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Judgments of exocentric direction in large-scale space

Jonathan W Kelly, Jack M Loomis, Andrew C Beall
Department of Psychology, University of California, Santa Barbara, CA 93106, USA;
e-mail: kelly@psych.ucsb.edu

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Abstract. Judgments of exocentric direction are quite common, especially when judging where others are looking or pointing. To investigate these judgments in large-scale space, observers were shown two targets in a large open field and were asked to judge the exocentric direction specified by the targets. The targets ranged in egocentric distance from 5 to 20 m with target-to-target angular separations of 45°, 90°, and 135°. Observers judged exocentric direction using two methods: (i) by judging which point on a distant fence appeared collinear with the two targets, and (ii) by orienting their body in a direction parallel with the perceived line segment. In the collinearity task, observers had to imagine the line connecting the targets and then extrapolate this imagined line out to the fence. Observers indicated the perceived point of collinearity on a handheld 360° panoramic cylinder representing their vista. The two judgment methods gave similar results except for a constant bias associated with the body-pointing response. Aside from this bias, the results of these two methods agree with other existing research indicating an effect of relative egocentric distance to the targets on judgment error — line segments are perceived as being rotated in depth. Additionally, verbal estimates of egocentric and exocentric distance suggest that perceived distance is not the cause for the systematic errors in judging exocentric direction.

1 Introduction

Despite the fact that vision is the primary sensory modality for perceiving spatial layouts, people regularly misjudge geometric properties of their environments under full-cue viewing conditions, including distances and directions between objects (Gilinsky 1951; Wagner 1985). Depth extents are commonly underestimated relative to width extents, such that changing one's viewing position can affect judgments of distance between the exact same stimuli (Levin and Haber 1993; Norman et al 1996; Toye 1986). When observers attempt to match depth and width extents, they generally require physically larger depths (Loomis et al 1992, 2002; Loomis and Philbeck 1999); the perceptual distortion is such that the depth-to-width ratio of the physical extents can be as large as 5 : 1 (Beusmans 1998). In addition, Koenderink et al (2002) have shown that perceived frontoparallel planes are physically curved at distances ranging from 2 to 10 m (for a similar finding over even larger distances, see Battro et al 1976). All of these lines of evidence point to large errors in visual space perception. However, other results suggest that perceived egocentric distance, under full-cue viewing, is linear in physical distance and accurate (Fukusima et al 1997; Loomis and Knapp 2003). Data from two recent studies (Foley et al 2004; Loomis et al 2002) go a long way in reconciling these seemingly conflicting results on perception of egocentric distance and perception of exocentric extents. Foley et al (2004) have developed a mathematical model of visual space, based on judgments of exocentric distance, which accounts for variations in perceived exocentric distance of intervals of constant physical length but varying in angular extent. These variations of exocentric distance occur even when egocentric distance is linear (or nearly so) in physical distance. Loomis et al (2002) have demonstrated a dissociation between the perception of target locations and the perception of exocentric distance (and shape) — shape judgments vary greatly between monocular and binocular viewing, whereas judgments of target location are unaffected by this manipulation.

Ellis et al (1991) reported a novel technique for probing properties of visual space, where observers judged the direction formed between two objects (herein referred to as an exocentric direction). Under outdoor viewing conditions, errors in judgments of exocentric direction seemed to be biased in depth, in a direction opposite to that predicted by an equidistance tendency (Gogel 1965). Koenderink and van Doorn (1998) were the first to interpret errors in exocentric direction in terms of the metric properties of visual space. In their task, observers aimed a remote-controlled pointing device at a target, thereby making a judgment of the exocentric direction between the pointer and the target. The pointer and target were always equidistant from the observer, creating an isosceles triangle with the observer at the vertex. Distance to the pointer and target ranged from 1.5 to 24 m, and both were always placed at eye level. On the basis of their findings, they concluded that visual space in the horizontal plane at eye height is elliptic in near space and hyperbolic beyond that. A number of other experimenters have since used judgments of exocentric direction to investigate visual space (Cuijpers et al 2000a; Hermens and Gielen 2003; Johnston et al 2003; Kelly et al, in press; Koenderink et al 2000, 2003; Schoumans and van der Gon 1999; Schoumans et al 2002). Cuijpers et al (2000a) found a strong dependence of exocentric pointing errors on the ratio of egocentric distances to the pointer and target, where accuracy was highest when the two were equidistant from the observer and systematic deviations occurred as the ratio increased or decreased. Kelly et al (in press) found a similar pattern of errors when observers were asked to assess what parts of a visual scene were visible to another person, demonstrating the real-world relevance of judging exocentric direction.

