Limits of peripheral direction discrimination of point-light walkers

Rick Gurnsey

Gabrielle Roddy

Nikolaus F. Troje

Department of Psychology, Concordia University, Montreal, QC, Canada

Department of Psychology, Concordia University, Montreal, QC, Canada

Department of Psychology, Queen's University, Kingston, ON, Canada

Many previous studies have used noise tolerance to quantify sensitivity to point-light walkers heading ±90° from straight-ahead. Here we measured the smallest deviations from straight-ahead that observers could detect (azimuth thresholds) in the absence of noise. Thresholds were measured at a range of stimulus sizes and eccentricities for (1) upright and (2) inverted walkers, (3) intact walkers, those without feet and those with only feet, and (4) in the presence and absence of a second, attention-absorbing task. At large stimulus sizes azimuth thresholds were very small (between 1 and 2°) except in the case of inverted walkers. Size scaling generally compensated for eccentricity dependent sensitivity loss, however in the case of inverted walkers the data were quite noisy. At large sizes walkers without feet elicited higher thresholds than those with only feet, suggesting a special role for the feet even when walkers are not viewed side-on. Unlike others, we found no evidence that competing tasks affected performance. We argue that the value of our modified direction-discrimination task lies in its focus on the limits of discrimination within the domain of interest, rather than the amount of noise needed to impair discrimination of widely separated stimulus values.

Keywords: biological motion, point-light walkers, size scaling, cortical magnification, peripheral vision


Introduction

Johansson showed that human observers are sensitive to many features of human motion conveyed by a small number of lights attached to the joints of individuals clothed in black (Johansson, 1973). Such stimuli have come to be known as point-light walkers or point-light actors. Since Johansson’s early work many experiments have been performed in which point-light actors are simulated on a computer monitor. In this extensive literature it has been shown that subjects can recognize point-light walkers that portray a familiar person (Cutting & Koslowski, 1977; Troje, Westhoff, & Lavrov, 2005; Westhoff & Troje, 2007) and can extract attributes such as sex, age, mental states, actions, and intentions from those that portray unfamiliar individuals (Barclay, Cutting, & Kozlowski, 1978; Blakemore & Decety, 2001; Dittrich, Trosclair, Lea, & Morgan, 1996; Mather & Murdoch, 1994; Pollick, Paterson, Bruderlin, & Sanford, 2001; Runeson, 1994; Troje, 2002a, 2002b).

A sub-genre within the biological motion literature addresses questions about the conditions under which biological motion can be detected (Garcia & Grossman, 2008; Grossman & Blake, 1999; Ikeda, Blake, & Watanabe, 2005; Thompson, Hansen, Hess, & Troje, 2007), the signal properties necessary to convey biological motion (Aaen-Stockdale, Thompson, Hess, & Troje, 2008; Ahlstrom, Blake, & Ahlstrom, 1997; Mather, Radford, & West, 1992), and which aspects of the biological motion stimulus convey the most salient information (Bertenthal & Pinto, 1994; Mather et al., 1992; Troje & Westhoff, 2006). Within this sub-genre two tasks are very common. The first requires discriminating various point-light actions (e.g., walking, jumping, throwing) from scrambled versions of the same (Garcia & Grossman, 2008; Grossman & Blake, 1999; Ikeda et al., 2005). The second is the walker direction discrimination task in which subjects are asked to determine whether a point-light walker is heading ±90° from straight-ahead (Aaen-Stockdale et al., 2008; Bertenthal & Pinto, 1994; Neri, Morrone, & Burr, 1998; Thompson et al., 2007; Thurman & Grossman, 2008). Both tasks are so easy that to limit performance walkers are presented in noise of various sorts (Aaen-Stockdale et al., 2008; Bertenthal & Pinto, 1994; Neri et al., 1998; Thompson et al., 2007; Thurman & Grossman, 2008). In fact, sensitivity is frequently defined in terms of the number of noise dots required to bring performance to threshold. The most effective noise is scrambled walker noise, which comprises many moving dots drawn from the...
population defining the action in question, with positions and phases randomized to eliminate any sense of coherent motion (Aaen-Stockdale et al., 2008; Bertenthal & Pinto, 1994; Thompson et al., 2007; Thurman & Grossman, 2008). So strong is the right–left walker signal, for example, that scores of scrambled walker noise dots are required to bring performance off the ceiling (Thompson et al., 2007). Given the subtlety of the information conveyed by point-light walker stimuli (e.g., sex, age, mental states, actions, and intentions) the standard walker direction discrimination task and the action vs. scrambled action task are decidedly unsubtle tools for studying biological motion.

It is possible to use the action vs. scrambled action task without noise to compare performance of normally developing and abnormally developing populations (Blake, Turner, Smoski, Pozdol, & Stone, 2003). Blake et al. found that normally developing children (5 to 10 years old) could easily distinguish normal actions from scrambled actions in the absence of noise (as expected) but children with autism (8 to 10 years old) had great difficulty doing so. The action vs. scrambled action task was modified recently to study the role of synchronicity in biological motion (Neri, Luu, & Levi, 2006). Neri et al. asked subjects to discriminate intact from scrambled actions and threshold was defined by the amount of scrambling needed to bring performance to threshold.

In this paper we introduce a modified version of the walker direction discrimination task, (similar to that of Neri et al., 2006) in which we measure the limits of walker direction discrimination, rather than fixing walker directions at ±90 deg and measuring accuracy or noise tolerance. We define azimuth as the absolute angular difference (Δθ deg) from straight ahead. Rightward heading walkers can move in any direction from 0 to 90 deg from straight-ahead and leftward heading walkers can move in any direction from 0 to −90 deg from straight-ahead. Therefore, azimuth thresholds represent the azimuth (i.e., direction difference) eliciting 81% correct performance in a two alternative forced choice discrimination task. An adaptive threshold procedure is used to determine azimuth thresholds. We use this paradigm, in a variety of tasks, to investigate sensitivity to biological motion across the visual field.

Measuring azimuth thresholds holds two advantages over the standard walker-in-noise task. First, the standard walker-in-noise task requires at least two conceptually distinct computations. The first requires segmenting the walker (or actor) from the noise and the second is to determine what the walker or actor is doing. It is certainly possible, at least in principle, to discern the presence of a point-light actor without identifying the action being carried out. Conversely, if a subject is unable to report a walker’s direction (or actor’s action) this may not reflect poor sensitivity to directions or actions but a failure of segmentation.

