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Do walkers follow their heads? Investigating the role of head rotation in locomotor control

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Abstract

Eye and head rotations are normally correlated with changes in walking direction, however it is unknown whether they play a causal role in the control of steering. The objective of the present study was to answer two questions about the role of head rotations in steering control when walking to a goal. First, are head rotations *sufficient* to elicit a change in walking direction? Second, are head rotations *necessary* to initiate a change in walking direction or guide steering to a goal? To answer these questions, participants either walked towards a goal located 7m away or were cued to steer to the left or right by 37°. On a subset of trials, participants were either cued to voluntarily turn their heads to the left or right, or they underwent an involuntary head perturbation via a head-mounted air jet. The results showed that large voluntary head turns (35°) yielded slight path deviations (1–2°) in the same or opposite direction as the head turn, depending on conditions, which have alternative explanations. Involuntary head rotations did not elicit path deviations despite comparable head rotation magnitudes. In addition, the walking trajectory when turning toward an eccentric goal was the same regardless of head orientation. Steering can thus be decoupled from head rotation during walking. We conclude that head rotations are neither a sufficient nor a necessary component of steering control, for they do not induce a turn and they are not required to initiate a turn or to guide the locomotor trajectory to a goal.

Introduction

Humans travel about the environment not aimlessly, but with an intended goal, and they steer their locomotion toward that goal. The visual system provides information about a goal's location and helps guide an individual toward it. But precisely how vision is used to control steering remains a contested issue. One popular account is that the direction of travel (i.e. heading) is controlled by fixating the goal and then aligning the head and body with the gaze direction – in short, people follow their eyes and head (Cutting, Readinger, & Wong, 2002; Land & Tatler, 2001; Sreenivasa et al., 2009; Wilkie, R.M., et al., 2010). Indeed, skiers and mountain bikers are advised to look where they want to go, not at obstacles in their path, on the belief that people steer where they look. In the present study, we investigate this *gaze angle strategy* for steering control in human walking by determining whether head rotations are necessary or sufficient to change the direction of locomotion.

Grasso and colleagues (1998, 1996) reported that when individuals are asked to walk along a pathway and make a 90° turn, rotations of their head about the vertical axis precede the turn, even in the absence of vision. Other researchers have also found that a head turn normally precedes a change in the direction of travel towards a new goal (Patla et al., 1999; Hollands

et al., 2001; Hicheur et al., 2005), and is proportional to the curvature of the path (Hicheur & Berthoz, 2005; Kadone et al., 2010). This finding is consistent with a “top-down” gaze angle strategy for steering control, in which the walker first fixates the goal and then rotates the head and the trunk to close the angle between the gaze direction and the locomotor axis. The gaze angle strategy could be implemented in the form of a neuromotor synergy for reorienting the locomotor axis, as proposed by Grasso et al., (1998). Such a *steering synergy* would generate a pattern of muscle activation that yields a coordinated sequence of yaw movements of the eyes, head, and trunk, thereby changing the direction of travel.

It has also been suggested that aligning the head with the goal provides a natural frame of reference for steering control because the head segment houses sensors that establish the perceived straight ahead and are relevant to guiding locomotion (i.e. visual, vestibular, and proprioceptive) (Pozzo et al., 1990; Vallis, Patla, & Adkin, 2001). These three sensory systems are all affected by a head rotation. However, it is uncertain as to whether the resulting sensory signals reciprocally affect steering following a head rotation, in the absence of an intention to change the direction of travel. Land and Tatler (2001) have also suggested that head movements elicit a set of visual expectations about the intended travel path, and if there is a discrepancy between the visual expectations and the observed scene, an error signal is used to correct the travel path.

Head rotations may normally be correlated with changes in walking direction, but whether they play a causal role in the control of steering remains unknown. This issue cannot be addressed by naturalistic observations of walking behavior, but requires the experimental manipulation of head orientation. In the present study, we investigate the contribution of active and passive head rotations to locomotor control when walking to a goal. The objective of these experiments was to answer two questions about steering control: First, are head rotations *sufficient* to elicit a change in walking direction – that is, do people follow their heads? Second, are head rotations *necessary* to initiate a change in walking direction or guide steering to a goal – that is, are they required for turning? Let us consider these two questions in more detail.

First, the observation that head rotations normally precede a turn suggests that they may be sufficient to elicit turning, implying that walkers steer where they look (Kadone et al., 2010; Sreenivasa et al., 2009). It is possible, for example, that during locomotion a head rotation automatically releases the steering synergy (Grasso et al., 1998). Indeed, Cutting, et al. (2002) found slight veering in the direction of a fixation target 5°–10° to the left or right, both with lights on and off (lateral deviation of 0.4m over a 5 m distance); however, they did not record head or eye movements. Vallis and Patla (2004) reported that when an involuntary head yaw perturbation was applied to the head while participants attempted to walk straight, they exhibited significant path deviations in the direction of the head rotation. In contrast, when participants made voluntary head turns while walking towards an explicit goal, they only exhibited small nonsignificant path deviations. The authors reasoned that for voluntary head movements, an efference copy of the motor command leads the Central Nervous System (CNS) to suppress the steering synergy. Thus, the slight (nonsignificant) path deviations were due to incomplete suppression of the steering synergy. With an involuntary perturbation there is no such efference copy, so the CNS interprets the rotation as a change in the head-centred reference frame, and hence in the perceived straight ahead, leading participants to veer towards the side of rotation. This pattern of results is consistent with the idea that involuntary head rotations are sufficient to elicit a change in the walking direction; however the observed path deviations are only a small fraction of the magnitude of the head perturbation.

