

Heading Through a Crowd

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www.psychologicalscience.org/PS**Abstract**

The ability to navigate through crowds of moving people accurately, efficiently, and without causing collisions is essential for our day-to-day lives. Vision provides key information about one's own self-motion as well as the motions of other people in the crowd. These two types of information (optic flow and biological motion) have each been investigated extensively; however, surprisingly little research has been dedicated to investigating how they are processed when presented concurrently. Here, we showed that patterns of biological motion have a negative impact on visual-heading estimation when people within the crowd move their limbs but do not move through the scene. Conversely, limb motion facilitates heading estimation when walkers move independently through the scene. Interestingly, this facilitation occurs for crowds containing both regular and perturbed depictions of humans, suggesting that it is likely caused by low-level motion cues inherent in the biological motion of other people.

Keywords

optic flow, biological motion, heading, navigation, vision, open data

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The pattern of radial optic flow produced on the retina by movement through the world is a rich source of information about our environment and can be used as a purely visual means for guiding locomotion (Gibson, 1950). When the physical environment is entirely rigid, estimates of the direction in which one is heading can be derived by analyzing the motion vectors in the optic flow pattern (Bruss & Horn, 1983; Longuet-Higgins & Prazdny, 1980). Humans are able to estimate their heading from rigid scenes with a degree of accuracy adequate for safe navigation (Cutting, Springer, Braren, & Johnson, 1992; Warren & Hannon, 1988; Warren, Morris, & Kalish, 1988).

Rigid scenes are frequently used in experimental settings; however, real-world encounters often encompass nonrigid environments. Natural scenes are regularly populated by externally moving objects and people, which pose potential problems for heading estimation. Though the computation of heading is fairly robust and remains accurate even at relatively low signal-to-noise ratios (van den Berg, 1992; Warren, Blackwell, Kurtz, Hatsopoulos, & Kalish, 1991), independent object movement in a scene disturbs the global pattern of optic flow and causes inaccuracies in heading detection (Andersen & Saidpour, 2002; Layton & Fajen, 2015, 2016; Royden & Hildreth, 1996; Warren &

Saunders, 1995). In crowds, this is exacerbated by the fact that people not only *translate* through space (i.e., change their spatial location over time) but also move their limbs while doing so.

Though limb motion adds further noise to the optic flow field, it also conveys information about the nature of a person's actions (Dittrich, 1993; Johansson, 1973), movement (Cutting, Moore, & Morrison, 1988; Graf et al., 2007; Masselink & Lappe, 2015; Thurman & Lu, 2016), and intentions (Blakemore & Decety, 2001; Diaz, Fajen, & Phillips, 2012). This information can be ascertained from the patterns of motion produced by the movement of the major joints, which is commonly referred to as biological motion (Blake & Shiffrar, 2007).

In theory, the visual system could take advantage of the additional information provided by biological motion to compensate for walker motion during self-motion, thus reducing the impact of other moving people on heading computation. For example, if biological-motion

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analysis were to provide the motion direction and speed of each walker, this common motion could theoretically be subtracted from the flow velocities to remove some of the nonrigid motion. Riddell and Lappe (2017) recently studied self-motion toward a single, approaching walker and found that observers could distinguish the motion produced by the walker from the optic flow produced by observer movement but confounded the two sources of motion in heading perception. In the present study, we examined the ability to estimate heading from displays depicting linear self-motion through crowds of point-light walkers in four experiments focusing on the role of the human figure, limb movement, walker movement, and stability with regard to the environment.

General Method

Observers

Observers for all of the experiments presented here were recruited from the University of Muenster. Separate samples were collected prior to beginning each experiment. Power analyses determined that sample sizes of at least 12 observers for Experiments 1 and 2, 14 observers for Experiment 3, and 8 observers for Experiment 4 would be appropriate for the current experiments to have 80% power for detecting effects with small to moderate effect sizes ($\eta_p^2 = .35$). Aside from one of the authors, who took part in all experiments, all observers were naive to the aims of the experiments. All observers had normal or corrected-to-normal visual acuity and gave written informed consent prior to the beginning of the experiment. Ethical approval for the testing of these observers was obtained from the ethics board of the Department of Psychology and Sport Science of the University of Münster.

Materials

Stimuli for all experiments were generated on an Apple MacBook Pro equipped with a 512 MB Intel HD Graphics 4000 onboard graphics card. A Marquee 8500 projector (VDC Display Systems, Cocoa, FL) was used to present the stimuli onto a 250- × 200-cm backlit screen. The projector operated at a resolution of 800 × 600 pixels, with a refresh rate of 60 Hz. Stimuli were designed using MATLAB (The MathWorks, Natick, MA) with the Psychophysics Toolbox (Version 3) add-on (Kleiner, Brainard, & Pelli, 2007). Responses were signaled using a single-button mouse.