Secondly, measuring azimuth thresholds permits a subtler probing of our sensitivity to point-light actions. It has been reported, for example, that the feet are particularly important for determining if a walker, embedded in noise, is heading ±90° (i.e., straight to the left or right). When heading ±90° from straight-ahead the walker’s feet are the fastest moving dots in the display, and consequently have the largest excursions, but this is no longer the case for walkers heading ±4° from straight-ahead. In the presence of noise it might not be possible to discriminate walkers heading ±4° from straight-ahead, whereas in the absence of noise this can be done perfectly (Gumsey, Roddy, Ouohana, & Troje, 2008). Therefore, one could ask if in the absence of noise the feet exert the same influence at ±4° that they do at ±90°. We examine exactly this question in Experiment 3.

**Peripheral sensitivity to biological motion**

In most studies of biological motion stimuli are presented at fixation. However, in the natural world biological motions can appear at arbitrary locations so we frequently draw conclusions about biological motions at non-central locations. Surprisingly, it has been argued that the fovea is specialized to encode biological motion (Ikeda et al., 2005). Ikeda et al. asked participants to discriminate between actions conveyed by point-light walkers (jumping, running, walking, kicking, or throwing a ball) from scrambled versions that did not elicit a percept of coherent biological motion. Discrimination thresholds (2AFC) were obtained at a range of sizes (.5 to 16° visual angle) and eccentricities 0, 4 and 12° in the right visual field. Thresholds were defined in terms of the number of added noise dots needed to elicit 84% correct detections. Ikeda et al. found that the maximum sensitivity achieved at fixation was never reached in peripheral locations. From this they concluded that stimulus magnification was insufficient to compensate for eccentricity dependent sensitivity loss in the case of biological motion.

In contrast, two other studies (Gibson, Sadr, Troje, & Nakayama, 2005; Gumsey et al., 2008) showed that stimulus magnification is sufficient to equate discrimination accuracy across the visual field in a walker direction discrimination task when walker direction differences are fixed at ±90° (Gibson et al., 2005) or ±4° (Gumsey et al., 2008). In both studies discrimination accuracy (2AFC) was measured for a range of stimulus sizes and eccentricities. Accuracy increased as a function of size at each eccentricity and the magnification needed to equate performance increased linearly with eccentricity. Hence, the linear function

\[ F_E = 1 + E/E_2, \]
describes the magnification \((F_E)\) at each eccentricity \((E)\) required to elicit performance equivalent to a foveal standard. The free parameter \(E_2\) indicates the eccentricity (in degrees visual angle, \(^\circ\)) at which stimulus size must double to elicit equivalent-to-foveal performance. (It should be noted that \(E_2\) is inversely related to the rate at which the required stimulus magnification increases with eccentricity; therefore, small \(E_2\) values reflect rapid eccentricity dependent sensitivity loss.)

For walkers heading \(\pm 90\) deg an average \(E_2\) of 3.5° was sufficient to compensate for eccentricity-dependent sensitivity loss \((N = 4, \text{ estimated } SEM = .147, 95\% \text{ confidence interval } = 3.03 \text{ to } 3.97)\) and for walkers heading \(\pm 4°\) an average \(E_2\) of .87 \((\text{ estimated } SEM = .136, 95\% \text{ confidence interval } = .53 \text{ to } 1.22)\) compensated for eccentricity-dependent sensitivity loss.

These results suggest that the limiting factor in the Ikeda et al. (2005) study was high sensitivity to noise in the periphery and not a low sensitivity to biological motion (Gurnsey, Poirier, Bluett, & Leibov, 2006; Gurnsey et al., 2008; Thompson et al., 2007). Furthermore, these results show that \(E_2\) is task dependent such that finer direction differences elicit a faster loss of sensitivity with increasing eccentricity. However, because both Gurnsey et al. (2008) and Gibson et al. (2005) employed fixed direction differences it is unclear (i) whether the limits of walker direction discrimination change with eccentricity and (ii) what \(E_2\) value would be obtained at the limits of performance. It might be that the \(E_2\) required to equate performance across the visual field at the limits of direction discrimination is less than previously found.

In Experiment 1 we asked how the limits of walker direction discrimination change with stimulus size across the visual field. We expected that stimulus magnification would be sufficient to equate azimuth thresholds across the visual field and that the \(E_2\) values would be inflated in the presence of a competing task and, if so, how such changes in thresholds might vary with eccentricity.

### Experiment 1

Previous research has shown that size scaling compensates for eccentricity dependent sensitivity loss in a walker direction discrimination task when walker direction differences are fixed at \(\pm 4°\) (Gurnsey et al., 2008) or \(\pm 90°\) (Gibson et al., 2005). In Experiment 1 we asked whether size scaling compensates for eccentricity dependent changes in walker direction discrimination thresholds and, if so, how the resulting \(E_2\) values compare to those found in previous studies.

### Methods

#### Participants

The participants included one of the authors (GR) and three naïve subjects (P1, P2 and P3). Three were female and all had normal or corrected-to-normal vision, as assessed by the Freiburg acuity test (Bach, 1996). Acuity was tested once at the beginning of the experiment from a viewing distance of 400 cm.

#### Apparatus

The experiments were conducted using an Intel MacPro Computer equipped with a ViewSonic G225f 21-inch multi-scan monitor with the refresh rate set to 85 Hz. All aspects of stimulus generation, presentation and data collection were under the control of MATLAB (Mathworks, Ltd.) and the Psychophysics Toolbox extensions (Kleiner, Brainard, & Pelli, 2007).

#### Stimuli

Point-light walkers were generated from a Fourier-based representation of human walking (Troje, 2002a, 2008) encoded in terms of the first 20 principal components of a data set comprising 100 motion-captured walkers (50 male, 50 female). Each point-light walker comprised 15 dots depicting the motions of markers fixed to the ankles, knees, hips, wrists, elbows, shoulders, pelvis, sternum, and head of an individual walking on a treadmill; see Figure 1. To synthesize a unique walker we used a vector \(a\) of 20 numbers representing the weights on the first 20 principle components. If all elements of \(a\) are set to zero then a neutral, average walker is generated representing the origin of “walker space.” Any other vector can be viewed as a direction through walker space.
and the length of the vector determines how different the walker is from the average walker. The three-dimensional \((x,y,z)\) coordinates for each of 15 points were generated and projected (orthographically) to the display screen. The fifteen dots composing each walker were rendered as anti-aliased circular disks. The stimuli were presented in the right visual field at eccentricities of 0, 1, 2, 4, 8 and 16 deg. Eccentricity of stimulus presentation—defined relative to the center of the stimulus—was manipulated by varying the position of the fixation dot; the stimuli were always presented in the center of the screen. Stimuli were viewed binocularly.