In spite of this finding, we note an important confound in the previous two studies. During the voluntary head turn condition, Vallis and Patla (2004) presented an explicit goal (a target on the wall) and found no significant path deviations, whereas in the head perturbation condition participants continued to walk ‘along the travel path’ without a goal and exhibited significant path deviations. Similarly, Cutting, et al. (2002) instructed participants to “walk straight ahead” without a locomotor goal and observed slight path deviations. It is likely that an explicit goal is important for steering control because it provides an environment-centered reference frame for guiding locomotion. Thus we insured there was an explicit goal in the present experiments.

Second, the finding that eye and head rotations normally precede a turn suggests that turning your head to look where you want to go is required for steering control (Vallis, Patla, & Adkin, 2001). Specifically, head rotations may be necessary to activate the steering synergy in order to reorient the locomotor axis. Contrary to this view, Vallis and McFadyen (2003) found that head and trunk rotations occur simultaneously when circumventing an obstacle en route to a goal. An alternative explanation is that head rotations are correlated with steering as part of ordinary gaze control, rather than a steering synergy. Coordinated eye and head rotations typically occur to fixate an eccentric visual target, depending on conditions (Fuller, 1992; Smeets, Hayhoe & Ballard, 1996). Thus, head rotations may normally precede a turn because participants ordinarily fixate in the intended walking direction. Looking in the walking direction would help to resolve the identity and location of the goal as well as other objects in the travel path, and the tendency may be sufficiently strong to induce gaze shifts even without vision (Grasso, et al. 1998, 1996). When circumventing an obstacle, gaze may be tangent to the obstacle so that head and trunk rotate together (Vallis & McFadyen, 2003). It is thus possible that a synergy serves to coordinate eye and head rotations involved in gaze shifts, but is not critical for steering control.

It is important to point out that alternatives to the gaze angle strategy are available for guiding locomotion to a goal (Warren, 1998). The visual direction of the goal with respect to the locomotor axis is perceptually specified whether or not the eyes and head are fixated on the goal itself. A more general steering strategy is to close the *target-heading angle* between the visual direction of the goal and the direction of travel, independent of one’s gaze direction (Fajen & Warren, 2003). One’s current heading direction is visually specified by optic flow (Gibson, 1950; Warren, 2008) as well as by podokinetic information about the locomotor axis, although with lower resolution (Telford, Howard, & Ohmi, 1995). Thus, steering might be controlled by two versions of the general target-heading angle strategy: an *egocentric direction strategy* based on the angle between the goal direction and the podokinetic locomotor axis (Rushton et al., 1998; Harris & Bonas, 2002) or an *optic flow strategy* based on the visual angle between the goal and one’s current heading specified by optic flow (Gibson, 1950; Warren et al., 2001). We have previously found that both contribute additively to the control of walking: the egocentric direction strategy dominates in the absence of optic flow (e.g. in the dark), whereas the optic flow strategy dominates in richly structured visual environments (Warren et al., 2001; Bruggeman & Warren, VSS 2010). However, these alternatives have not been experimentally dissociated from the gaze angle strategy.

In summary, the aim of this study is to determine whether head rotations are sufficient or necessary to initiate a turn to an explicit goal. To answer these questions, we designed conditions that would test whether voluntary or involuntary head turns elicit a change in the walking direction, and whether participants can successfully turn toward a goal without preceding head rotations. To investigate the contribution of optic flow, these conditions were performed in illumination and in darkness. We hypothesize that steering to an explicit

goal is independent of head rotation, contrary to the gaze angle strategy, but is consistent with a more general target-heading angle strategy.

General Methods

Apparatus

The study was conducted in the Virtual Environment Navigation Lab (VENLab) at Brown University, using real objects arranged in an 8m x 8m area. Three light poles, each with three coloured lamps (red, green, and blue) mounted at about eye-level, were located at the end of a 7m pathway. Green lights served as locomotor goals, and red lights as fixation targets. One light pole was located in line with the midline of the pathway while the other two were located 3m to the right and left of the midline. Five yellow poles (20cm in diameter and 2.2m in height) were randomly placed on either side of the walkway in order to provide some visual structure in the surround. An optical switch located at a distance of 3m from the starting position served as an event trigger to initiate a head perturbation or to illuminate one of the target lights. Each participant wore a head-mounted air-jet (0.5 kg) that perturbed the head about the vertical axis (see Vallis and Patla, 2004 for more details). Briefly, a 76cm long crosspiece mounted on the head emitted a 2s pulse of compressed air (100 psi) at either end to apply a yaw torque to the head. The participant's head position and orientation were measured using a hybrid ultrasonic-inertial tracking system (Intersense IS-900) with six degrees of freedom, at a sampling rate of 30Hz.

Procedure

Prior to the experiment, each participant was outfitted with the air-jet and exposed to two head perturbations (i.e. left and right) about the vertical axis. This was done in order to familiarize participants with the device and minimize initial responses to an unnatural perturbation. The participants were told to respond naturally when they received a head perturbation during the experimental trials. Participants were then informed about the events in each experimental condition and how to respond: if only a green light was illuminated, they should face and walk toward it, whereas if a red light was also illuminated, they should orient their head toward the red light and walk toward the green light. They were instructed to walk at their normal, self-selected pace towards the specified goal. On each trial, the green goal light always began in the centre location and could remain in the same location, change to the left or right location ($\pm 37^\circ$) when the participant reached the event trigger (at 3 m), or extinguish after the participant walked 1m; the red fixation target might appear in the right, left, or centre location. Prior to testing, participants were given practice trials in each condition, and data collection did not begin until they were able to follow the instructions without errors. In each experiment there were eight conditions, presented in a completely random order to each participant. There were 8 trials in each condition (4 to the left and 4 to the right for turns and head rotations) for a total of 64 trials.