On the basis of errors in judged exocentric direction, some authors have concluded that visual space is defined by a Riemannian curvature, with both expansive and compressive regions (Cuijpers et al 2000a; Koenderink and van Doorn 1998; Koenderink et al 2000). However, in none of these studies to date have experimenters thoroughly investigated the relationship between relative distance and perceived exocentric direction under full-cue conditions in large-scale space. To that end, in the following experiment we employ two novel response types (collinearity judgments and body pointing) to investigate this relationship under full-cue viewing in a large open field.

2 Method

2.1 *Participants*

Eleven students at the University of California, Santa Barbara, were paid for their participation. Each participant completed two 1 h sessions on two separate days, performing a different task (corresponding to the two different response types, collinearity and body pointing) on each day. Thus, each of the eleven observers participated in both tasks. All had normal or corrected-to-normal vision and were naïve to the purposes of the experiment.

2.2 *Stimuli*

Experiments were conducted in a large open field, approximately a 70 m × 120 m rectangle, bounded by a fence on all sides. The field was covered predominantly with short grass and occasional dirt patches, providing a rich ground texture. In some places (approximately 180° of the view) the surrounding chain-link fence afforded a view of buildings and trees beyond, and in other places (approximately the remaining 180°) the fence was backed with an opaque surface occluding any view directly behind. The fence was approximately 2 m tall, and even when it was covered with the opaque backing, taller structures were still visible behind it. Figure 1 shows a small section of the scene from the observers' view (this photograph was selected from the 360° panorama used in the experiment and described below).

Figure 1. Photograph of the field used in the experiment. This photograph was taken from the larger 360° panorama used for responses.

Throughout the experiments, each observer stood at the origin, which was approximately at the center of the field. In front of the observer were 16 wooden posts, arranged along 4 radials (spaced 45° apart) with 4 posts on each radial placed at 5, 10, 15, and 20 m from the observer. Thus, all 16 posts spanned a 135° area in front of the origin (see figure 2). Each post was 1 m tall, with a 10 cm × 10 cm white sheet of paper affixed to the top, identifying the post by a letter of the alphabet. All posts were visible throughout the experiment.

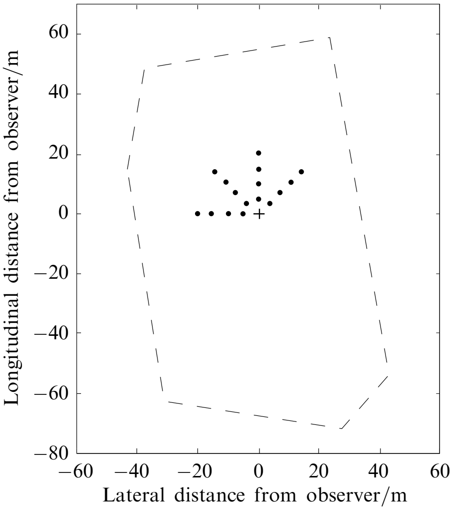

Figure 2. Stimulus configuration for both tasks. A + marks the position of the observer; the dashed line indicates the boundaries of the field. A ● denotes a post.

2.3 *Procedure*

In both the collinearity and the body-pointing tasks, the experimenter pointed out pairs of posts, identified by their corresponding letter (A through P). For each trial, the participant was asked to imagine a line from one post to the other. In the collinearity task, observers responded by indicating where this imaginary line would intersect with the bounding fence. Essentially, observers were making a three-point collinearity judgment: they were given two posts in space and asked to determine the point on the fence collinear with those two posts. Observers indicated their responses on a 360° panorama they held in their hand, which showed the entire scene from the observers' vantage point. The panorama itself was pasted onto the outside of a cylinder with a radius of approximately 15 cm, creating a convex panorama that wrapped around.