On each trial each of the 20 coefficients of \(a\) were drawn from a standard normal distribution to create a novel walker. The resulting walker could be made to move to the left or right by rotating it about the vertical axis by an angle \(\pm \Delta \theta\) deg. The objective of the experiment was to find thresholds for a range of stimulus sizes at a range of eccentricities. At each eccentricity nine logarithmically spaced stimulus sizes were chosen such that \(\Delta \theta\) thresholds ranged from asymptotically low, at large sizes, to roughly 30 to 70 deg at small sizes. For all stimuli the walker dot diameters were always 1/36 of the stimulus height; in other words, dot size scaled with stimulus size. Stimulus size was manipulated by varying viewing distance and/or stimulus size on the monitor. Viewing distances were varied from 57 to 456 cm and were chosen to satisfy the twin constraints of (i) keeping the fixation dot and stimulus on the screen and (ii) maximizing the number of pixels per dot. For example, stimuli presented at fixation were always viewed from 456 cm and those presented at 16° were viewed from 57 cm.

**Procedure**

On each trial a single walker was presented going through one full gait cycle (approximately 1.2 s), which began at a randomly chosen point (phase) of the gait cycle. Throughout the trial the participant maintained fixation on a small green dot. Responses were made through appropriate button presses and a 300 Hz tone signaled errors. An adaptive procedure (QUEST) (Watson & Pelli, 1983) was used to determine the threshold (81% correct in a 2AFC) value of \(\Delta \theta\) deg at each stimulus size and eccentricity. Prior to data collection subjects received sufficient practice to become familiar with the task. Two thresholds were determined for each combination of size and eccentricity and then averaged.

**Results**

The results are summarized in Figure 2. The top panels (A to D) show the raw thresholds obtained from each of the four subjects at each stimulus size and eccentricity. In all cases thresholds dropped as stimulus size increased (as expected) and all curves appear to be essentially shifted versions of each other. Figure 2 shows that there was no systematic relationship between minimum threshold and eccentricity. That is, all functions asymptote at about the same threshold. To assess this statistically we computed the average threshold at the two largest sizes at each eccentricity for each subject and submitted the means to a one-factor, within-subjects ANOVA. The analysis showed no statistically significant effect of eccentricity, \(F(5, 15) = .703, p = .603, \eta^2 = .19\).

Figure 2 shows that as stimulus size \((\sigma)\) increases \(\Delta \theta\) thresholds decrease until they reach an asymptotically small value \((\Delta \theta_{\text{min}})\). Therefore, at each eccentricity we can fit the data with a predicted threshold \((\Delta \theta')\) at each size \((\sigma)\) using the following negatively accelerated curve

\[
\Delta \theta' = \Delta \theta_{\text{min}}[1 + a/\sigma]^b,
\]

where \(a\) and \(b\) are free parameters. Because the curves in Figure 2 (top) are shifted versions of each other this
suggests that determining $F = 1 + E/E_2$ would allow us to collapse all data in to a single curve

$$\Delta \theta' = \Delta \theta_{\text{min}}[1 + a/(\sigma/F_E)]^b.$$  \hspace{1cm} (3)

In this case $\sigma/F_E$ represents scaled stimulus size.

For each subject values were found for $E_{\text{min}}, a, b$ and $E_2$ that minimize the deviation of the data from the parametric curve. The quality of the fit is reported as $r^2$ to express the proportion of variability in the data explained by the fit; the correlation was formed between log($\Delta \theta'$) and log($\Delta \theta$), which are the actual and predicted thresholds respectively. The data were fit using the error minimization routine (fminsearch) provided in MATLAB (Mathworks Ltd.). The scaled data are shown in the bottom panels of Figure 2 (panels E to H). The average $E_2$ value was .95 (estimated $SEM = .051$, 95% confidence interval = .79 to 1.11). This range of $E_2$ values is consistent with the results of Gurnsey et al. (2008) for walkers heading $\pm 4^\circ$ from straight ahead; average $E_2$ value was .87 (estimated $SEM = .136$; 95% confidence interval = .53 to 2.22). Therefore it seems that the two tasks are subject to very similar eccentricity dependent limitations.

Experiment 1 shows that azimuth discrimination provides a useful measure of sensitivity to biological motion. As expected, thresholds decrease as size increases. The function relating size to threshold is similar at each eccentricity so size scaling compensates for eccentricity dependent sensitivity loss; as it does in a host of 2D discrimination tasks (Rovamo, Virsu, & Nääs, 1978; Saarinen, 1988; Sally & Gurnsey, 2001, 2003, 2004, 2007; Sally, Poirier, & Gurnsey, 2005) and several 3D discrimination and identification tasks (Gurnsey et al., 2006; Melmoth, Kukkonen, Mäkelä, & Rovamo, 2000). The limits of walker direction discrimination do not change with eccentricity and asymptote at about $\pm 1.5^\circ$. The size scaling required to compensate for eccentricity dependent sensitivity loss is characterized by an $E_2$ of about .95, which is in good agreement with a previous estimate of .87 determined with $\Delta \theta$ fixed at $\pm 4^\circ$ (Gurnsey et al., 2008).

### Experiment 2

There is a substantial literature showing that detection and discrimination of point-light walkers is impaired when walkers are inverted (Pavlova & Sokolov, 2003; Shipley, 2003; Troje, 2003; Troje & Westhoff, 2006) much like face discrimination is disrupted by inversion.

Figure 2. Results of Experiment 1. Panels A–D plot mean thresholds ($\Delta \theta$) for upright walkers as a function of size for eccentricities 0, 1, 2, 8 and 16° in the right visual field for each of the four subjects. Panels E–H show the best fitting function through the size scaled data, along with the $E_2$ values used to scale the sizes and the proportion of variance ($r^2$) explained by the fits.
Such inversion effects do not seem to arise in tasks unrelated to biological motion or face discrimination (Farah, Wilson, Drain, & Tanaka, 1998; Pavlova & Sokolov, 2003; Reed, Morrison, & Arant, 2009). Ikeda et al. (2005) showed that inversion effects decreased with eccentricity in a biological motion identification task. However, in their task noise sensitivity did not scale with eccentricity. Hence the reduced inversion effect with eccentricity may have simply reflected increasing difficulty segregating biological motion from noise in the periphery. As noted, however, Ikeda et al. (2005) did not separate eccentricity dependent changes in sensitivity to biological motion from eccentricity dependent changes sensitivity to masking noise (Gurnsey et al., 2006, 2008; Thompson et al., 2007). The walker direction discrimination task introduced here does not involve noise contamination and it is therefore appropriate to address the open question whether inversion effects change with eccentricity.