Point-light-walker generation

All point-light walkers were derived from motion-tracking data of a single walking human male. The average walking

speed of the actor was 1.4 meters per second (mps), with a single step cycle taking 1,240 ms. Translational movement was removed in Experiment 1 so the walkers appeared to walk in place. In Experiments 2 to 4, translational motion was not removed so walkers appeared to walk across the scene. The point-light walkers themselves consisted of 12 white points corresponding to the left and right ankle, knee, hip, hand, elbow, and shoulder joints. Each individual point subtended 0.86 degrees of visual angle.

In addition to the normal point-light walker stimuli, we used two different forms of nonbiological control stimuli, namely scrambled and inverted biological motion, that are matched with regard to their local motion properties. Scrambling disrupts the structure of the human figure by displacing each joint to a random location while keeping the motion trajectories of each point the same (e.g., Cutting, 1981). Scrambled walkers were generated by randomizing the starting positions of each walker point while retaining the original trajectories of the individual points. Inversion also inhibits the processing of a point-light walker's form, and in addition, disrupts local motion cues pertaining to the gravity-driven motion pattern of the feet, which can be used to identify the walking and facing direction of point-light walkers independently of form information (Troje & Westhoff, 2006). Inverted walkers were created by rotating normal walkers by 180° around the z-axis so the walkers appeared upside down. Example normal, scrambled, and inverted point-light walkers can be seen in Figures 1b, 1c, and 1d.

Scene

The scene consisted of eight point-light walkers located on a ground plane with a width of 6 m and a depth of 10 m. Walkers were life size (182 cm in height) and were scaled using perspective projection to appear at an appropriate size according to their distance from the observer. The ground plane lay at a height equivalent to the real ground, given the observers' seated eye height of 140 cm. In Experiments 1 to 3, the ground plane was not visible. In Experiment 4, we randomly positioned 0, 1, 2, 3, 4, 6, 9, 14, or 20 points on the ground plane. Walkers were also randomly positioned. The facing direction of the walkers was randomized. Depending on the condition, walkers could appear as scrambled, inverted, or normal (see the Point-Light-Walker Generation section; also Fig. 1), with all walkers in the scene being of the same type. In Experiment 1, all translational movement was removed from the walkers so they appeared to be walking in place. In Experiments 2 to 4, walkers translated at their natural speed in the direction they were facing. An example walker crowd is depicted in Figure 1a.

Observer self-motion was simulated by moving the camera through the scene toward the heading location