Data Analysis

The time series of head position and orientation (i.e. yaw angle) for each trial were low-pass filtered at 0.6Hz using a second order Butterworth filter to reduce the effects of gait oscillations. The time series of heading (direction of travel) was then computed from the head displacement on successive frames (see Fajen & Warren, 2003). The following dependent measures were computed from the filtered data for each trial (refer to Figure 1): heading error (β angle) relative to the centre light, medial-lateral (M-L) deviation from the midline of the walkway, and head rotation magnitude about the vertical axis (yaw angle). Since the head perturbation lasted for 2s, these measures were computed at each frame of data from 1.5s prior to the event trigger to 2s following the trigger (i.e. 105 data points) for each trial. One-way Repeated Measures ANOVAs were used to analyze differences between

relevant experimental conditions, including leftward and rightward turn directions, for each of the dependent variables: signed maximum heading error (rightward=positive), signed maximum M-L deviation (leftward=positive), and signed maximum head yaw (rightward=positive).ⁱ

Experiment 1: Do walkers follow their heads?

The first experiment was designed to address several questions about the gaze angle strategy for steering control. First, to determine whether voluntary head rotations induce a path deviation, we asked participants to turn their heads to face a target light, while continuing to walk straight towards the original goal. Second, to test whether involuntary head rotations elicit a path deviation, we used Vallis and Patla's (2004) air-jet apparatus to administer a yaw perturbation to the head while the participant continued walking toward the original goal. We repeated this condition in a darkened room to see whether path deviations are greater when only podokinetic information for heading is available. Third, to test whether head rotations are necessary to control steering, participants turned to walk toward a new goal while maintaining head orientation toward the original goal. We report the experimental conditions (Figure 2) relevant to each of these questions as sub-experiments of Experiment 1.

Participants

Nine (5 males, 4 females) healthy undergraduate students (between 18 and 20 years old) from Brown University participated in Experiment 1. All reported having normal or corrected to normal visual acuity and gave written consent to participate in the study. They were paid \$8 for their participation in the study.

Experiment 1a: Voluntary head turns—The first sub-experiment asked whether active head rotations induce a change in the walking direction. Previous research (Vallis & Patla, 2004) indicated that when participants voluntarily rotate their heads while walking to a goal, they deviate off the travel path by approximately 4cm in the direction of the head turn.

Procedure: Participants were instructed to always walk straight toward the central green goal light. In the Head Turn condition, a red fixation target was illuminated 37° to the right or left when the participant passed the 3m trigger. In response to this target light, participants were asked to voluntarily rotate their head to face its location, while continuing to walk straight towards the original green goal light. Steering behaviour during the Head Turn condition was compared to a Control condition (8 trials) in which participants walked to the central green goal light while keeping their head oriented toward it.

Results: Participants deviated 1°–2° in the direction of the target light (Figure 3). A one-way ANOVA on maximum heading error (β) revealed significant differences between the Control, left Head Turn, right Head Turn conditions, $F(2,8) = 30.59$, $p < 0.001$. A Tukey *HSD* test showed that rightward head turns led to larger positive heading errors than leftward head turns and walking straight whereas leftward head turns led to larger negative heading errors than the other two conditions (Figure 3A). A one-way ANOVA on M-L deviation revealed a significant difference across conditions, $F(2,8) = 26.19$, $p < 0.001$. A Tukey *HSD* test revealed that the average deviation for the rightward head rotations led to a larger negative deviation than the other two conditions and a leftward head rotation led to larger positive deviations than the other two conditions (Figure 3B). Mean head rotations of about 35° were similar to

ⁱWe did not use circular statistics to analyze the angular variables because the head rotations and heading angles were in a small restricted range, and could be approximated by linear analyses.

the target's eccentricity (37° at the trigger), and a one-way ANOVA on maximum yaw angle confirmed that they were significant, $F(2,8)=73.13$, $p<0.001$; a Tukey *HSD* test revealed the expected differences between all three conditions (Figure 3C). Table 1 contains the average and standard deviation of each dependent variable for each condition.

Discussion: Participants deviated slightly but significantly in the direction of an active head turn (4–7cm after 2s), in contrast to the nonsignificant deviations reported by Vallis and Patla (2004) (2–4cm after 1.5s). However, although the deviations were statistically significant, it is important to note that they were just a small fraction of the head turn. The mean head rotation of approximately 35° yielded a mean change in walking direction of only 1.3° after 2s, that is, the steering shift was only 3.7% of the head rotation. The observed path deviations are thus not of the magnitude expected from a steering synergy or gaze angle strategy.

What else might account for these small deviations? The main difference between Vallis and Patla's (2004) active head turn condition and the present condition is that we presented a visual cue rather than an auditory cue to signal the head turn. This raises the possibility that the visual transient associated with the onset of the target light served to capture the walker's attention (Franconeri et al., 2005). On this account, the spatial shift of attention briefly redirects the intended walking direction, inducing a small path deviation. We remedy this in Experiment 2 by signalling a head turn auditorily rather than visually.

Experiment 1b: Involuntary head perturbations (Light and Dark)—The second sub-experiment asked whether involuntary head rotations induce a path deviation while walking to a goal. Vallis & Patla (2004) reported that when the participant's head was externally perturbed while walking straight without an explicit goal, the involuntary yaw rotation elicited a significant path deviation of about 4cm in the direction of the perturbation. We used the same apparatus to apply yaw perturbations during walking to a visible goal, such that the target-heading angle was continuously specified, in both an illuminated and darkened room. This allowed us to compare path deviations with full visual information and with only podokinetic information for heading direction.

Procedure: In the Head Perturbation condition, the participant was instructed to walk toward the centre green goal light while keeping their head oriented toward it, with normal room illumination. When they passed the 3 m trigger, a rightward or leftward external yaw perturbation of the head was initiated and participants were asked to respond naturally to the perturbation, while the participant continued walking towards the central goal. The Head Perturbation (Dark) condition was the same, except that the room was darkened in order to reduce the visibility of environmental surfaces and texture; only the goal light and area surrounding it was clearly visible. These conditions were compared with the previous Control condition, in which the participant faced and walked toward the central goal light.