**Method and results**

All aspects of Experiment 2 were identical to Experiment 1 except that walkers were inverted; i.e., subjects had to judge, at a range of sizes and eccentricities, whether inverted walkers were heading left or right. **Figure 3** (panels A to D) shows the raw thresholds obtained from each of the four subjects in the inverted condition at each stimulus size and each eccentricity. Thresholds, in most cases, dropped to similar levels as stimulus size increased, however it is much less obvious that asymptotic performance was achieved. As in Experiment 1, the average threshold at the two largest sizes at each eccentricity for each subject was computed and the means submitted to a one-factor, within-subjects ANOVA. An analysis of these average thresholds showed no statistically significant effect of eccentricity, $F(5, 15) = 1.69, p = .197, \eta^2 = .36$. In particular, the linear trend was not statistically significant, $F(1, 3) = .024, p = .887, \eta^2 = .008$, meaning there was no statistically significant increase in minimum $\Delta\theta$ with eccentricity.

The data of Experiment 2 are not nearly as orderly as those in Experiment 1. The scaled data are shown in the second row of **Figure 3** (panels E to H). The average $E_2$ value was 1.15 (estimated $SEM = .153$, 95% confidence interval = .66 to 1.64). Clearly the $E_2$ values were more variable for inverted than upright walkers. However, we note that three of the subjects show relatively large $E_2$ values (mean = 1.29) and the fourth (GR) a very small $E_2$ of .71. This seems to be because her data were shifted somewhat further leftward at fixation and somewhat

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further rightward at $16^\circ$. In other words, she was a little better at fixation and a little worse in the periphery.

There are three other factors that distinguish the upright and inverted walkers. Figure 2 shows that the upright walker data are much cleaner than the inverted walker data in Figure 3, and this is reflected in the quality of the fits to the data. The average $r^2$ value for upright walkers was $.90$ ($N = 4$; estimated $SEM = .015$; 95% confidence interval = .85 to .95) and $.80$ ($N = 4$; estimated $SEM = .037$; 95% confidence interval = .68 to .91) for the inverted walkers. The inability to extract precise heading information from inverted walkers (resulting in highly variable thresholds) may be a consequence of lack of familiarity/practice with such stimuli or a more fundamental encoding limitation; perhaps because the inverted walkers produce movements inconsistent with the effect of gravity on bodies (Shipley, 2003).

The effect of size is also different for the upright and inverted walkers. Panels E to H of Figures 2 and 3 show roughly negative linear functions relating thresholds to size (in log–log space). Therefore we computed the best fitting linear fit of log($\Delta \theta$) to log(Scaled Size) for all subjects in both conditions. The average slopes for the upright conditions were $-1.40$ ($N = 4$; estimated $SEM = .035$; 95% confidence interval = $-1.29$ to $-1.51$), and $-1.05$ ($N = 4$; estimated $SEM = .105$; 95% confidence interval = $-1.72$ to $-1.38$) for the inverted condition. Therefore, there was a more gradual decrease in thresholds with stimulus size for the inverted walkers than the upright walkers.

The minimum thresholds achieved in the upright condition ($1.57$ deg; $N = 4$; estimated $SEM = .205$; 95% confidence interval = .92 to 2.22) were much lower than those obtained in the inverted condition ($6.52$ deg; $N = 4$; estimated $SEM = 1.14$; 95% confidence interval = 2.89 to 10.15). (Again, these minimum thresholds were determined from the average $\Delta \theta$ thresholds at the two largest sizes for each eccentricity.) This is one of the most consistent differences between the two conditions. It’s not clear to what extent this deficit could be overcome with practice.

Figure 4 shows the average threshold (averaged over subjects) at each stimulus size and eccentricity for the upright and inverted walker. It is clear that at all sizes and

![Figure 4](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932794/ on 10/25/2018)

Figure 4. Each panel characterizes the inversion effect at each eccentricity. Blue dots depict the average threshold (averaged over subjects) for each stimulus size for upright walkers. Green dots depict the average thresholds for the inverted walkers. At each eccentricity the inverted thresholds fall above the upright thresholds.
eccentricities the thresholds for inverted walkers are higher than those for upright walkers, except at the very smallest sizes where thresholds reach ceiling levels (i.e., 90 deg). To assess the magnitude of the inversion effect we computed the ratio of inverted threshold to upright threshold for each stimulus size, at each eccentricity, for each subject. The average of this ratio at each eccentricity ($I_E$) represents a rough measure of the magnitude of the inversion effect. We submitted the $I_E$ scores to a within-subjects ANOVA and found no statistically significant effect of eccentricity, $F(5,15) = .606, p = .69, \eta_p^2 = .168$. Therefore, there is no evidence that the magnitude of the inversion effect changes with eccentricity.

**Experiment 3**

A frequent question in the biological motion literature concerns the information carried by different components of the point-light walker. There is accumulating evidence that the motions of the feet provide particularly strong cues to walker direction (Chang & Troje, 2008, 2009; Troje & Westhoff, 2006). As mentioned, the motion profiles of the feet change substantially as a function of azimuth. In the present walker direction discrimination task the characteristic motions of the feet at threshold for large stimuli are quite different from the characteristic motions of feet in past studies because in the latter walkers typically move ±90 deg from straight ahead whereas in the former walker directions are closer to ±1.5° from straight ahead. Therefore, the role of the feet may be quite different in the current task than in the traditional ±90 deg walker direction discrimination task.

In **Experiment 3** we measured azimuth thresholds as a function of size at 0 and 16° eccentricity. In one condition the stimulus was an intact walker (exactly as in **Experiment 1**). In a second condition only the two dots corresponding to the feet were presented and in a third condition all dots except the feet were presented.

**Method and results**

Most aspects of **Experiment 3** were identical to **Experiment 1** with the following exceptions: only two eccentricities were used (0 and 16°), there were three stimulus conditions (intact, feet alone and no feet), and subjects P1 and P3 were replaced with subjects P4 and P5, both of whom were female and had normal or corrected-to-normal vision. We retain the convention that stimulus size refers to the size of the intact walker, even though the actual sizes of the feet alone and no feet walkers differ from this nominal size. Because the sizes of the dots that compose the stimulus are proportional to the size of the intact walker, the nominal size is simply a multiple of the dot size in all three conditions.