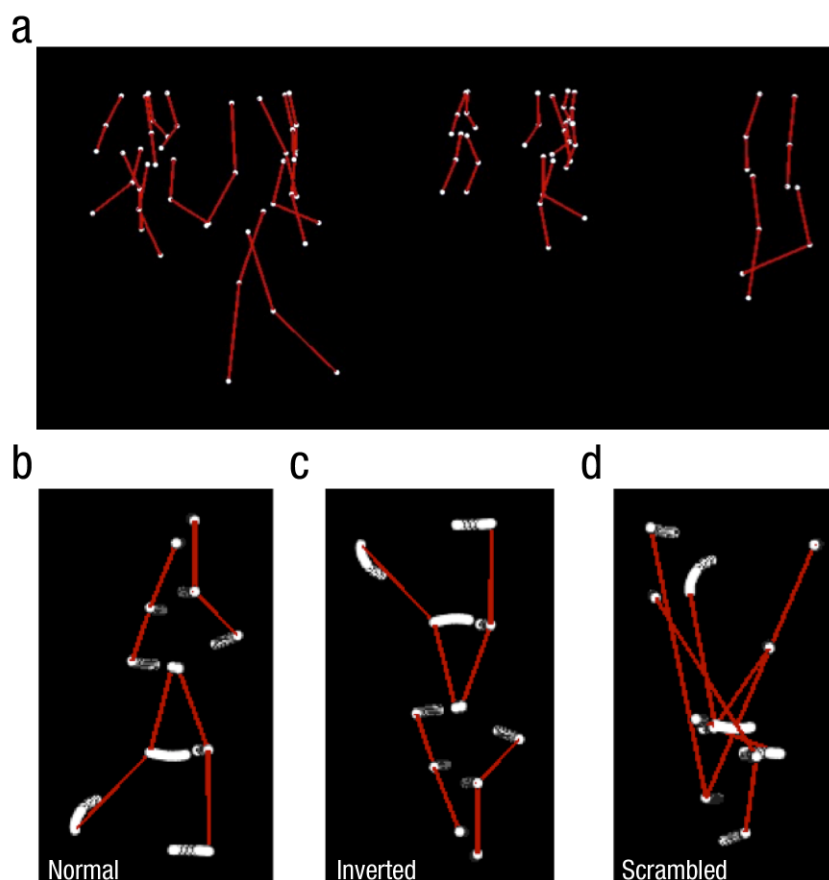


Fig. 1. Example of a walker crowd scene (a) and individual point-light walkers (b–d). The experiments presented optic flow generated by simulated observer movement through such a scene. In different conditions, walkers could appear to be moving across the ground, to be walking in place, or as static figures that maintain a single posture. A crowd of normal point-light walkers is shown in (a). In different conditions, walkers could appear in normal (b), inverted (c), or spatially scrambled (d) depictions of human motion. Walker limbs are shown here in red to help the reader recognize the underlying form of the walker. The limbs were not present during the experiments. Panels (b), (c), and (d) also depict brief trajectories of each point during walking.

at a speed of 1.5 mps. The heading location was randomized for each trial and could appear up to 15° of visual angle to the left or right of the center of the screen. In all experiments, if a walker disappeared from the field of view, it was repositioned on the horizon of the ground plane at a new random position. Repositioned walkers retained their original facing direction.

General trial procedure

All experiments followed the same general procedure. To begin with, each trial was preceded by a blank interval of 500 ms, after which the scene appeared, and movement began immediately. This movement phase lasted 2,500 ms. After the movement phase, all motion ceased, and a red probe line appeared at a random location on the horizon of the display. Observers were

instructed to move this probe line to indicate their perceived direction of heading. When they had placed the probe line at their perceived direction of heading, they clicked the mouse button to register their response. Walkers remained visible but stationary while observers estimated their heading. There was no time limit on responses. All testing took place in a quiet, darkened room. Observers were seated 100 cm from the display at an eye height of 140 cm.

Experiment 1

The purpose of Experiment 1 was to gauge the degree to which the limb motion of walkers moving in place disrupts flow processing during self-motion in comparison with the static, single-posture figures, which essentially form a rigid environment. Observers viewed displays

depicting self-motion through crowds consisting of eight point-light walkers that either walked in place or maintained a single static posture. All walkers maintained a fixed position in the scene in this experiment (i.e., they walked in place as if on a treadmill). Limb movement introduces motion into the visual scene that is not related to the observer's self-motion; optic flow processing systems should therefore treat this limb motion as noise. If this is the case, we would expect heading estimates to deteriorate in the presence of biological limb motion. In addition, Experiment 1 tested whether biological motion provides some information about the movement of walkers in the scene by comparing heading estimates in crowds of normal walkers to crowds of inverted and scrambled controls. If biological-motion perception were to provide relevant information to the task, we would expect differences in the influence of limb motion between normal walkers and inverted or scrambled walkers.

Method

A total of 14 individuals (11 female; age: $M = 24.64$, $SD = 7.10$) participated. Trials were grouped by walker type (normal, scrambled, inverted) and limb-motion condition (single posture, articulating) into six separate blocks. Each block contained 15 trials, with the experiment containing 90 trials in total. Blocks of trials were presented in a random order for each observer. Before beginning the experiment, observers completed an

additional 15 trials containing single posture, normal point-light walkers as practice to ensure that they understood the heading task. Individual trials followed the procedure outlined in the General Method section.

Prior to beginning the experiment, observers were told that in some blocks of trials, the walkers would appear as human, whereas in the other block, they would appear as nonhuman. They were not informed of the order in which these blocks would appear and were instructed to disregard walker type and limb motion during the experiment. In total, the experiment took approximately 15 min to complete.

Results

Heading errors were defined by the difference between the observer's heading estimate and the actual heading position and are shown in Figure 2. Differences in heading errors between walker type and limb-motion conditions were tested using a two-way repeated measures analysis of variance (ANOVA). When walkers performed limb movements in place, heading errors were larger than when figures maintained a single posture, $F(1, 13) = 21.27$, $p < .001$, $\eta_p^2 = .62$. The finding that limb motion negatively affects heading estimation suggests that biological motion significantly perturbs the optic flow field. This is consistent with the proposal that limb motion introduces noise into the optic flow field, disturbing the global organization of the flow pattern and negatively impacting heading detection.