Results: The perturbations produced average head yaw rotations of 25° leftward and 10° rightward, yet they failed to elicit measurable deviations of the walking direction in either the illuminated or darkened room (Figure 4 and Table 1). A one-way ANOVA on heading error showed no significant differences between left and right Head Perturbation or Control conditions, in the light or the dark, $F(4,8)=0.84$, $p>0.5$ (Figure 4A). The ANOVA on M-L deviations also failed to reach significance, $F(4,8)=0.41$, $p>0.5$ (Figure 4B). In contrast, the ANOVA on maximum yaw angle confirmed that the perturbations produced significant head rotations, $F(4,8)=9.68$, $p<0.001$ (Figure 4C). A Tukey *HSD* test found that the yaw angle magnitudes for rightward and leftward perturbations were significantly different in both the light and dark conditions, however they were not different from the Control condition.

Discussion: In contrast to Vallis and Patla (2004), we found that involuntary head rotations did not elicit path deviations, despite comparable head perturbations (about 25° leftward). Participants did not follow their heads in the light or in the dark. The main difference between these two experiments is that Vallis and Patla (2004, Experiment 2) instructed their participants to walk along the travel path without an explicit goal, whereas we presented a continuously visible goal. Our purpose was to clearly specify the target-heading angle so it could be used to guide locomotion regardless of head orientation. The presence of a goal appears to eliminate path deviations, whether the heading direction is specified by optic flow or podokinetic information. Therefore, the lack of significant path deviations with an explicit goal was most likely due to a clearly defined target-heading angle. The presence of an explicit goal in Vallis and Patla's (2004) active head turn condition might thus explain the lack of significant deviations in that condition.

This pattern of results is inconsistent with view that an involuntary head turn elicits a change in walking direction. However, the present results might be explained if walkers followed their eyes but *not* their heads. Presumably, the vestibulo-ocular reflex (VOR) would have compensated for the head perturbation, stabilizing gaze on the goal (Berthoz, 1989), thereby avoiding a path deviation. If so, then the VOR would have similarly stabilized gaze in Vallis and Patla's (2004) perturbation condition, and yet they observed path deviations. Thus, the pattern of results cannot be explained by observers following their eyes; it appears to be more consistent with a general target-heading angle strategy for guiding locomotion.

Experiment 1c: Steering to an Eccentric Goal—The final sub-experiment sought to test whether head rotations are necessary for successful steering. The participants began walking toward the central goal and upon passing the trigger turned to walk toward an eccentric goal, either voluntarily oriented their heads toward the new goal, or voluntarily counter-rotating their heads to continue facing the old goal. If a head rotation is necessary to initiate a turn, then we would expect a larger change in walking direction when participants orient the head to the new goal than when they keep the head facing the original goal. Alternatively, if steering is independent of head rotations, the walking direction should change similarly in the two conditions.

Procedure: In the Steer-Head Turn condition, the centre green light was on at the beginning of a trial. When the participant passed the 3m event trigger, the centre green light turned off and the left or right green light came on ($\pm 37^\circ$); participants were instructed to face and steer towards the new goal light. In the Steer-Head Straight condition, the centre red light was on at the beginning of a trial and participants were instructed to face and walk toward it. At the 3m trigger, the left or right green goal light came on ($\pm 37^\circ$), while the centre light remained red; participants were instructed to steer towards the green goal light while keeping their heads oriented toward the red centre light.

Results: Changes in walking direction in the two conditions were indistinguishable (Figure 5 and Table 1). A one-way ANOVA on maximum heading error (Figure 5A) revealed significant differences between the Steer Left, Steer Right, and Control conditions, $F(4, 8) = 70$, $p < 0.001$. A Tukey *HSD* test showed that the Steer Left-Head Turn and Steer Left-Head Straight conditions were both different from the Control and Steer Right conditions, but were not statistically different from each other; the symmetric pattern was true for the Steer Right-Head Turn and Steer Right-Head Straight conditions. An analogous ANOVA on maximum M-L deviation (Figure 5B) was also significant, $F(4, 8) = 330$, $p < 0.001$, and the Tukey *HSD* test produced exactly the same pattern of results. Thus, the path deviations did not depend on head rotation.

This lack of difference in path deviations might be due to a lack of difference in the head rotations. To check this, a one-way ANOVA on the maximum Yaw angle (Figure 5C) found significant differences between the Steer Left, Steer Right, and Control conditions, $F(4,8) = 310$, $p < 0.001$. A Tukey *HSD* test revealed that all five conditions were significantly different from each other, such that the magnitude of rotation was largest in the Steer Left-Head Turn condition followed by the Steer Left-Head Straight and the Control condition, with a symmetric pattern for the Steer Right-Head Straight and Steer Right-Head Turn conditions. This indicates that the Steer-Head Straight conditions elicited significant partial head rotations toward the new eccentric goal even though participants were instructed to keep their head facing straight toward the original goal. However, head yaw was significantly larger in the Steer-Head Turn conditions than the Steer-Head Straight conditions, and yet there were no corresponding differences in the walking path.

Discussion: The results showed that the walking trajectory to steer toward an eccentric goal was the same whether the head reoriented to the new goal or remained facing the original goal. This indicates that head rotations to a goal are not necessary to guide steering to that goal, contrary to the gaze angle strategy. The similar walking trajectories cannot be explained by similar head rotations, for the head yaw was significantly greater in the Steer-Head Turn conditions than the Steer-Head Straight conditions. However, there was a brief, partial head rotation of 10° – 15° toward the 37° eccentric goal in the latter condition, despite instructions to continue facing the original goal (Figure 5C). Thus, it might be argued that this partial head turn served to initiate the change in walking direction, consistent with a steering synergy, even if it wasn't required to guide the entire steering trajectory. However, gaze shifts to fixate targets in the visual periphery are typically composed of coordinated eye and head rotations, which can be intentionally suppressed (Smeets, Hayhoe & Ballard, 1996). It is thus likely that the onset of the eccentric goal light evoked eye and head rotations to fixate the target. We sought to eliminate these partial head rotations in Experiment 2 by instructing participants on each trial to keep the head facing forward.