Panels A to D of **Figure 5** show the raw thresholds obtained from each of the four subjects at eccentricities of 0 and 16° in each of the three conditions. Within each panel the data from 0 deg cluster on the left (near the y axis) and those from 16 deg cluster to the right. The lower panels (E to H) plot thresholds as a function of scaled size, along with the $E_2$ values associated with each of the three conditions. The $E_2$ values were submitted to a one-factor, within-subjects ANOVA and the omnibus $F$ was not statistically significant, $F(2, 6) = 2.94, p = .163, \eta_p^2 = .454$. For the intact walkers the mean $E_2$ value was .87 ($N = 4$, estimated $SEM = .033$, 95% confidence interval = .76 to .97); for the feet-only walkers the mean $E_2$ value was .94 ($N = 4$, estimated $SEM = .102$, 95% confidence interval = .61 to 1.26); for the no-feet walkers the mean $E_2$ value was 1.14 ($N = 4$, estimated $SEM = .092$, 95% confidence interval = .85 to 1.43). Therefore, the eccentricity dependent shifts of the 16° walker direction discrimination from straight ahead. Therefore, the role of the feet provide particularly strong cues to walker direction (Chang & Troje, 2008, 2009; Troje & Westhoff, 2006). As mentioned, the motion profiles of the feet change substantially as a function of azimuth. In the present walker direction discrimination task the characteristic motions of the feet at threshold for large stimuli are quite different from the characteristic motions of feet in past studies because in the latter walkers typically move ±90 deg from straight ahead whereas in the former walker directions are closer to ±1.5° from straight ahead. Therefore, the role of the feet may be quite different in the current task than in the traditional ±90 deg walker direction discrimination task.

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Panels A to D of **Figure 5** show the raw thresholds obtained from each of the four subjects at eccentricities of 0 and 16° in each of the three conditions. Within each panel the data from 0 deg cluster on the left (near the y axis) and those from 16 deg cluster to the right. The lower panels (E to H) plot thresholds as a function of scaled size, along with the $E_2$ values associated with each of the three conditions. The $E_2$ values were submitted to a one-factor, within-subjects ANOVA and the omnibus $F$ was not statistically significant, $F(2, 6) = 2.94, p = .163, \eta_p^2 = .454$. For the intact walkers the mean $E_2$ value was .87 ($N = 4$, estimated $SEM = .033$, 95% confidence interval = .76 to .97); for the feet-only walkers the mean $E_2$ value was .94 ($N = 4$, estimated $SEM = .102$, 95% confidence interval = .61 to 1.26); for the no-feet walkers the mean $E_2$ value was 1.14 ($N = 4$, estimated $SEM = .092$, 95% confidence interval = .85 to 1.43). Therefore, the eccentricity dependent shifts of the 16° walker direction discrimination task the characteristic motions of the feet at threshold for large stimuli are quite different from the characteristic motions of feet in past studies because in the latter walkers typically move ±90 deg from straight ahead whereas in the former walker directions are closer to ±1.5° from straight ahead. Therefore, the role of the feet may be quite different in the current task than in the traditional ±90 deg walker direction discrimination task.

In **Experiment 3** we measured azimuth thresholds as a function of size at 0 and 16° eccentricity. In one condition the stimulus was an intact walker (exactly as in **Experiment 1**). In a second condition only the two dots corresponding to the feet were presented and in a third condition all dots except the feet were presented.
The absolute value of Hedges’s $g = (\bar{x}_1 - \bar{x}_2)/s_p$ was computed for all pairs of minimum thresholds (averaged over eccentricity) as a measure of effect size. The results were $g_{\text{intact,feet-only}} = 2.07$, $g_{\text{intact,no-feet}} = 1.88$ and $g_{\text{feet-only,no-feet}} = 3.85$. The corresponding $t$-tests (uncorrected) for paired samples were $t_{\text{intact,feet-only}} = 2.729$, $p = .072$, $t_{\text{intact,no-feet}} = -3.016$, $p = .057$ and $t_{\text{feet-only,no-feet}} = -4.882$, $p = .016$. For completeness we computed effect sizes and $t$ scores for the eccentricity effect within each of the three conditions. The results are as follows: intact walkers, $g = .155$, $t = .246$, $p = .882$; feet-only walkers, $g = 1.955$, $t = 2.596$, $p = .081$; no-feet walkers, $g = .861$, $t = -1.383$, $p = .261$. Therefore, there was a modest effect of eccentricity on minimum thresholds for the feet-only condition but not the other two.

Experiment 3 shows that the eccentricity dependence in the three conditions is similar in that the shifts required to align the $0^\circ$ and $16^\circ$ curves are similar; i.e., roughly the same $E_2$ value in each condition. However, the functions relating size to threshold are not identical in the three conditions. Thresholds in the no-feet condition are generally higher than those in the intact condition. Thresholds in the feet-only condition are higher than those in the intact condition at small sizes but lower at large sizes. Note that a 1 deg feet-only stimulus was derived from the Figure 6. Thresholds for the feet-only (green circles) and no-feet (red circles) walkers relative to the intact walkers ($\Delta\theta$). (The two smallest sizes were eliminated because floor effects distorted the data.) On the left are shown data from $0^\circ$ and on the right data from $16^\circ$.}

Figure 5. Results of Experiment 3. Panels A–D plot mean thresholds ($\Delta\theta$) for the three walker conditions as a function of size for eccentricities 0, 1, 2, 8 and $16^\circ$ in the right visual field for each of the four subjects. Thresholds at $0^\circ$ cluster to the left of the panels, while thresholds for $16^\circ$ cluster to the right. Blue circles correspond to the intact walkers, green squares to the feet-only walkers and red triangles to the no-feet walkers. Panels E–H show the best fitting function through the size scaled data, along with the $E_2$ values used to scale the sizes in each of the three conditions.
1 deg intact walker by just deleting all dots but the feet. Consequently, a 1 deg feet-only display subtends only about 0.2 degrees of visual angle. If we were to define stimulus size in terms of the vertical extent, the curves representing the feet only condition in Figure 6 would shift 0.7 log units to the left and differences between the feet-only and the no-feet conditions would be even more pronounced.

Experiment 4

Many experiments have shown that stimulus magnification is sufficient to compensate for eccentricity dependent sensitivity loss for a wide range of stimuli. One may wonder, however, whether threshold level performance is achieved in the same way for different stimulus sizes and eccentricities. It might be, for example, that more attentional and strategic resources are devoted to achieving a fixed level of performance in the periphery than at more central locations. Because subjects can devote any necessary resources to achieving the required performance, changes in the allocation of resources in response to different task demands (e.g., stimulus size and eccentricity) are not obvious.

Two studies suggest that the perception of point-light walker direction is not a purely data-driven process. It has been shown that the time required to detect a walker heading in one direction increases with the number of walkers heading in the opposite direction (Cavanagh, Labianca, & Thornton, 2001). That is, visual search for a disparate point-light walker is inefficient or shows the features of attentive search (Treisman & Gelade, 1980). Furthermore, it has been shown that right–left walker discrimination in central vision is impaired in the presence of a second task requiring subjects to detect a change in orientation in one of four simultaneously presented rectangles (Thornton, Rensink, & Shiffrar, 2002). This result is relevant to the issue of segmenting a walker from noise and making decisions about the properties of the walker. Thornton et al. placed the walker in scrambled walker noise. Had the walker not been in noise it seems quite likely, if not certain, that deciding whether it was heading left or right would have been unaffected by the second task. However, it is not clear whether the distracting task would have affected the limits of walker direction discrimination. And it is not clear whether any such effect would be different in the periphery than at fixation.

