2007) 303–319.
[34] J.C. Cheng, L. Li, Effects of reference objects and extra-retinal information about pursuit eye movements on curvilinear path perception from retinal flow, J. Vis. 12 (3) (2012) 1–21 (article no. 12).
[35] R.M. Wilkie, J.P. Wann, R.S. Allison, Active gaze, visual look-ahead, and locomotor control, J. Exp. Psychol. Hum. Percept. Perform. 34 (2008) 1150–1164.
[36] S. Rushton, D. Salvucci, An egocentric account of the visual guidance of locomotion, Trends Cogn. Sci. 5 (2001) 6–7.
[37] R. Held, J. Bossom, Neonatal deprivation and adult rearrangement: Complementary techniques for analyzing plastic sensory-motor coordinations, J. Comp. Physiol. Psychol. 54 (1961) 33–37.
[38] S. Morton, A. Bastian, Cerebellar control of balance and locomotion, Neuroscientist 10 (2004) 247–259.
[39] G.M. Redding, B. Wallace, Cognitive interference in prism adaptation, Percept. Psychophys. 37 (1985) 225–230.

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