Heading Through A Crowd

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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 show 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.

Heading Through A Crowd

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 non-rigid 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, 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, 2015) 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 in order to compensate for walker

motion during self-motion, thus reducing the impact of other moving people on

heading computation. For example, if biological motion 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 non-

rigid motion. Riddell and Lappe (2017) recently studied self-motion towards 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 focussing on the role of the human figure, limb movement, walker

movement, and stability with regard to the environment.

General Methods

Observers

Observers for all of the experiments presented here were recruited from

the University of Muenster, Germany. Separate samples were collected for each

experiment prior to beginning the 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 of, $\eta^2_p = 0.35$. Aside from one of the authors who took part in all experiments, all observers were naïve 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 subjects was obtained from the ethics board of the Department of Psychology and Sport Science of the University of Muenster, Germany.

Materials

Stimuli for all experiments were generated on an Apple MacBook Pro equipped with a 512MB Intel HD Graphics 4000 on-board graphics card. A VDC Display Systems Marquee 8500 projector projecting onto a 250x200cm backlit screen was used to present the stimuli. The projector operated at a resolution of 800x600 pixels, with a refresh rate of 60Hz. Stimuli were designed using Matlab (Mathworks) with the Psychophysics Toolbox (version 3) add-on (Kleiner et al., 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 m/s, with a single step cycle taking 1240ms. Translational movement was removed in

Experiment 1 so that the walkers appeared to walk in place. In Experiments 2 to 4 translational motion was not removed so that 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 non-biological control stimuli, namely scrambled and inverted biological motion, that are matched with regards 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 degrees around the z-axis so that the walkers appeared upside down. Example normal, scrambled and inverted point-light walkers can be seen in Figure 1B, C and D.

Scene

The scene consisted of eight point-light walkers located on a ground plane with a width of six meters and a depth of 10 meters. 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 140cm. In Experiments 1 to 4 the ground plane was not visible. In the

last experiment 0, 1, 2, 3, 4, 6, 9, 14 or 20 points were randomly positioned 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 point-light walker generation section; also

Figure 1), with all walkers in the scene being of the same type. In Experiment 1,

all translational movement was removed from the walkers so that 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 towards the heading location at a speed of 1.5 meter per second. The

heading location was randomized for each trial and could appear up to 15

degrees of visual angle 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 500ms, after which the scene appeared,

and movement began immediately. This movement phase lasted 2500ms. After

the movement phase all motion ceased and a red probe line appeared at a

random location on the horizon of the display. Participants 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 clicking the

mouse button registered their response. Walkers remained visible but stationary

while observers estimated their heading. There was no time limit placed on

responses. All testing took place in a quietened, darkened room. Observers were

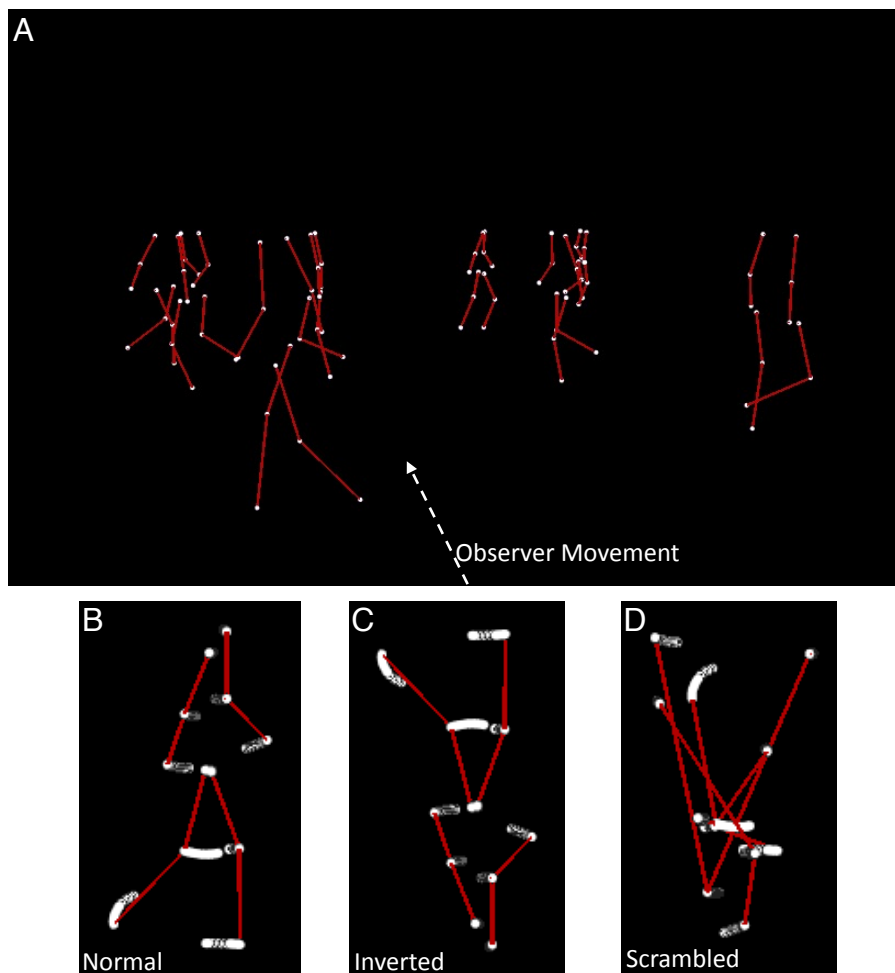seated 100cm from the display at an eye height of 140cm.