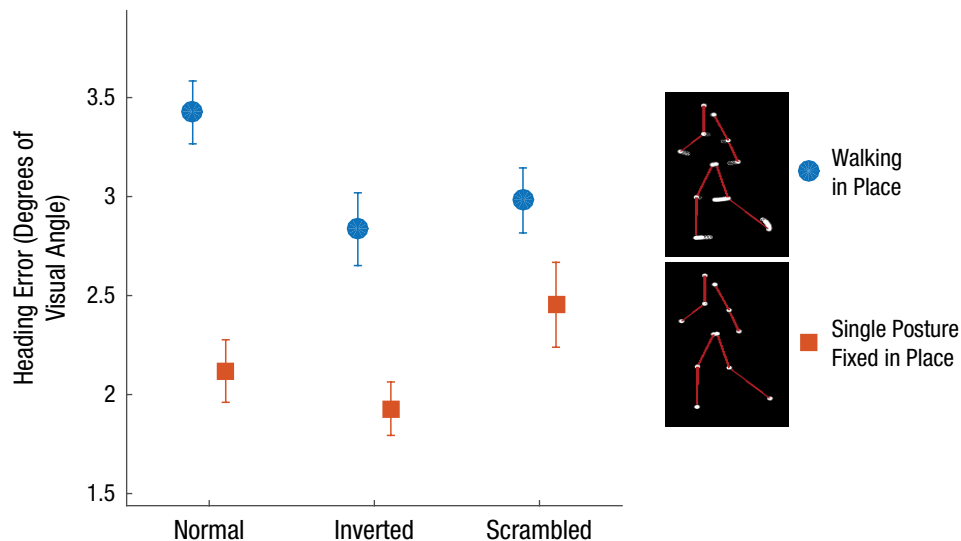


Fig. 2. Average magnitude of heading errors in Experiment 1, in which observer translation was simulated through crowds of normal, inverted, and scrambled point-light walkers that either walked in place (blue circles) or maintained a single posture at a fixed position in the scene (red squares). Error bars represent standard errors adjusted for the within-subjects design.

In addition, the ANOVA also showed a main effect of walker type, $F(2, 26) = 3.80$, $p = .036$, $\eta_p^2 = .23$, with false-discovery-rate-adjusted post hoc tests revealing that heading estimates were worse for normal walkers than for inverted walkers ($p = .048$). This result implies that the presence of biological motion interferes with the computation of the optic flow pattern.

This interference could occur for a number of reasons. For example, the assignment of attention to biological motion reduces performance on a concurrent task (Thompson & Parasuraman, 2012; Thornton, Rensink, & Shiffrar, 2002), thus some division of attention could have produced this result. Alternatively, in the current experiment, a walker's limb motion suggests a walker that translated, whereas in actual fact the point-light walker's physical position in the scene was fixed in place. This conflicting information might also explain why walkers produced larger heading errors than inverted walkers, whose articulation pattern is not suggestive of biological ambulation (Troje & Westhoff, 2006). The interaction between walker type and limb motion approached but did not meet the threshold for statistical significance, $F(2, 26) = 2.95$, $p = .070$.

Experiment 2

Having shown that limb motion negatively impacts heading perception, we conducted a second experiment to measure heading accuracy for movement through a more ecologically valid crowd of walkers. Real people rarely perform walking movements without simultaneously translating across the ground. The translational component of biological motion has been studied to a lesser degree than biological limb motion, but there is evidence showing it influences both the perception of actions from point-light displays (Masselink & Lappe, 2015; Thurman & Lu, 2016) and their perceived animacy (Thurman & Lu, 2013).

While translation is important for biological-motion perception, it is detrimental for heading computation, as translating objects disrupt the rigid structure of the scene that is important for optic flow analysis during self-motion (Andersen & Saidpour, 2002). This represents an interesting dichotomy. On the one hand, the addition of independent walker translation should reduce the accuracy of heading estimation; but on the other hand, biological-motion information may become more informative or valid if translation is added. It may be that the cues provided by biological limb motion are useful for heading estimation only when they provide information about a walker's translation, which is the aspect of walker motion that should be most disadvantageous to the computation of self-motion.

In Experiment 2, observers were tested on a task requiring them to estimate heading from stimuli depicting self-motion through crowds of point-light walkers that translated through the scene independently from the observer while either articulating their limbs or maintaining a single posture. In this experiment, the single-posture walkers translated through the scene in the same way as the articulating walkers but without moving their limbs, much like a figure skater might do. This condition provided a gauge of the detrimental effects of independent translation on heading estimation and served as a comparison for any potential influence of biological limb motion in this task. Given the results of the previous experiment, we might expect that the combination of limb articulation and independent walker translation should produce the largest heading errors, as both limb motion and translation introduce noise to the visual scene. However, if biological limb motion becomes informative in the presence of walker translation, we might expect heading estimates to improve for walkers that articulate their limbs while translating.

Method

A new group of 15 observers (12 female; age: $M = 24.73$, $SD = 6.85$) was recruited for Experiment 2. Apart from using translating as opposed to stationary walkers, Experiment 2 followed the exact same procedure as Experiment 1. Single-posture walkers in the current experiment also translated independently through space but did not move their limbs. Fifteen trials containing normally articulating walkers were used as practice stimuli.