Therefore, in Experiment 4 we asked if dividing attention between walker direction discrimination and a second (competing) task would have different effects across the visual field. In Experiment 4 we measured direction discrimination thresholds exactly as in Experiment 1 and then in a dual task in which subjects had to identify the color of the walker (red or green) first and then report walker direction.

Method

Subjects GR and P1 participated in the experiment. Stimuli were presented at 0 and 16° in the right visual field. The stimuli in Condition 1 (single task) were identical to those used at 0 and 16° in Experiment 1. In Condition 2 (dual task) the dots were of a lower mean luminance; in the achromatic case the red, green and blue guns were set to 75% of their maximum level. A chromatic bias was introduced by simultaneously raising and lowering the levels of the red and green guns by the same amount (ε); raising the red gun and lowering the green gun produced a reddish walker and the opposite change produced a greenish walker. In the dual task condition an adaptive procedure was used to find threshold Δε while a second adaptive procedure simultaneously varied Δθ. Subjects were instructed to give priority to the color discrimination task and to report walker color before reporting walker direction. A threshold run was terminated only when both adaptive procedures reached the criterion for threshold. The logic of the experiment is to measure walker direction thresholds in a context in which the color task difficulty was maintained at a constant level; i.e., the color contrast was always at QUEST’s best estimate of threshold.

Results

The results of Experiment 4 are presented in Figure 7. Panels A and B show the results for subjects GR and P1 respectively. The single task Δθ thresholds are shown in blue and the dual task Δθ thresholds are shown in green. Within each panel the data from 0° are to the left and those from 16° are to the right. It is clear that for both subjects the single and dual task curves superimpose almost perfectly. There is no evidence that asymptotic thresholds fall to different levels in the single and dual-task conditions and the computed $E_2$ values are essentially identical in both tasks for the two subjects. Therefore, there is no evidence that Δθ thresholds are impaired when obtained in the presence of a competing color discrimination task.

Experiment 5

Experiment 4 showed that attention could be divided between a color discrimination task and the walker direction discrimination task without cost to direction discrimination. Therefore, the evidence suggests that color discrimination and walker direction discrimination do not compete for resources (Garner, 1974; Treisman & Gelade,
Our results differ from those of Thornton et al. (2002) who found that dividing attention between walker direction discrimination and a change-detection task impaired walker direction discrimination. There are a number of differences between their experiment and ours. An important structural difference is that their competing task required subjects to attend to blinking rectangles superimposed on the stimulus whereas our competing task required attending to the dots of the walker itself. We wondered, therefore, if $E_{\text{threshold}}$ would be affected when attention is divided between the walker and a stimulus that surrounds that walker.

To address this question we used a different dual task procedure in which subjects judged whether a radial frequency pattern (Wilkinson, Wilson, & Habak, 1998) had a radial frequency of 3 or 4. The radius of the pattern at angle $\theta$ is defined as:

$$r(\theta) = r_0(1 + A \sin(\sigma \theta + \phi)),$$

where $r_0$ is the average radius of the pattern, $\sigma$ is radial frequency (in this case either 3 or 4), $\phi$ is the phase of the sinusoidal modulation, which was randomized on each trial, and $A$ is the amplitude of the radial frequency modulation, which ranged from 0 to 1. The cross section of the radial frequency pattern was Gaussian and a static frame of one stimulus is shown in Figure 8. On each trial the radial frequency pattern appeared and disappeared simultaneously with the walker. Subjects first judged radial frequency then walker direction.

## Method

The subjects were GR, P1, P2 and P5. The methodology of the experiment was exactly as in Experiment 4 except that the competing task required judging radial frequency rather than color. An adaptive procedure determined the RF amplitude eliciting 81% correct responses. There were three conditions of the experiment, two single tasks and one dual task. In the dual task condition subjects first judged the radial frequency pattern then walker direction. Both the amplitude ($A$) of the radial frequency pattern and walker direction ($\Delta \theta$) were controlled by independent adaptive procedures. As in Experiment 4, a threshold run terminated only when both of the procedures achieved termination conditions. In one of the single task conditions subjects judged the walker direction while ignoring variations in the radial frequency pattern; to make the conditions of the single task comparable to those of the dual task the amplitude ($A$) of the radial frequency pattern varied in proportion to $\Delta \theta$. To avoid interference with the walker, $A$ was capped at 10%. In the second single task condition, subjects judged radial frequency while ignoring walker direction. To make the conditions of the single task comparable to those of the dual task the amplitude ($A$) of the radial frequency pattern varied in proportion to $\Delta \theta$. To avoid interference with the walker, $A$ was capped at 10%.

Figure 7. Results of Experiment 4. Panels A and B show results for the two subjects. Azimuth thresholds ($\Delta \theta$) were obtained at 0° and 16° under single task conditions (blue circles) and dual task conditions (green circles). The results were indistinguishable in the two conditions. W indicates walker alone and W + C indicates the dual task, walker discrimination + color discrimination.

Figure 8. One frame of a stimulus from Experiment 5. The walker was always surrounded by the radial frequency pattern. The radial frequency could be 3 or 4 cycles.
comparable to those of the dual task walker direction varied in proportion to $A$.

**Results**

Figure 9 summarizes the results of Experiment 5. The top panel shows walker direction thresholds for each of the four subjects for both single ($W$: walker alone, blue dots) and dual task conditions ($W + RF$: walker + radial frequency, green dots). As in Figure 7, the data from fixation are to the left (in each panel) and those from 16° are to the right. For three of the four subjects the results from the dual task condition are indistinguishable from those in the single task. The mean $E_2$ for walker direction in the single task was 1.31 and in the dual task it was 1.37. Therefore, there is little, on average, to distinguish single task and dual task performance. However, we note that subject P5 showed lower asymptotic thresholds in the single task than in the dual task at 0°. This is consistent with the idea that the radial frequency task and the walker direction discrimination task compete for resources. However, this effect was not seen for P5 at 16° or any of the other subjects at either eccentricity. Therefore, the weight of evidence suggests no cost to walker direction discrimination in the dual task.

The bottom panels of Figure 9 show thresholds for each of the four subjects for both single (RF: radial frequency alone, blue dots) and dual task (RF + W: radial frequency + walker, green dots) conditions. For three of the four subjects the results from the dual task condition are indistinguishable from those in the single task. The exception is P2’s dual task results. These tend to be rather noisy and $E_2$ is so large as to be meaningless; an $E_2$ of 158 (see Figure 9, panel G) means that peripherally presented stimuli have to be moved 158° from fixation before stimulus size has to double to elicit equivalent to foveal performance. Therefore, the data do not permit a meaningful fit.