Figure 1. (A) An example of the walker crowd scene. The experiments presented

optic flow generated by simulated observer movement (depicted by the white

dashed arrow) through such a scene. In different conditions, walkers could be

appear as moving across the ground, as walking in place, or as static figures that maintain a single posture. The figure depicts a crowd of normal point-light walkers. In different conditions walkers could appear as the normal walkers (B) shown in the figure, or as inverted (C) or spatially scrambled (D) depictions of human motion. Walker limbs are highlighted in red to help the reader recognize of the underlying form of the walker. The limbs were not present during the experiments. B, C, and D also depict brief trajectories of each point during walking.

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 to 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 if 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.

Methods

Observers

14 subjects (11 female, mean age M = 24.64, SD = 7.10) participated.

Procedure

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

observers understood the heading task. Individual trials followed the procedure

outlined in the general methods section.

Prior to beginning the experiment observers were told that in some

blocks of trials the walkers would appear as human, while in the other block they

would appear as non-human. 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 minutes 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 ANOVA. When walkers performed limb movements in place, heading errors were larger than when figures maintained a single posture ($F(1,13) = 21.27$, $p < .001$, $\eta^2_p = .62$). 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.

Additionally, the ANOVA also showed a main effect of walker type ($F(2,26) = 3.80$, $p = .036$, $\eta^2_p = .23$), 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, while 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 ($F(2,26) = 2.95$, $p = .070$).
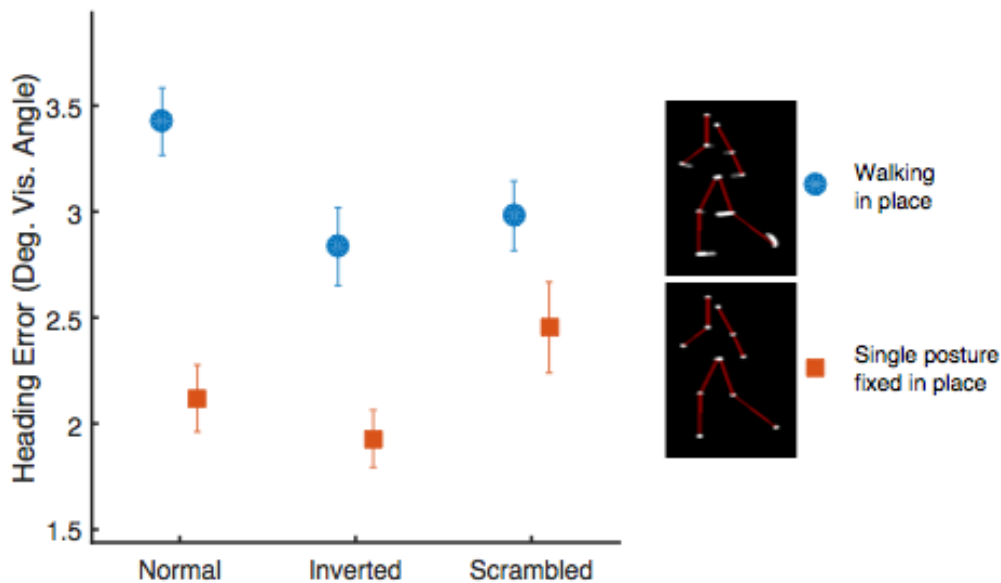