For each trial, observers indicated on the panorama the perceived point of collinearity. This was a directional response, representing the direction of the perceived intersection point from the origin. By using the dimensions of the fence, the Cartesian coordinates of the response location could be calculated later. The panorama was taken at sufficient resolution to identify details on the fence that might aid in the task. Observers were encouraged to find a point in space they thought was collinear with the two posts, identify that point with a landmark on the fence (eg a fence post, bush, or lamp), and then return to the panorama to find that landmark and make their response.(1) Observers never reported any difficulty in finding an appropriate landmark, suggesting that the fence was detailed enough to make these judgments.

Each response was made by drawing a vertical line on the panorama, through the point of collinearity. Responses were labeled according to the trial number and remained on the panorama throughout the experiment. There were 60 trials in each 1 h session, based on 30 unique combinations of separation angle as well as relative and absolute egocentric distances to the two targets and the bidirectionality of those combinations. Specifically the distances (in meters) of the target pairs were 5 – 5, 5 – 10, 5 – 15, 5 – 20, 10 – 10, 10 – 15, 10 – 20, 15 – 15, 15 – 20, and 20 – 20 for each separation angle and both directions.

The body-pointing task took place in the same field, with the same stimuli. This time, when the experimenter pointed out pairs of posts, the observer was asked to imagine the line from one post to the other and face her/his body in a direction parallel to the imagined line. The observer's body orientation was measured with a digital compass worn on her/his back, affixed with a belt. The compass had been calibrated and was accurate to 1°.

For the final 15 trials of both sessions, observers made exocentric-distance judgments for each pair of posts presented. This estimate was made after their initial pointing judgment (or collinearity judgment, depending on the session). In addition, each observer made 10 egocentric-distance judgments of posts ranging from 3 to 25 m on their second day. Among these 10 judgments were the egocentric distances present in the initial stimulus set (ie 5, 10, 15, and 20 m) as well as 6 other distances (3, 8, 12, 16, 22, and 25 m) interspersed to prevent the stimulus regularity from influencing the verbal response. All ten targets were lettered posts (like those used for the exocentric-direction judgments) arranged along a radial extending away from the observer. The posts were alternately tilted approximately 10° to the side so as not to occlude one another. In all cases, the point where the post intersected the ground plane was clearly visible. For all distance judgments (both egocentric and exocentric) observers responded verbally and were free to use any unit of length, though most chose feet or yards. A length of rope corresponding to the unit of measurement chosen was laid out in front of the observer (with one end placed at his/her feet) and was available at all times for reference. For the egocentric-distance judgments, the rope extended along the same radial that the posts were placed on. For the exocentric-distance judgments, the rope extended in the general direction of the posts but was not realigned for each pair.

The order of the sessions was counterbalanced. The order of trials was arranged such that the final 15 trials on day one and day two represented the full set of 30 pairs. This was done to ensure that observers reported exocentric-distance judgments for all combinations of posts. Aside from this constraint, the order of trials was randomized. The observer was permitted to rotate his/her head and body, as well as eye gaze, at all times.

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(1) Since the panorama was used as a response device only, the convex display was simple to use: observers needed only to find the corresponding point from the physical fence. For that matter, a completely flat panorama would have served the same purpose, but the cylindrical device was more intuitive.

3 Analysis

Figures 3a and 3b detail the setup for the collinearity judgment and body-pointing response, respectively. The independent variables were the distances to the two posts (r_{T_1} and r_{T_2}) and the angular separation of the two posts (δ). In the collinearity task (figure 3a), the observer's response is indicated by the 'X' on the fence (the fence is represented by the curved line). A response corresponding to the 'O' on the fence is correct, and any deviation from the veridical is considered an error, denoted by $\Delta\phi$. Error is measured as the angle between the correct response and the observer's response, with the vertex of this angle located at the bisector of the line connecting the two targets. If the response reflects an error in the direction away from the observer, the error ($\Delta\phi$) is positive. Likewise, if the response is an error towards the observer, the corresponding error is negative. For body-pointing responses (figure 3b) the independent variables are the same (distance to posts and angle of separation), and any deviation from the veridical is an error called $\Delta\alpha$. Error in a direction away from the observer results in a positive $\Delta\alpha$, and a response towards the observer is negative.