Results

Heading errors for this experiment are presented in Figure 3. Comparing the heading errors from the current experiment (all conditions: $M = 4.53$, $SD = 1.57$) with those in the previous experiment (all conditions: $M = 2.62$, $SD = 1.80$) shows that translation had a distinctly negative impact on heading accuracy, two-tailed independent-samples $t(27) = 3.41$, $p = .002$. Translation induces even larger perturbations in the optic flow field than articulation in place, and this decrease in heading performance is therefore consistent with the idea that heading is computed using the global pattern of motion in the scene.

A two-way repeated measures ANOVA to assess the differences between limb-motion conditions (articulating walker vs. single posture) and walker types (normal, scrambled, inverted) revealed that heading errors were significantly lower when walkers within the crowd

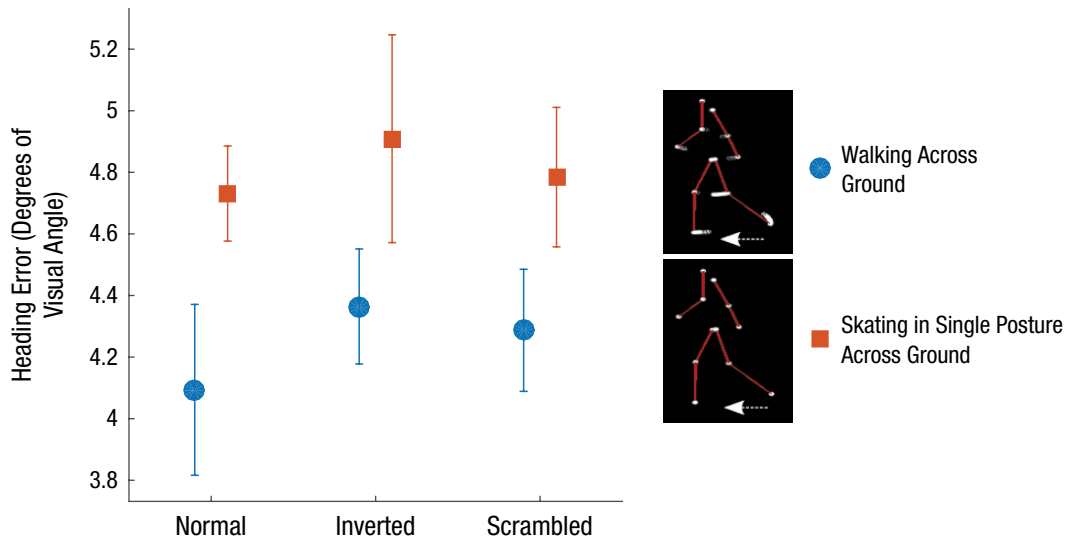


Fig. 3. Average magnitude of heading errors in Experiment 2, in which self-motion was simulated through crowds of normal, inverted, and scrambled point-light walkers that translated independently to observer motion. Walkers either moved their limbs while translating across the ground plane, producing a natural-looking walking rhythm (blue circles), or held a single posture while skating across the ground plane (red squares). The dashed white arrows indicate the direction of movement. Error bars represent standard errors adjusted for the within-subjects design.

moved their limbs, $F(1, 14) = 5.89$, $p = .029$, $\eta_p^2 = .30$. Initially, this result may seem to be at odds with the results of the previous experiment, which showed that limb motion introduces additional noise into the scene and complicates heading estimation. Here, however, we found that some cue in the pattern of biological limb movement produced by point-light walkers improves heading detection when walkers translate. We conclude that this limb articulation contains information that reduces the disturbances introduced by walker translation when heading through a crowd of walkers.

Surprisingly, no significant differences were found between walker types, $F(2, 28) = 0.29$, $p = .750$, and there was no interaction between the limb-motion condition and walker type, $F(2, 28) = 0.10$, $p = .903$. Because both inversion and scrambling disrupt the perception of biological motion, it can therefore be concluded that the responsible cue was not derived by analyzing walkers in the crowd. This rules out potential explanations based on the prediction of walker motion from gait patterns or the segmentation of walker motion from the scene.

Experiment 3

Given the above results, we reasoned that the cue responsible for the facilitation must be contained in some aspect of the local motion pattern of the individual walker points that is inherent to all three walker types used in Experiment 2. Over the course of walking, the points of a walker undergo brief phases in which they are stable with respect to the environment.

Throughout these immobile phases, the stable points in the walker represent rigid points in the scene. Any movement of these rigid points in the optic flow corresponds to movement produced by the observer's self-motion and signals heading. For example, during the stance phase of a gait cycle, the foot contacts the ground, and the forces of friction dictate that it remains stationary while the rest of the body swings forward. By the definition of walking, at least one foot must be contacting the ground at any point in time. Other points, such as the hands, also undergo transient stable phases, though with less regularity. Importantly, these transient stable phases of local points are present also in the scrambled and inverted walkers because the local motion trajectories of the joints mirror those of an intact walker. Conversely, these cues do not exist in the translating single-posture figures, for which motion of the individual points is constant.