Figure 2. Average magnitude of heading errors for Experiment 1, in which

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).

Heading estimation is less accurate when articulation is present. Vertical bars represent standard errors adjusted for within subjects designs.

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, 2015), as well as 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 only useful for heading estimation 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 though 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. Based on 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.

Methods

Observers

A new group of 15 observers (12 female, mean age M = 24.73, SD = 6.85) was recruited for Experiment 2.

Procedure

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. 15 trials containing articulating-normal 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 ($M_{all\ conditions}$ = 4.53, SD = 1.57) to
the previous experiment ($M_{all\ conditions}$ = 2.62, SD = 1.80) shows that translation
had a distinctly negative impact on heading accuracy (two-tailed independent
measures t-test ($t(27)$ = 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
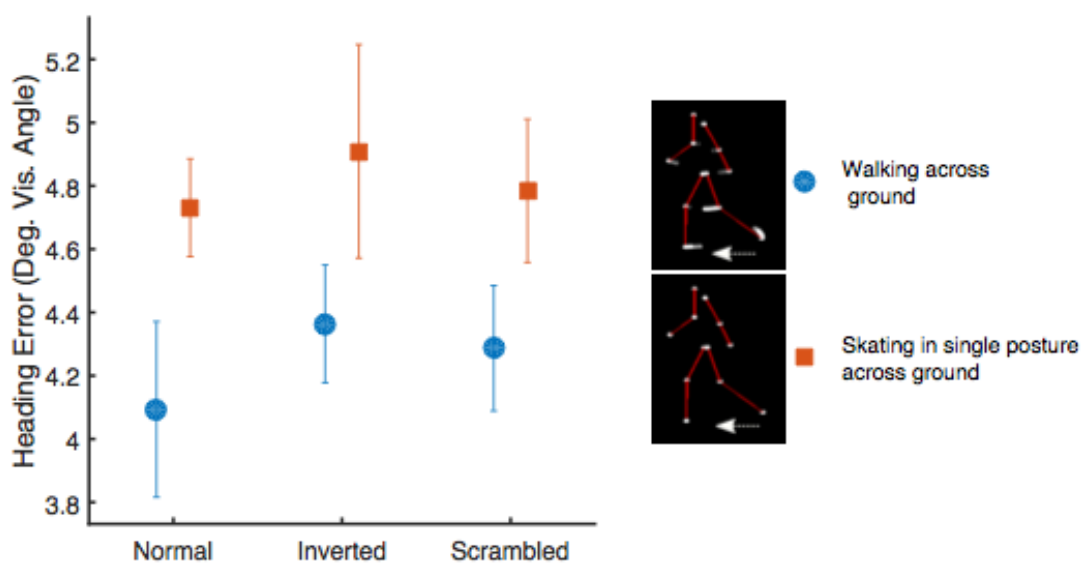computed using the global pattern of motion in the scene.

Figure 3. Average magnitude of heading errors for 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). Heading improves with the addition of limb motion. Vertical bars represent standard errors adjusted for within subjects designs.

A two-way repeated measures ANOVA to assess the differences between limb motion conditions (articulating walker versus single posture) and walker types (normal, scrambled, inverted) revealed that heading errors were significantly lower when walkers within the crowd moved their limbs ($F(1,14)$ = 5.89, p = .029, η^2_p = .30). Initially, this result may seem 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 find that some cue in the pattern of biological limb movement produced by point-light walkers serves to improve heading detection when walkers translate. We conclude that this limb articulation contains information that reduces the disturbances introduced by walker translation when heading though a crowd of walkers.