Except for the data just described, there seems to be little difference between the radial frequency amplitude thresholds in the single and dual task conditions. Asymptotic thresholds are similar in both conditions as are the $E_2$ values (see Figure 9). These data suggest that failing to attend to the radial frequency task cannot explain similarity of the single and dual task results for the walker discrimination data (Figure 9, panels A to D). Therefore, we conclude that the walker direction discrimination task does not compete for resources with the radial frequency task.

We note that the $E_2$ values in the walker direction discrimination task tend to be smaller than in the radial frequency task. The average $E_2$ in the walker discrimination

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**Figure 9.** Results of Experiment 5. Results for azimuth discrimination (panels A–D) and radial frequency discrimination (panels E–H). Panels A–D: Azimuth thresholds ($\Delta \phi$) were obtained at 0° and 16° under single task conditions (blue circles) and dual task conditions (green circles). The results were indistinguishable in the two conditions. Panels E–H: Radial Frequency thresholds (% $\Delta A$) were obtained at 0° and 16° under single task conditions (blue circles) and dual task conditions (green circles). The results were indistinguishable in the two conditions.
task was 1.34 and in the radial frequency task (excepting the $E_2$ of 158 in Figure 9, panel G) was 2.78. This corresponds to an effect size of $g = 3.079$. When the data were subjected to a paired samples $t$-test the difference was statistically significant, $t(3) = 3.373, p = .047$. This difference means that there is a faster loss of sensitivity with eccentricity for the walker direction discrimination task than for the radial frequency task.

### General discussion

We introduced the azimuth discrimination task as an alternative to discriminating the direction of walkers heading rightward and leftward ($\pm 90$ deg from straight ahead) while embedded in noise. Our initial questions were whether stimulus magnification is sufficient to equate azimuth thresholds ($\Delta\theta$) across the visual field and if so how the needed magnification relates to previously reported results. Experiment 1 showed that size scaling was indeed sufficient to compensate for eccentricity dependent sensitivity loss. The azimuth-vs-size curves were very similar at all eccentricities and so dividing actual stimulus size by $F = 1 + E/E_2$ collapsed data from all eccentricities onto a single curve. The fits were generally very good and explained about 90% of the variability in the data on average. The average $E_2$ in Experiment 1 was .95, which is consistent with the average $E_2$ value of .87 reported by Gurnsey et al. (2008) for walkers heading $\pm 4^{\circ}$ from straight-ahead. Furthermore, the minimum thresholds at the largest stimulus sizes did not change with eccentricity. Therefore, we conclude that the eccentricity dependent magnification required at the limits of walker direction discrimination is not different from that at a fixed difference of $\pm 4^{\circ}$ from straight-ahead.

At one time it was hoped that the $E_2$ value associated with a task would identify the anatomical locus (e.g., retinal or cortical) of the eccentricity dependent limitation (Wilson, Levi, Maffei, Rovamo, & DeVelois, 1990). This hope has dimmed in recent years, in part because estimates of $E_2$ can be quite variable and in part because manipulations of contrast, for example, can alter the $E_2$ recovered in a particular task (Sally & Gurnsey, 2007), suggesting an effect on physiological mechanisms rather than the anatomical locus of the limitation. On the other hand, there is evidence that associations can be made between known structural properties of the visual system and $E_2$. For example, it has been shown that for color discrimination the $E_2$ associated with L/M contrast detection is much smaller than that required for S/LM discrimination, which is consistent with the distributions of L, M and S cones in the retina (Vakrou, Whitaker, McGraw, & McKeefry, 2005). The $E_2$ values reported here are generally in the neighborhood of 1, which traditionally suggests a cortical limitation because resolution limits imposed by the retina increase at a much lower rate (cf. Drasdo, 1991). Therefore, it seems reasonable to assume that the limitation in the present task does not reflect difficulty resolving the presence of the stimulus itself but with extracting the information required to infer direction.

The azimuth discrimination task was also used to assess the inversion effect across the visual field. Inverted walkers elicited azimuth thresholds that decreased more slowly with size and reached higher asymptotic levels than did upright walkers. We measured the inversion effect at each eccentricity and found no evidence that its magnitude changed with eccentricity. Thus, unlike the conclusions of Ikeda et al. (2005) we find no evidence that the inversion effect diminishes with eccentricity. The data were noisier for inverted walkers than upright walkers and size scaling produced poorer fits to the data than in the case of upright walkers.

Previous reports have suggested an important role for the feet in detecting biological motion (Troje & Westhoff, 2006) and discriminating walker direction (Mather et al., 1992). These studies have typically involved point-light walkers heading $\pm 90$ deg from straight ahead and we therefore wondered if there would be a special role for the feet in the azimuth task because near threshold, for large stimuli, the motion profiles of the feet are much different than in the standard $\pm 90^{\circ}$ condition. The results show that walkers without feet produced higher thresholds at almost all sizes and eccentricities than walkers with feet. Therefore, removing the feet comes at a cost. On the other hand, eliminating all dots except the feet had more interesting consequences. For small sizes the feet-only stimuli produced slightly higher thresholds than the intact walkers. However, for the four or five largest sizes the feet-only walkers elicited thresholds that were equal to or lower than those elicited by the intact walkers. Clearly, the feet alone provide better information about walker direction than do the remaining dots.

The lower thresholds for the feet-only condition relative to the intact walker at large sizes might suggest a special role for the feet. On such a view the intact walkers produce intermediate thresholds because of obligatory holistic processing in which the advantage of the feet alone is polluted by the disadvantage of the no-feet condition. However, a simpler answer might involve the consequences of varying stimulus size. The results show clearly that footless walkers elicit higher thresholds in general than intact walkers. As stimulus size increases the feet move to greater vertical eccentricities meaning that less informative dots are closer to fixation than the feet. Nevertheless, the present evidence is consistent with a special role for the feet even in cases in which walkers are not moving $\pm 90^{\circ}$ from straight-ahead. On the other hand, there is no advantage of the feet-only condition at smaller sizes. Under these conditions thresholds increase and walkers are seen more in profile, as in the usual walker direction discrimination task.
One may accept that the feet play a special role in the perception of walkers while recognizing that walking is only one aspect of biological motion and question whether the feet may make any contribution to discriminating other biological actions, such as swinging a baseball bat. To this we would argue that walking is a particularly important instance of biological motion and probably the most frequent ‘whole body’ motion generated by all living creatures with feet. Therefore, it would not be surprising if we were particularly sensitive to walking and that specific aspects of walkers (i.e., the feet) hold special importance. And one could easily see why predator and prey might be more likely to develop specific sensitivity to the movements of feet during locomotion than, say, the way the feet move during the swing of a bat.