Experiment 3 tested whether the cues provided by stable phases in the gait pattern of normal walkers may account for the improvement in heading performance. We presented stimuli that contained predominantly stable or unstable points of normal walkers. We predicted that the stimuli presenting more-stable points produce smaller heading errors than stimuli presenting less-stable points.

Method

A total of 14 observers (9 female; age: $M = 26.64$, $SD = 7.32$) participated. Seven of these observers had

previously participated in Experiments 1 or 2. Experiment 3 presented crowds of normal, translating walkers following the same procedure as in Experiment 2; however, in the current experiment, we applied a further manipulation to the stimuli to distinguish the contribution of stable phases in the walking cycle. A stable phase of a point of the walker occurs when the movement of the point with respect to the ground is zero or close to zero. Analysis of each point's speed with respect to the ground in each frame of the animation showed that three points per walker went through stable phases during the walking cycle (see Fig. S1 in the Supplemental Material available online). These points were the foot point contacting the ground plane in the stance phase, the corresponding knee point, and the hand on the opposite side of the body. In contrast, the remaining points did not provide stable phases because their movement during walking was rather smooth and constant, coinciding fairly consistently with the overall translation of the center of mass of the body. These points thus continuously translate across the ground plane.

In the less-stable condition of Experiment 3, the feet, knee, and hand points were omitted from the stimulus during their stable phases. Conversely, the more-stable condition presented only those points and only during their stable phases. To keep the number of points in the stimuli for the two conditions the same, we increased the number of walkers to 24 in the more-stable condition, whereas in the less-stable condition, crowds consisted of 8 walkers.

In both conditions, the above-mentioned points were appearing and disappearing on the screen during part of each walking cycle. Whenever they were shown, they were moving on the screen according to their normal ambulation in biological motion. However, in the more-stable condition, their ambulation led to the comparative stability of the point with respect to the ground.

Conditions were run in blocks containing 30 trials each. The order of presentation was counterbalanced across observers. Prior to beginning the experiment, observers completed 15 randomly selected practice trials to familiarize themselves with the task. The experiment took approximately 10 min to complete.

Results

Heading errors for Experiments 3 are presented in Figure 4. An independent-samples t test showed that the less-stable condition of Experiment 3 produced significantly larger heading errors than the full-walker condition in Experiment 2, $t(27) = 2.35$, $p = .026$. This is likely because the full-walker condition in Experiment 2 contained stable phases, whereas the less-stable stimuli in

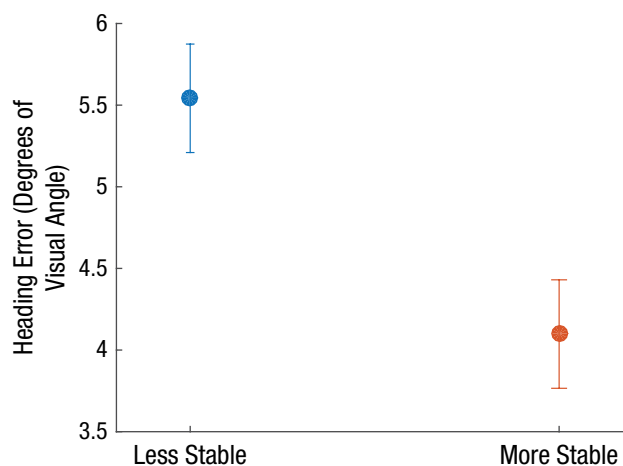


Fig. 4. Average magnitude of heading errors in Experiment 3 when stimuli presented only selected points and phases of the walking cycle. We determined instances in the stimulus in which points presented stable phases in the scene (the foot point contacting the ground during the stance phase, the corresponding knee point, and the hand on the opposite side of the body). In the less-stable condition, those instances were removed from the stimulus; that is, respective points were not shown at those times. Conversely, in the more-stable condition, only those instances were shown. The number of points in the display was equated between both conditions by adjusting the number of walkers that were presented. Error bars represent standard errors adjusted for the within-subjects design.

Experiment 3 did not. This finding supports the notion that stable phases in the gait cycle facilitate heading detection. The direct comparison between the less-stable and more-stable condition furthermore showed that heading errors were lower in the more-stable condition than in the less-stable condition, single-tailed paired-samples $t(13) = 2.96$, $p = .011$. These results confirm that improvements in heading estimates produced by the simultaneous presentation of walker limb motion and translation as was observed in Experiment 2 are predominantly derived from the stable phases within the walking cycle.

Experiment 4

In Experiment 4, we assessed whether the briefly presented stable instances in a gait pattern facilitate heading even in more densely textured environments. We deliberately added a small number of rigid environmental points and tested for improved heading estimates, as would be predicted if heading estimation relies on rigid scene information available from both the environment and biological motion.