Surprisingly, no significant differences were found between walker types ($F(2,28)$ = .29, p = .750) and there was no interaction between the limb articulation and walker type ($F(2,28)$ = .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.

Experiments 3

Based on 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 forwards. 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 since 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.

Methods

Observers

14 observers (9 female, mean age M = 26.64, SD = 7.32) participated. Seven of these participants had previously participated in Experiments 1 or 2.

Stimuli and Procedure

Experiment 3 presented crowds of normal, translating walkers following the same procedure as Experiment 2; however, in the current experiments 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 (Supplementary Figure) 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 is 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, the number of walkers was increased to 24 in the more-stable condition,

while in the less-stable condition, crowds consisted of eight 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 comparatively stability of the point with respect to the

ground.

     Conditions were run in blocks containing 30 trials. 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

minutes to complete.

Results

     Heading errors for Experiments 3 are presented in Figure 4. An

independent measures 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 Experiment 3 did not and 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 sample t-test, $t(13) = 2.96$, 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.
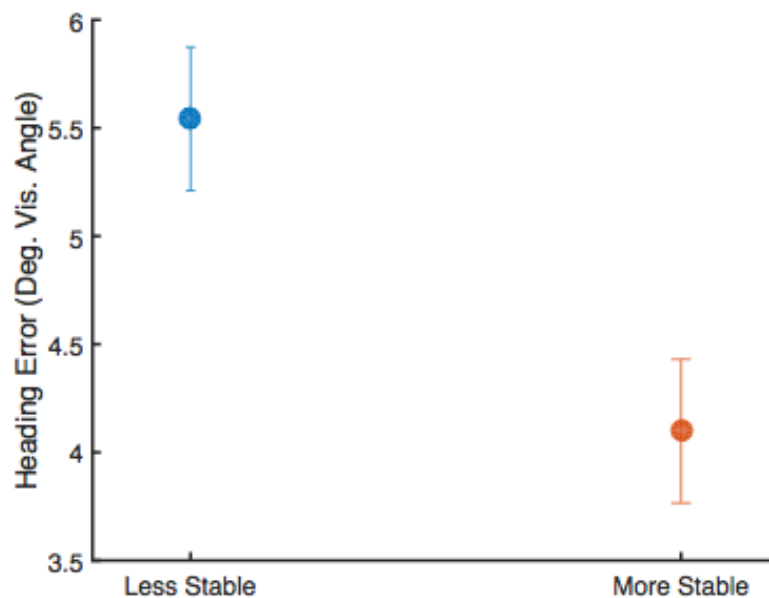
Figure   *4.*

Heading errors 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, i.e. respective points were not shown at those times. Conversely, in

the more-stable condition only those instances were shown. Number of points in

the display was equated between both conditions by adjusting the number of

walkers that were presented. Vertical bars represent standard errors adjusted

for within subjects designs.

Experiment 4

Experiment 4 assessed whether the briefly presented stable instances in a

gait pattern facilitate heading even in more densely textured environments. We

deliberately added as 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.

Methods

Observers

A new group of 13 observers (9 female mean age M = 26.31, SD = 5.12) were recruited for the current study.

Stimuli

Observers were presented with scenes that contained crowds of 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.

Procedure

Trials were grouped by the number of fludicial points (0, 1, 2, 3, 4, 6, 9, 14 or 20) and limb motion condition (single posture vs. articulating walker) pairs into 18 separate blocks. 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 fludicial points as practice. Observers were not informed of the order in which blocks would appear and were instructed to disregard the walkers as best as possible during experiment. In total the experiment took approximately 45 minutes 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 ($F(1,12) = 5.57$, $p = 0.36$, $\eta^2_p = .31$).

The number of ground plane points also had an influence on heading estimation

($F(8,96) = 3.96$, $p_{\text{Greenhouse-Geisser}} = .017$, $\eta^2_p = .25$). The number of ground points

did not interact with articulation ($F(8,96) = 1.60$, $p_{\text{Greenhouse-Geisser}} = .209$).