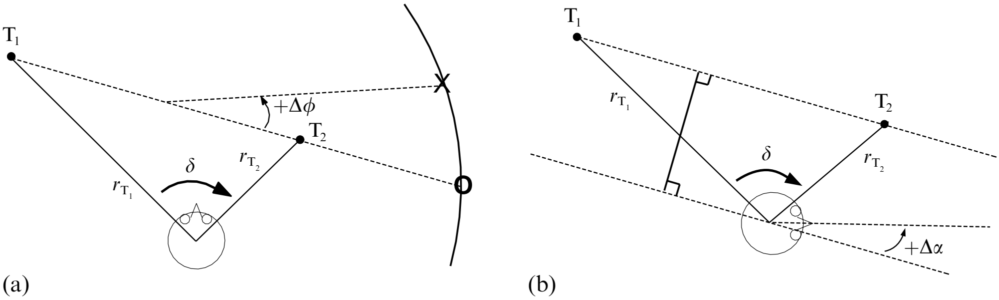

Figure 3. Layout and error coding for collinearity response (a) and body-pointing response (b).

4 Results

4.1 *Exocentric-direction judgments*

All data are expressed in terms of angular deviation from the veridical. Positive angular error reflects response error in a direction away from the observer, and negative error reflects error towards the observer (refer to figure 3). Upon initial inspection of the data, the mean collinearity judgment shows a slight negative bias (−0.84° of angular error) and the body-pointing response has a large negative bias (−18.09° of angular error) when averaged over all observers and all stimulus configurations (see figure 4). All observers demonstrated this negative bias with body pointing, meaning that they all consistently misreported the stimulus orientation in a direction towards themselves. A calibration error with the compass used in body pointing would not show up in the mean data, because all lines are presented in both directions (this would effectively cancel out any calibration error when viewing mean observer data across all configurations).

The negative bias in body pointing is best illustrated by comparing configurations that are physically equivalent but imply an opposite direction (eg when the two posts are equidistant from the observer and the observer responds both to the left and to the right). In these cases, data show a negatively biased response for both directions. This implies that observers respond negatively for one direction, and fail to simply turn around 180° when they respond in the other direction (see figure 5).

The average absolute error for the collinearity judgment, when averaged over all observers and all conditions is only 7.43°, indicating the precision with which these highly involved judgments are made. This is especially impressive, considering that observers sometimes had to turn through large angles when viewing the pair of posts and then looking for the point of collinearity. Figure 6 demonstrates this accuracy by a

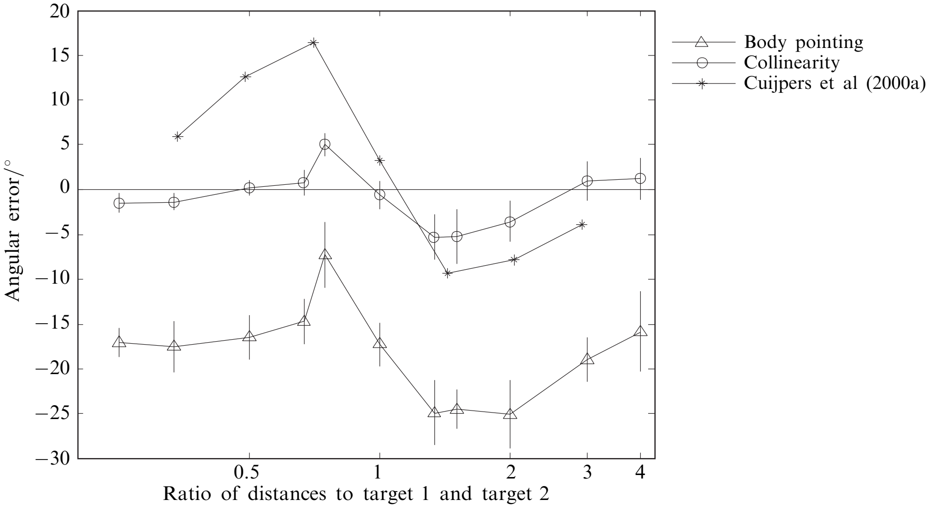

Figure 4. Mean angular error as a function of the relative egocentric distances to the two targets, collapsed across separation angle. Data from Cuijpers et al (2000a) are replotted for comparison.