Method

A new group of 13 observers (9 female; age: $M = 26.31$, $SD = 5.12$) were recruited for Experiment 4. Observers were presented with scenes that contained crowds of

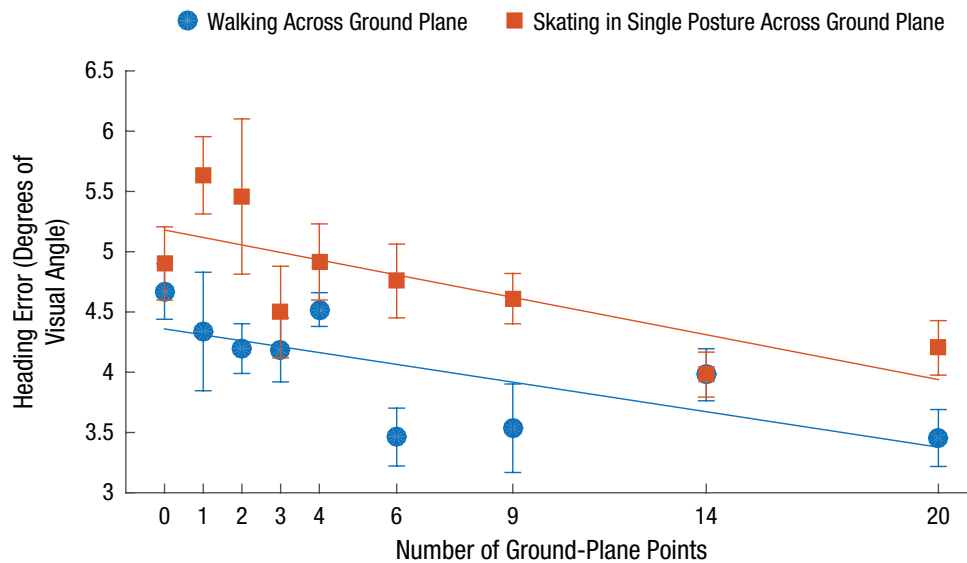


Fig. 5. Average magnitude of heading-estimation errors in Experiment 4 for self-motion through crowds of static and articulating point-light walkers. The number of rigid ground-plane points that were also present in the scene is shown on the *x*-axis. Slopes represent the linear fit for each walker condition as a function of the number of ground points. Error bars represent standard errors adjusted for the within-subjects design.

normal walkers that either articulated their limbs or maintained a single posture while translating independently through the environment. Unlike in the previous experiments, 0, 1, 2, 3, 4, 6, 9, 14, or 20 stable points were placed on the ground beneath the walkers.

Trials were grouped into 18 separate blocks by the number of ground-plane points (0, 1, 2, 3, 4, 6, 9, 14, or 20) and limb-motion condition (single posture vs. articulating walker) pairs. Walkers in the current experiment always translated, and only crowds of normal point-light walkers were used. Each block contained 15 trials; in total, the experiment contained 270 trials. Before beginning the experiment, observers completed an additional 15 trials containing articulating walkers and 20 ground-plane points as practice. Observers were not informed of the order in which blocks would appear and were instructed to disregard the walkers as best they could during the experiment. In total, the experiment took approximately 45 min to complete.

Results

Heading errors produced in Experiment 4 are presented in Figure 5. A two-way repeated measures ANOVA was used to assess the effects of limb articulation and the number of ground-plane points on heading estimation. Where appropriate, Greenhouse-Geisser corrections were implemented to account for violations of the sphericity assumption. As in the previous experiment, heading errors were smaller when walkers moved their limbs than when walkers maintained a single posture, $F(1,$

12) = 5.57, $p = .036$, $\eta_p^2 = .31$. The number of ground plane points also had an influence on heading estimation, $F(8, 96) = 3.96$, Greenhouse-Geisser $p = .017$, $\eta_p^2 = .25$. The number of ground points did not interact with articulation, $F(8, 96) = 1.60$, Greenhouse-Geisser $p = .209$.

To further investigate the relationship between rigid ground information and walker articulation, linear fits for heading errors as a function of the number of ground-plane points were calculated for each walker condition (see Fig. 5). The relationship between the number of ground-plane points and heading errors was significant, $F(1, 12) = 21.41$, $p = .001$. The slope of the linear fits did not differ significantly between walker conditions, $F(1, 12) = 0.21$, $p = .659$. This suggests that the rigid ground points added equal information in both conditions and were not influenced by the walker's articulation. The facilitation provided by the cues in walker articulation can therefore be considered as a constant that is added to the signal available from the existing optic flow field.

These results show that even when stable environmental information is available, cues derived from the biological articulation pattern still improve heading estimation. This suggests that these cues can be useful even in densely textured, naturalistic settings.