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 Figure 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 ($F(1,12) = .21$, $p = .659$). 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 serve to

improve heading estimation. This suggests that these cues can be useful even in
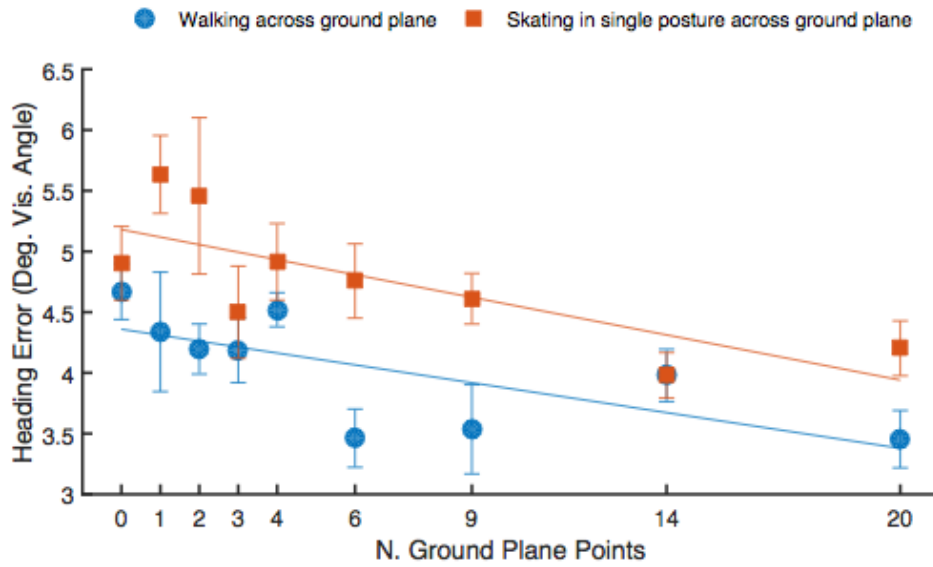
densely textured, naturalistic settings.

Figure 5. Heading estimation errors 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. Solid lines represent the linear fit for each walker condition as a function of the number of ground points. Vertical bars represent standard errors adjusted for within subjects designs.

Discussion

The current series of experiments show 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 due to the fact that 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, create 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 participants. Additionally, 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, due to the fact that 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 behaviourally relevant, especially from an evolutionary perspective.

In a previous study (Riddell & Lappe, 2017) we measured heading perception for simulated self-motion towards 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. Based on 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 degrees of error generally observed in rigid environments (e.g. Cutting et al, 1992; Warren & Hannon, 1988; Warren et al, 1988). However, for the typical walking speeds in crowded environment of 1 to 2 meters per second heading errors of around 4 deg appear 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; Rushton, Harris, Loyd and Wann, 1998; Li and Warren, 2002).

Open Practices Statement

This study was not formally preregistered. Data from all experiments will be made available on https://zenodo.org.

Author Contributions

M. Lappe developed the study concept. Both authors contributed to the design of the study. H. Riddell programmed the stimuli and collected the data for the experiments. Both authors contributed to the analysis and interpretation of the data. H. Riddell drafted the manuscript, with M. Lappe providing considerable input and revisions. Both authors approved the final version of the manuscript.

Acknowledgements [7 words]