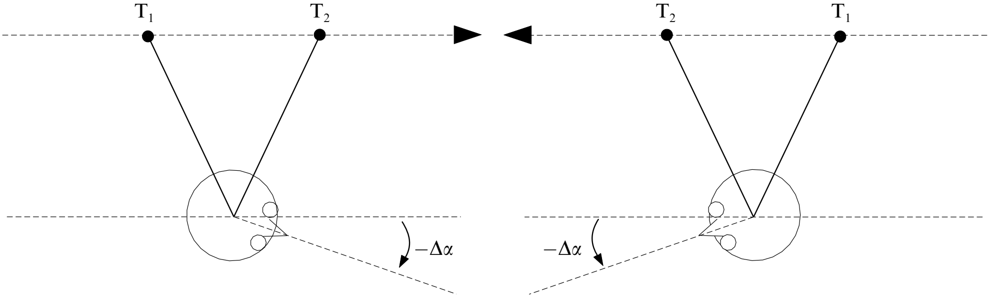

Figure 5. Illustration of the negative bias for body pointing. Observers err towards themselves when pointing in both directions for the same stimulus.

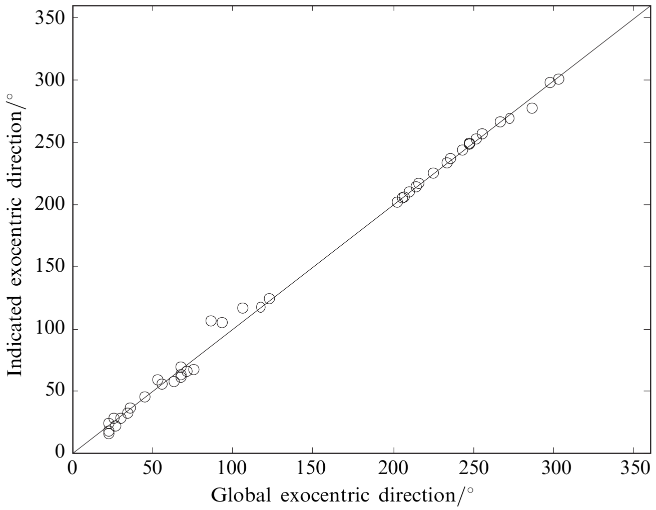

Figure 6. Mean perceived line orientation by true global orientation, in degrees, as measured in the collinearity task. The solid line represents correct responses.

plot of the global orientation of each stimulus (relative to North) against the exocentric direction indicated by the collinearity response. All mean data points lie either directly on or very near the line representing the veridical. Nevertheless, there are small systematic (signed) errors that are quite reliable. These are considered next. The absolute error for body pointing is much larger (19.22°) owing to the strong negative bias.

Cuijpers et al (2000a) found that both the size and the direction of angular errors are highly dependent upon the ratio of egocentric distances to the two targets. Because for each trial we specified directionality in the stimulus configuration of the present study (observers were asked to imagine the line from one post to another), posts will now be referred to as targets one and two. Target one is the first post in a pair (the starting point of the imagined line) and target two is the second post. Thus, data from the same two posts presented in different directions are kept separate when expressed as ratios. Figure 4 shows findings similar to those of Cuijpers et al (2000a): angular errors for both response types are highly dependent on the ratio of the egocentric distance to target one (r_{T_1}) over the egocentric distance to target two (r_{T_2}). The average standard error of the mean is 2.90° for the body-pointing response and 1.79° for the collinearity response. As seen in figure 4, there is a clear dependence of angular error on the relative distances. When target one was closer to the observer than target two ($r_{\mathrm{T}_1}/r_{\mathrm{T}_2} < 1$), the pair exhibited error in the positive direction (away from the observer), and when target one was further than target two ($r_{\mathrm{T}_1}/r_{\mathrm{T}_2} > 1$), the pair exhibited negative error (error towards the observer). The perceived exocentric direction can be described as rotated in depth in both cases. This is the case for both response types, but the body-pointing response is shifted by $-18°$. When target one and target two were equidistant from the observer, the collinearity judgment errors were not significantly different from zero ($t_{263} = 0.95$, ns).