Discussion

The current series of experiments shows that during locomotion through a crowd of moving people, visually

guided navigation can benefit from the information provided by a translating walker's limb motion. This is likely because when a walker moves, its pattern of articulation provides transient stable points, which supplement the computation of heading.

Gibson (1950, 1979) proposed that the visual world is made up of invariant cues that remain valid regardless of an observer's motion or the particular objects in the environment. We suggest that the cues contained in stable phases of the biological locomotion pattern could represent such an ecological invariant. On their own, movements of the limbs and translation of the body produce motion noise that impacts heading estimation. Their combination in natural locomotion, however, creates cues that provide information about an observer's self-motion, which is directly available from the optic array. These cues simplify the computation of heading in dynamic crowds without necessitating higher-level cognitive input and supplement the information derived from the stable environment. Interestingly, they also play a role in biological-motion perception (Chang & Troje, 2008; Troje & Westhoff, 2006) and are consequently informative for multiple visual tasks.

Our findings have significance for models of heading perception that pool motion signals across the scene (e.g., Beintema & Van den Berg, 1998; Lappe & Rauschecker, 1993; Perrone & Stone, 1994). Because the cues identified in the current experiments do not rely on any information outside of the optic flow field, perceptual mechanisms for optic flow should be able to use these cues immediately. Moreover, pooling motion information over the entire field of view ensures that the occurrence of stable phases is included in the optic flow pattern in a manner similar to the observed behavior of our observers. In addition, our results suggest that the visual system is able to capitalize on briefly presented instances of stability in the visual field. Thus, any model of heading estimation that is to account for the current findings must be able to sample and integrate optic flow dynamically.

Extracting cues contained in the stable phases of a gait pattern does not require an analysis or interpretation of biological walking. Theoretically, any articulated object with parts that, at some point, appear stable with respect to the world would produce a similar effect. This was demonstrated in the scrambled and inverted conditions of Experiment 2. In these conditions, biological-motion processing is disrupted, yet because the local motion trajectories of the joints mirror those of an intact walker, points in the stimuli still undergo brief stable phases in which they present rigid positions in the world.

Both scrambled and inverted point-light walkers, however, are highly artificial and do not occur naturally.

In fact, with the exception of biological organisms, very few real-world objects produce patterns of motion with predictable stable phases. Conversely, most legged animals maneuver in this way. We propose that these patterns are thus associated with biological motion and may represent an efficient, simple, and reliable cue for heading detection in crowds. Furthermore, these cues are available directly from the optic array and would theoretically be informative in the presence of any group of legged animals, making them highly generalizable and behaviorally relevant, especially from an evolutionary perspective.

In a previous study (Riddell & Lappe, 2017), we measured heading perception for simulated self-motion toward a single point-light walker. The results showed that heading judgments were best explained by a combination of walker motion and self-motion, indicating that heading estimation does not take biological motion into account but instead pools the entire flow field. This is consistent with the finding of the present study. Given the results of Experiments 3 and 4, we expect a single walker to contain the equivalent of approximately three stable environmental points, which is unlikely to be sufficient for heading estimation from a single walker in the presence of the additional noise from limb movements.

Heading errors in our experiments are quite large in comparison to the 1° to 2° of error generally observed in rigid environments (e.g., Cutting et al., 1992; Warren et al., 1988; Warren & Hannon, 1988). However, for typical walking speeds in a crowded environment of 1 to 2 mps, heading errors of around 4° appear to be within the margin for safe control (Cutting et al., 1992). Moreover, in real walking situations, some rigid environmental structure would likely be visible, which improves heading accuracy, as was demonstrated in Experiment 4. Furthermore, it should be noted that the control of walking is a more complex problem than heading estimation and may require additional control strategies and information (Cutting et al., 1992; Li & Warren, 2002; Rushton, Harris, Lloyd, & Wann, 1998).

Action Editor

Alice J. O'Toole served as action editor for this article.

Author Contributions

M. Lappe developed the study concept. Both authors designed the study. H. Riddell programmed the stimuli and collected the data for the experiments. Both authors analyzed and interpreted the data. H. Riddell drafted the manuscript, with M. Lappe providing considerable input and revisions. Both authors approved the final version of the manuscript for submission.

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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Supplemental Material

Additional supporting information can be found at <http://journals.sagepub.com/doi/suppl/10.1177/0956797618778498>

Open Practices



All data have been made publicly available via Zenodo and can be accessed at <https://zenodo.org/record/1217215>. The materials for this study have not been made publicly available, and the design and analysis plans were not preregistered. The complete Open Practices Disclosure for this article can be found at <http://journals.sagepub.com/doi/suppl/10.1177/0956797618778498>. This article has received the badge for Open Data. More information about the Open Practices badges can be found at <http://www.psychologicalscience.org/publications/badges>.

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