Note that the partial head turn in the Steer-Head Straight condition was quickly halted and reversed (beginning around 400ms, Figure 5C), with no effect on the locomotor trajectory, contrary to a steering synergy. This result appears to be inconsistent with Experiment 1a: if an active head turn produced path deviations toward the fixation target in Experiment 1a, then an active counter-rotation of the head should have produced deviations toward the original goal in the present experiment. This might be explained by the absence of a visual transient at the original goal location, in contrast to the visual transient at the fixation target in the previous experiment. On this account, path deviations were due to attentional capture, so active counter-rotation of the head did not influence steering.

Conclusions: Experiment 1 provided preliminary evidence that head rotations are neither sufficient nor necessary to steer the direction of walking. Involuntary head rotations during walking to an explicitly defined goal were clearly insufficient to elicit measurable path deviations – in the light, in the dark, or with a remembered goal location. Participants did not follow their perturbed heads. These findings are independent of differences in approach walking speed because there was no difference in walking speeds prior to the event trigger across the conditions, $F(5,417) = 0.905$, $p > 0.05$. This suggests that the target-heading angle is sufficient to guide locomotion, uninfluenced by passive head rotations, even when the goal direction must be updated in the dark. Voluntary head rotations did induce small path deviations in the direction of the head turn, but they were only 3.7% of what was required to actually follow the head, and might be due to attentional capture. We test this hypothesis in Experiment 2 by removing the visual transients.

Conversely, when steering to a new goal, the walking trajectory was the same whether the head rotated toward the new goal or counter-rotated toward the old goal. This indicates that it is not necessary to orient the head toward the goal in order to steer to that goal, contrary to the gaze angle strategy. However, the onset of steering was preceded by a brief, partial head turn toward the new goal, which likely reflects normal eye-head shifts when fixating a peripheral target. To test whether such head rotations are necessary to initiate steering, as suggested by a steering synergy, we sought to eliminate them in Experiment 2.

These results clearly indicate that the gaze angle strategy is not essential to control steering to a goal. However, it remains possible that there are small influences of voluntary head rotation on changes in walking direction, consistent with a steering synergy. We pursue this question in Experiment 2.

Experiment 2: Controls for visual transients and partial head rotations

The previous experiment found small path deviations in the direction of a voluntary head turn (Head Turn condition), as well as partial head turns preceding the onset of steering (Steer-Head Straight condition), which could reflect the influence of a steering synergy. However, both of these effects have alternative explanations, which we investigated in Experiment 2. First, to determine whether small path deviations were elicited by voluntary head turns or visual transients, we had participants turn their heads on a verbal rather than a visual signal. Second, to determine whether partial head rotations are necessary to initiate changes in walking direction, we sought to eliminate them via instructions at the beginning of each trial. Finally, to check whether involuntary head rotations might have more influence during an intended change in walking direction, we perturbed the head so that it would assist or resist an intended turn.

Participants

A different group of nine (6 males, 3 females) healthy undergraduate students (between 18 and 20 years old) from Brown University participated in Experiment 2. All reported having normal or corrected to normal visual acuity and gave written consent to participate in the study. They were paid \$8 for their participation in the study.

Experiment 2a: Voluntary head turns without visual transients (Light and Dark)—In the first sub-experiment, we asked whether voluntary head rotations are sufficient to elicit small path deviations in the direction of the head turn in the absence of visual transients. We eliminated the transients that were present in Experiment 1a by asking participants to turn their heads in response to a verbal rather than a visual cue. This was repeated in a darkened room to test whether path deviations are greater when only podokinetic information for the heading direction is available.

Procedure: Only the centre green goal light was illuminated during a trial; the eccentric target lamps were present but unilluminated (refer to Figure 6A–D). To indicate the direction of a voluntary head turn, a verbal command was given by an experimenter standing at the starting position. In the Control condition, participants were instructed to orient their head in the direction of the goal and walk towards it. In the Head Turn condition, a verbal command (“head left” or “head right”) was given to cue the direction of head rotation when the participant passed the 3m event trigger, while they continued walking toward the centre goal light. The Control (Dark) condition was identical to the Control condition, except that the room was darkened in order to reduce the visibility of the surrounding environment; only the green goal light was clearly visible. Finally, the Head Turn (Dark) condition was similar to the Head Turn condition, except that the room was darkened and the eccentric target lamps were not clearly visible.

Results: Participants exhibited small path deviations of about 2° , but in the direction *opposite* the head turn, both in the light and in the dark (Figure 7, Table 2). A one-way ANOVA on maximum heading error found significant differences between leftward and rightward Head Turn (Light and Dark) and Control (Light and Dark) conditions, $F(5,8) = 26.35$, $p < 0.001$ (Figure 7A). A Tukey *HSD* test revealed that the leftward Head Turn (Light and Dark) conditions, which veered to the *right*, were significantly different from the rightward Head Turn (Light and Dark) conditions, which veered to the *left*, but did not differ from each other. These conditions were significantly different from the Control (Light and Dark) conditions, with the exception of the rightward Head Turn (Dark) condition. A second one-way ANOVA on M-L deviations in these conditions was also significant, $F(5,8) = 11.45$, $p < 0.001$, and a Tukey *HSD* test revealed the same pattern of significant differences between conditions, with maximum deviations up to 12cm opposite the head rotation (Figure 7B). A final one-way ANOVA on maximum head yaw in these conditions was also significant, $F(5,8) = 136.13$, $p < 0.001$, and a Tukey *HSD* test again showed the same pattern of differences among conditions (Figure 7C). The average head rotation (yaw) magnitude for the Head Turn (Light and Dark) conditions was approximately 50° , compared to approximately 35° in Experiment 1a.