Figure 7 shows the effect of distance ratio on angular error for both response types for the 45°, 90°, and 135° separation angles. Qualitatively, the same pattern of errors seen in figure 4 is present in many of the subplots in figure 7. In nearly every case, local maxima occur at distance ratios of 0.75 and local minima occur at ratios of 1.3 or 1.5. This pattern is most exaggerated when the targets are separated by 45°. When the distance ratio is one (ie the targets are equidistant from the observer), errors are close to zero, and when the distance ratio is extremely large or small (ie the targets approach a pure radial extent), angular errors return to zero. Nonlinear regressions performed on each separation angle for each response type suggest that a cubic function describes the collinearity data for separation angles of 45° and 90° ($F_{3,216} = 11.52$ and 7.36, respectively, $p < 0.001$) but not for the 135° separation ($F_{3,216} = 1.9$, ns). Cubic functions describe the body-pointing data for separations of 45° and 135° ($F_{3,216} = 5.01$ and 7.34, respectively, $p < 0.01$) but not for the 90° separation ($F_{3,216} = 1.35$, ns).

4.2 *Distance judgments*

For both egocentric-distance and exocentric-distance judgments, the relationship between perceived distance and physical distance is well fit by a linear function with zero intercept ($r^2 = 0.998$ and 0.96 for egocentric and exocentric, respectively). Figures 8 and 9 show plots of the data for egocentric and exocentric distance, respectively. The slope of the exocentric-distance function was larger than that of the egocentric-distance function (0.80 compared with 0.68). The larger variability seen in the exocentric distance estimates is likely due to larger physical intervals as well as varying angles of separation between targets, which ranged from 45° to 135°. Given the clear linear relationship between physical and perceived distance to the targets, it is unlikely that the exocentric-direction errors can be due to misperceived target locations. Even if the perceived configuration is a uniformly rescaled representation of the physical configuration, as suggested by figures 8 and 9, exocentric-direction judgments should be unaffected.

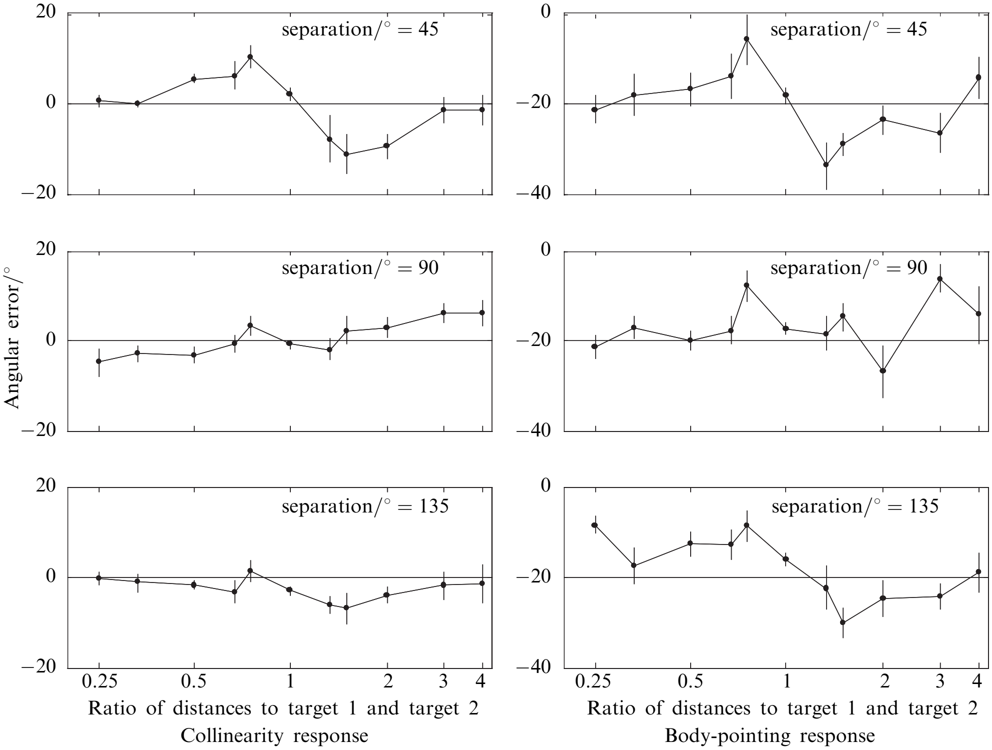

Figure 7. Mean angular error as a function of the relative egocentric distances to the two targets, broken down by target separation angle and response modality.