As a final application of the azimuth task we asked whether dividing attention between walker-azimuth discrimination and a competing task would affect azimuth discrimination. Because previous research had suggested a role for attention in the perception of biological motion it seemed reasonable to ask whether the involvement of attention changes across the visual field. In spite of the compelling evidence from previous studies (Cavanagh et al., 2001; Thornton et al., 2002) that attention is critical to discriminating biological motions, Experiments 4 and 5 showed that the addition of a second, attention-demanding task had no influence on azimuth thresholds.

There are several possible reasons for our failure to find converging evidence concerning the role of attention in discriminating biological motion direction. We note that both the “attention-absorbing” tasks and the biological motion tasks differ between our experiments and those of Thornton et al. (2002). Their biological motion task required subjects to discriminate right–left walker direction for walkers embedded in noise whereas we used direction discrimination in the absence of noise. Their attention-absorbing task involved change detection whereas we used color discrimination and radial frequency discrimination. It is possible that our attention task did not compete for resources with the azimuth task. This is most plausible in the case of Experiment 4, in which subjects discriminated walker color. It is quite possible that color is separable from the form or motion information needed to perform the azimuth discrimination task. Furthermore, the color information is integral to the walker so there is no location-conflict between the two tasks. However, the radial frequency task (Experiment 5) did require subjects to attend to points that did not overlap with the walker, and yet did not affect azimuth thresholds. If the difference in the second (attention-absorbing) task is responsible for the discrepant results in our experiments and those of Thornton et al. (2002) then claims about the role of attention in the perception of biological motion must be narrowed to specify the nature of the second task and some explanation must be provided about what resources the two tasks compete for. It is not clear why a change detection task should be more damaging to the discrimination of walker direction than a radial frequency task.

It may be that it is not differences in the second task that explains the difference between our results and those of Thornton et al. (2002), but the fact that their walkers were embedded in noise and ours were not. Thornton et al. (2002) asked subjects to judge whether walkers were heading ±90° from the line of sight whereas we measured azimuth thresholds, which at large sizes tended to be on the order of ±1.5°. Intuition suggests that if biological motion is susceptible to resource competition then ±90° walkers should make fewer demands on attention than ±1.5° walkers. We noted earlier the possibility that the difficulty subjects had under those dual task conditions was one of segregating the walker from the noise rather than one of encoding the properties of the walker itself. Our results suggest that had their walkers not been embedded in noise it seems certain that walker direction discrimination would have been on the ceiling in both single and dual-task conditions.

We noted in the Introduction that scrambled walker noise is often used simply because the standard walker task is so easy otherwise. It may be that the results of Thornton et al. (2002) tell us more about segregating signal from noise than anything specific about biological motion. Of course this is an empirical question. One way to address it would be to measure walker direction thresholds with and without noise and with and without the “attention absorbing task” (change detection) employed by Thornton et al. We predict the second task will have no effect on thresholds in the absence of noise but thresholds will increase with noise in the dual task relative to the single task.

Although our task is most directly comparable to that of Thornton et al. (2002) our results are also at odds with those of Cavanagh et al. (2001) who showed that rightward heading walkers did not pop out of leftward heading walkers (and vice versa) in a visual search task; i.e., walker direction discrimination seems to require attention in a visual search task. Several points that might explain this discrepancy are worth noting. First, subjects found this task to be very difficult. Reaction times were very long even when a single stimulus was presented (∼1250 ms on target present trials). This may be partly because the stimuli were presented about 4° from fixation (with walker height apparently 4 to 5°). Furthermore, although Michelson contrast was high (about .9) the display luminance was very low (2.12 c/m²), placing it close to, if not in, the mesopic range. This latter point may explain the difficulty subjects had with the task. For upright walkers at 4° eccentricity and 4° in height our subjects achieved discrimination thresholds of about 3°. Although we did not measure reaction time it’s clear that our subjects would have found ±90° walkers trivially easy to discriminate under conditions that subjects in the Cavanagh et al. study found very difficult. Therefore, it would be worth redoing their experiment at higher luminance...
levels. Note as well that Grossman and Blake (1999) found a reduced sensitivity to biological motion under low luminance conditions, although their stimuli were degraded with noise, whereas those of Cavanagh et al. were not.

Furthermore, judging walker direction in peripheral vision in low luminance conditions may be subject to crowding effects (Tripathy & Cavanagh, 2002). Thus, the increase in reaction time with set size may not reflect limitations on processes specific to biological motion but more general limitations associated with integrating complex stimuli under low light conditions in the periphery. These are empirical questions worth exploring.

**Conclusions**

We have argued that our walker direction discrimination task offers a useful alternative to noise-tolerance methods of studying biological motion. Our task measures sensitivity to walker direction because we have methods available to synthesize walkers and manipulate their direction of heading. One could imagine any number of “action spaces” that permit continuous variations between exemplars. For example, one could conceptualize “baseball bat swinging space” with Babe Ruth, Reggie Jackson and Manny Ramirez occupying different loci. It would certainly be interesting to ask about our sensitivity to differences in batting styles and such a task, were it available, would probably be of great interest to other researchers.

Whatever action space might be studied one could ask how sensitivity to variations in the action change with variations in eccentricity (Ikeda et al., 2005), light level (Grossman & Blake, 1999), chromatic contrast (Garcia & Grossman, 2008) or first and second order motion (Aaen-Stockdale et al., 2008; Ahlstrom et al., 1997; Mather et al., 1992) to name just a few instances. One could also ask which segments of the gait-cycle are most informative (Thurman & Grossman, 2008). Following the work of Thurman and Grossman one would predict discrimination thresholds to be lowest when the motions of the extremities produce local opponent motion. Again, this is an empirical question easily tested.

Although the noise tolerance technique is not without value it does introduce difficulties of interpretation. For example, under low light conditions (Grossman & Blake, 1999), peripheral presentation (Ikeda et al., 2005) and isoluminance (Garcia & Grossman, 2008) for example, impaired sensitivity to biological motion might be attributable to increased difficulty segmenting signal from noise as opposed to decreased sensitivity to properties of biological motion per se. One of the earliest studies to examine sensitivity to biological motion in noise made this point explicitly (Neri et al., 1998). Neri et al. measured noise tolerance thresholds for detection of point-light walkers and direction discrimination thresholds for point-light walkers. They found that sensitivity was much greater for walker detection than direction discrimination. Therefore, if one is interested in measuring sensitivity to aspects of biological motion, there may be situations in which it might be useful if not essential to avoid noise.

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Corresponding author: Rick Gurnsey.

Email: Rick.Gurnsey@Concordia.ca.

Address: Department of Psychology, Concordia University, 7141 Sherbrooke St. West, Montreal, QC, Canada, H4B 1R6.

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