Discussion: In the absence of a visual transient, participants in the present experiment deviated slightly *away* from the direction of the head turn, both in the light and in the dark – precisely the opposite of Experiment 1a. This result clearly demonstrates that walkers do not follow their heads when walking to an explicit goal. It also implies that the result in Experiment 1a was most likely due to the presence of a visual transient at the fixation target, which presumably captured the participants' attention and led to a slight deviation toward the target. The observed deviation opposite the head turn was again very small, only 2° after 2s, or only 4% of the head rotation.

These findings are similar to those of Jahn et al. (2006) who also found that walkers deviated between 2.7° and 3.7° in the direction opposite to voluntary head turns. However, their participants wore a blindfold and had their heads locked in a fixed orientation with a neck device. The authors claimed that the path deviations opposite to the intended head turn could have been due to compensation for apparent path deviations in the direction of the intended head turn due to lack of visual feedback (Jahn et al., 2006). This explanation cannot account for the present result because our participants deviated opposite to a free head turn, in both the light and the dark.

Alternatively, the slight deviation opposite the head turn might be explained by a mislocalization of the goal in the participants' retinal periphery. Let us assume that when participants rotated their heads by an average of 50° , they shifted fixation to the unilluminated target lamp at 37° , or even farther. This would put the green goal light at a retinal eccentricity of 37° in a direction opposite the head turn. Bock (1986,1993) found that the eccentricity of a visual target is overestimated by 1.3° at retinal eccentricities of 10° to 30° , as measured by an egocentric motor response (pointing). This is comparable to the magnitude of the observed locomotor heading error in the present experiment (about 2° opposite the head turn). Thus, when the participant turned the head rightward, the apparent egocentric direction of the goal would shift about 1.3° leftward, leading to a similar leftward path deviation.

Experiment 2b: Steering to a goal without partial head turns—In the second sub-experiment, we asked whether steering can be initiated in the absence of a head rotation toward the new goal. We eliminated the partial head rotations observed in Experiment 1c by instructing participants at the start of every steering trial to keep the head oriented towards

the centre goal light. In addition, the room was illuminated in all conditions, unlike Experiment 1c. This succeeded in preventing head rotations toward the new goal.

In addition, it is possible that the head perturbations in Experiment 1b had little effect because the steering synergy only comes into play during an intended turn. That is, when an individual has the intention to change direction, the synergy is activated in order to sequence the body segment rotations (i.e. eyes, head, trunk, legs), whereas on other occasions the segments are not coupled. To check this possibility, we applied an external yaw perturbation to the head at the time of an intended turn, when the steering synergy should be engaged. If the perturbation is applied in the same direction as the intended turn, then one might expect it to assist the turn so the participant overshoots the normal walking trajectory. Conversely, if the perturbation is in the direction opposite to the turn, then one might expect it to resist the turn, so the participant undershoots the normal trajectory.

Procedure: All conditions were tested in an illuminated room (refer to Figure 7E–H). The Steer-Head Turn condition was the same as in Experiment 1c: the centre green goal light was on at the beginning of a trial, and when the participant passed the 3m event trigger, it was extinguished and the left or right green light came on; participants were instructed to rotate their head to face and steer towards the new goal light. The Steer-Head Straight condition was also the same as in Experiment 1c, except that at the start of each trial, prior to passing through the event trigger, the participant was reminded to keep the head facing forward. The centre red light was on at the beginning of a trial and at the 3m trigger, the left or right green goal light came on, while the centre light remained red; participants were instructed to steer towards the green goal light while keeping their heads facing in the direction of the red centre light. The Steer Assist condition was the same as the Steer-Head Turn condition, except that the event trigger initiated an external head yaw perturbation in the direction of the new goal. Finally, the Steer Resist condition was the similar to the Steer Assist condition, except that the head perturbation was in the direction opposite to that of the new goal.

Results: Partial head turns toward the new goal were eliminated in this experiment (Figure 8C). To test this, a one-way ANOVA on the maximum head yaw angle following the trigger was performed on the unperturbed conditions, revealing a significant main effect, $F(4,8)=250$, $p<0.001$. A Tukey *HSD* test indicated that the Steer Left-Head Straight, Steer Right-Head Straight, and Control conditions were not significantly different from each other, whereas the Steer Left-Head Turn condition differed from the other four conditions, as did the Steer Right-Head Turn condition. Thus, when steering to an eccentric goal, participants completely counter-rotated their heads to maintain orientation toward the original goal, as instructed. This could be due to the verbal reminder to keep the head facing forward, or possibly to the fact that the room was illuminated and not dark as in Experiment 1c.

Active and perturbed head rotations had little influence on the steering trajectory (Figure 8 and Table 2). We performed a one-way ANOVA on maximum heading error (Figure 8A) during the following conditions: Steer-Head Turn, Steer-Head Straight, Steer Assist, and Steer Resist conditions for both leftward and rightward steering. The results showed that there was a significant difference between these conditions, $F(7, 8) = 500$, $p<0.001$. A Tukey *HSD* test indicated that all the Steer Left conditions were different from all the Steer Right conditions, but the leftward conditions did not differ among themselves, nor did the rightward conditions. We performed an analogous one-way ANOVA on maximum lateral displacement (Figure 8B) and also found a main effect, $F(7,8)= 160$, $p<0.001$. A Tukey *HSD* test similarly indicated that the Steer Left conditions were different from the Steer Right conditions but did not differ among themselves, except that the Steer Left-Head Straight and Steer Right-Head Straight conditions exhibited greater displacements than the

other conditions. This means that lateral deviations in the Steer-Head Straight conditions overshot the typical path to a new goal by about 20cm, opposite the head counter-rotation.