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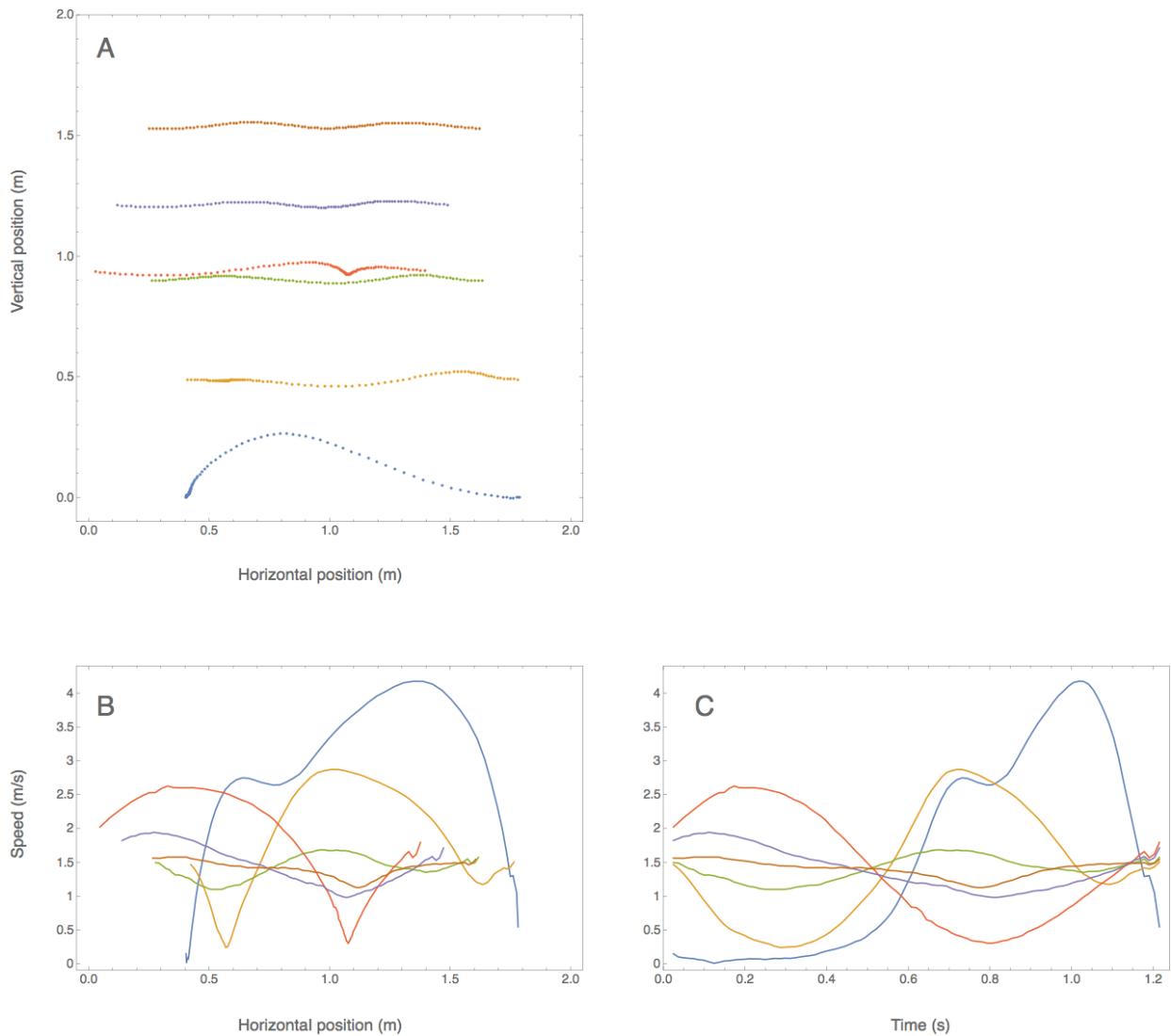
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Supplementary Figure: Illustration of stable phases in the walking cycle

A: Horizontal and vertical positions of the joints of the walker as the walker performed one walking cycle. Only the right half of the body is shown. The points are: shoulder (brown), elbow (violet), hand (red), hip (green), knee (yellow), foot (blue). For example, the foot is on the ground at position 0.4m, then lifted up, moved forward, and put on the ground again at position 1.8m. The walking cycle was digitized into 100 frames. Each dot in the figure corresponds to the location of the joint in one of those frames. The shoulder, elbow, and hip show a fairly constant spacing between dots, indicating a smooth and constant motion of these joints. The foot, knee, and hand show larger variability. Phases of large separation between dots, indicate fast movement while phases in which the dots are close together, indicating slow movement.

B: Speed of each joint at the positions shown in A. The speeds of the foot (blue), knee (yellow), and hand (red) at certain positions drop, indicating that these points remain fairly stable at these positions.

C: Speed of each joint as a function of time. The stable phases of the foot (blue), knee (yellow), and hand (red) last for roughly half the duration of the walking cycle.