Finally, a one-way ANOVA on head yaw angles in all eight steer conditions (Figure 8C) yielded a main effect, $F(7,8) = 420$, $p < 0.001$. A Tukey *HSD* test confirmed that head rotations in the Steer Left conditions were significantly different from those in the Steer Right conditions. Within each steering direction, the Assist condition was significantly different from the Resist condition, and both were different from the Head Straight condition; the Assist condition also differed from the Steer-Head Turn condition, but the Resist condition did not. These findings indicate that the desired differences in head yaw were obtained (with the exception of the Resist condition), and thus the similarities in heading errors and M-L deviations cannot be attributed to non-significant differences in head orientation.

Discussion: The results demonstrate that even partial head turns in the direction of a new goal are not necessary to initiate a change in the walking direction. When the partial head turns observed in Experiment 1c were eliminated by a verbal reminder, steering was still successfully initiated with the same heading trajectory as during free head turns. The only difference was small oversteering (M-L deviation) toward the new goal when counter-rotating the head to maintain fixation on the original goal – the opposite of what would be expected from a steering synergy or the gaze angle strategy. This finding is similar to that of Experiment 2a, in which the walking path deviated opposite a head rotation and overshot a peripheral goal. In the present case the locomotor goal was again 37° in the retinal periphery, and thus a slight overestimation of its eccentricity (Bock, 1987, 1993) could account for the observed overshooting of the path to the goal. These results indicate that it is not necessary to orient the head toward a goal, even partially, to initiate steering, contrary to the steering synergy and the gaze angle strategy.

The head perturbation conditions reveal that even when there is an intention to change direction, perturbed head rotations still do not elicit path deviations. If an intended change in the travel path serves to activate a steering synergy, it might be expected that an assistive head perturbation would elicit oversteering, and a resistive perturbation understeering, yet neither of these effects were observed. The lack of understeering might be attributed to the fact that the Resist perturbations did not produce statistically significant head yaw, but the Assist perturbations did so, and yet did not induce oversteering. Thus, even during steering, involuntary head rotations do not influence the locomotor path.

Conclusions: In summary, Experiment 2 shows that when visual transients and partial head turns are controlled, there is no evidence that voluntary head rotations elicit path deviations in the direction of the head turn, or are required to initiate a change in the walking direction, in the presence of an explicit goal. The slight but significant steering deviations in the direction opposite to the head turn may be accounted for by eccentric mislocalization of the goal in the retinal periphery, rather than an overcompensation as suggested by Jahn et al. (2006).

General Discussion

The main objective of this study was to determine whether a head turn is necessary or sufficient to change the direction of locomotion when walking to a goal. Although the literature clearly indicates that head rotations normally precede a change in walking direction (Grasso et al., 1998; Patla et al., 1999; Hollands et al., 2001), the question is whether they are merely correlated with turning or play a causal role in the control of steering. We find no evidence that they do.

First, the results from the current study indicate that neither voluntary nor involuntary head turns are *sufficient* to elicit a change in the walking direction away from the intended goal, either in the light or in the dark. People do not follow their heads. In Experiment 1a we observed a slight path deviation in the direction of a voluntary head turn to a target light (1.3° for a 35° head rotation, or 3.7%), but this was most likely due to the visual transient at target onset. Such a transient is known to capture attention (Franconeri et al., 2005), which may induce a brief shift in the intended direction of travel (only 3.5% of the attentional shift). When the visual transient was eliminated in Experiment 2a, participants no longer deviated in the direction of the voluntary head turn, but instead deviated slightly in the *opposite* direction (2°). This can be attributed to the known overestimation of target eccentricity in the visual periphery by about 1.3° (Bock, 1988, 1993). In Experiment 1b, we found that involuntary head perturbations elicited no observable path deviations from an intended goal. We conclude that head rotations do not induce a locomotor turn or release a steering synergy.

These results are opposite to those reported by Vallis and Patla (2004), who found no significant path deviations during voluntary head turns, but significant deviations in the direction of an involuntary head perturbation. The authors attributed the latter result to the release of a steering synergy, and the former result to suppression of the steering synergy by an efference copy of the head rotation command. However, we believe there is an alternative explanation. Vallis and Patla (2004) presented a visible goal in the voluntary head turn condition, so the target-heading angle was clearly defined, whereas participants merely walked ‘along the travel path’ in the involuntary head turn condition, so the target-heading angle was not specified. In the present study, we insured that the goal was explicitly defined, so the target-heading angle was specified in all conditions. We found no effect of head perturbations once the goal was explicitly defined.

Second, the present results also indicate that head turns are not *necessary* to guide steering or initiate a change in the walking direction. People do not have to follow their heads in order to steer. In Experiment 1c, when participants steered to an eccentric goal, we observed the same walking trajectories whether the head turned to face the new goal or counter-rotated to face the old goal, demonstrating that orienting the head toward the current goal is not required to guide walking. In Experiment 2b, the partial head turns observed in the previous experiment were eliminated, confirming that even small head rotations toward the new goal are not required to initiate a locomotor turn. We noted a slight oversteering to the new goal in this case, opposite the direction of head counter-rotation, but this can again be attributed to overestimation of the goal’s eccentricity in the retinal periphery. We conclude that head rotations are not necessary for the control of steering.

Taken together, these results indicate that the direction of locomotion can be controlled independent of head orientation up to a difference of at least $\pm 56^\circ$ (2s after the event trigger) when walking to an explicit goal. This finding is inconsistent with the gaze angle strategy for steering control, according to which an individual first fixates the goal and then aligns the head, trunk, and locomotor axis with the fixation direction in order to perform a turn. It is also inconsistent with a compulsory neuromotor steering synergy (Grasso et al., 1998) that activates a temporal sequence of eye, head, and trunk rotations to change the direction of travel. Such a sequence of segment rotations may be normally observed with free eyes and head relative to the intended direction of travel. However, the present results show that when head orientation is inconsistent with intended direction of travel, the travel path is largely unaffected. This implies that head rotations are not an essential component of steering control, for they neither induce a change in the walking direction nor are they required to initiate such a change or guide the locomotor trajectory. One might think that perturbing the

head during a turn once the steering synergy is engaged would yield a path deviation, but we did not observe such an effect.

The present results thus demonstrate that steering can be decoupled from head rotations during walking, implying that neither the gaze angle strategy nor a steering synergy play a compulsory role in steering control at walking speeds. It remains possible that locomotor control is highly flexible and the gaze angle strategy is merely one of several available strategies that might be recruited to perform a turn. However, neither the literature nor the present experiments offer evidence that head rotations actually play a causal role in steering control, as opposed to merely being a correlate of turning. We suggest that head movements are normally correlated with steering as a byproduct of gaze shifts to fixate the goal or the intended walking direction (Smeets, Hayhoe & Ballard, 1996).

On the other hand, the current results are consistent with a more general target-heading angle strategy (Fajen & Warren, 2003). On this account, steering is controlled by closing the angle between the direction of the goal and the current direction of travel, independent of head orientation. On occasions when the walker fixates the goal, the gaze angle happens to correspond to the target-heading angle, but steering control is functionally based on closing the target-heading angle, not the gaze angle. Hence, head rotations neither elicit path deviations in the direction of the head turn, nor are necessary to change the walking direction.

However, the target-heading angle strategy does require information about both the direction of the goal and the current direction of heading. As noted above, we believe the presence of an explicit goal accounts for the difference between our results and those of Vallis and Patla (2004). The finding that walking toward the goal can be maintained in the light and the dark suggests that the current heading direction can be determined both from visual information such as optic flow, and from podokinetic information about the direction of walking (Telford, Howard, & Ohmi, 1995; Warren et al., 2001).

The present results for legged locomotion differ from related findings for high-speed locomotion in a driving simulator. When fixation is manipulated, steering with a steering wheel appears to be slightly biased in the direction of gaze (e.g. lateral deviations up to 0.15m or 0.5m, depending on conditions), both when driving a straight roadway (Readinger et al., 2002) and when following a curve (Mars, 2008; Robertshaw & Wilkie, 2008; Kountouriotis, et al., 2011). The effect persists when the relation between the steering wheel and gaze direction is reversed, indicating that it is not due to a muscle-specific coupling such as a motor synergy or the tonic neck reflex (Heuer & Klein, 1999; Readinger et al., 2002), and it is overridden by visual constraints such as a narrow roadway (Robertshaw & Wilkie, 2008). The relation between these findings and the present results are unclear. On the one hand, the control principles may be similar, such that small influences of gaze are revealed at high speeds because the lateral deviation is proportional to the longitudinal displacement. On the other hand, the inconsistent inertial information in a static driving simulator is known to yield difficulty with steering (Reymond, et al., 2001) and might exaggerate the influence of gaze direction. Finally, as pointed out by Mars (2008), walking and driving are very different tasks, and it would not be surprising if they were regulated differently. Gaze direction relative to the roadway may provide very sensitive informative for maintaining lane position at high speed (Land & Lee, 1994; Wilkie, et al., 2010) but be irrelevant to the task of walking toward a goal in the open field.

In conclusion, our findings indicate that head rotations are neither necessary nor sufficient to induce changes in the direction of locomotion when walking to a goal. To test whether the

present findings hold for eye as well as head rotations, future research should investigate the causal role of fixating the goal in the control of steering.

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Figure 1.

Calculation for both Heading Error and M-L Deviation. The participants walked diagonally across the room and the calculations reflect this and that the coordinate axis of the room was pre-determined. Heading Error (β) was calculated as the angle between the direction that the participant was walking at any point in time and the location of the goal within the room. M-L Deviation was the lateral distance in meters between the participant's location at any point in time and the imaginary line connecting the starting position and the goal.

Figure 2.

The eight different experimental conditions used in Experiment 1. The dark shaded conditions indicate that they were preformed in the dark. The centre light was the goal in which participants were instructed to walk towards initially. The side lights were used to either indicate the direction in which participants should turn their heads (Head Turn) or as a new goal (Steer-Head Turn)

Figure 3.

The average Heading Error, M-L Deviation, and Head Yaw angle across all participants during the Control and Head Turn conditions (Experiment 1A). The data points were sampled from 1.5 seconds prior to the event trigger until 2 seconds after the event trigger.

Figure 4.

The average Heading Error, M-L Deviation, and Head Yaw angle across all participants during the Control, Head Perturbation, and Head Perturbation (Dark) conditions (Experiment 1B). The data points were sampled from 1.5 seconds prior to the event trigger until 2 seconds after the event trigger.

Figure 5.

The average Heading Error, M-L Deviation, and Head Yaw angle across all participants during the Steer-Head Turn and Steer-Head Straight conditions (Experiment 1c). The data points were sampled from 1.5 seconds prior to the event trigger until 2 seconds after the event trigger.

Figure 6.

The eight different experimental conditions used in Experiment 2. The dark shaded conditions indicate that they were preformed in the dark. The design of the conditions were in response to the findings from Experiment 1 in order to better understand the role of head position in steering direction.

Figure 7.

The average Heading Error, M-L Deviation, and Head Yaw angle across all participants during the Control, Head Turn, Control (Dark), and Head Turn (Dark) conditions (Experiment 2A). The data points were sampled from 1.5 seconds prior to the event trigger until 2 seconds after the event trigger.

Figure 8.

The average Heading Error, M-L Deviation, and Head Yaw angle across all participants during the Steer-Head Turn, Steer-Head Straight, Steer-Head Assist, and Steer-Head Resist conditions (Experiment 2B). The data points were sampled from 1.5 seconds prior to the event trigger until 2 seconds after the event trigger.