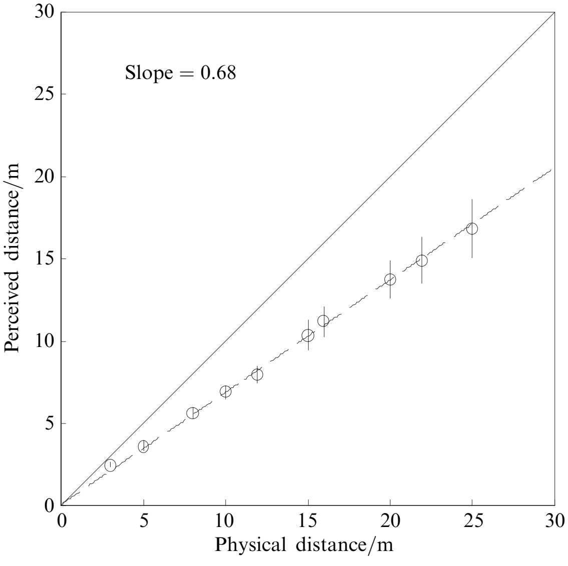

Figure 8. Mean egocentric-distance estimates (open circles) and the slope of the best-fitting line.

Of additional interest is the finding that, under conditions where targets were separated by 135°, distance judgments failed to satisfy triangle inequality (the largest side of the triangle was judged greater than the sum of the two smaller sides). Table 1 shows that for target separations of 135°, 7 of 10 cases violate triangle inequality, where the sum of the estimated egocentric distances to the two targets is less than the estimate of the exocentric extent between the targets. Others have also found evidence

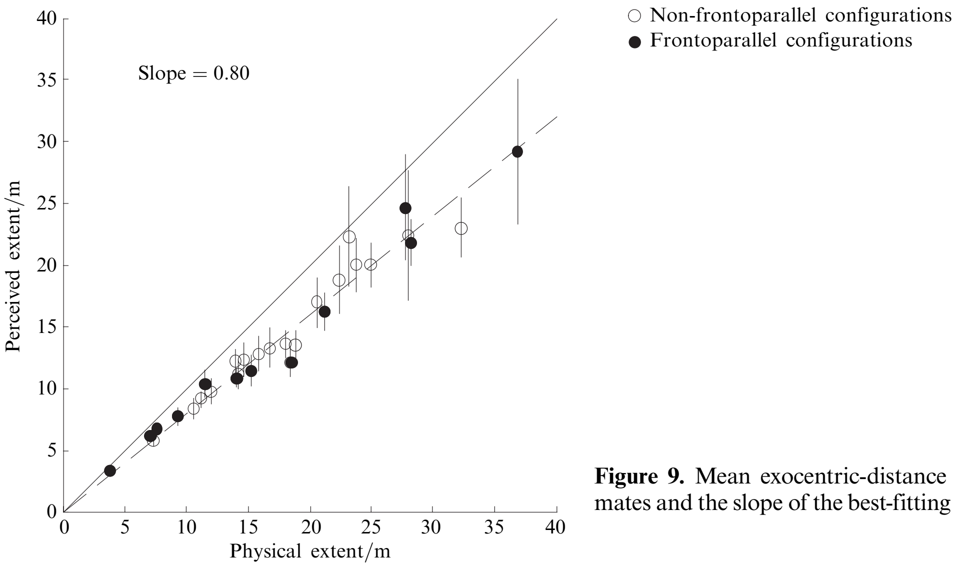

Figure 9. Mean exocentric-distance estimates and the slope of the best-fitting line.

Table 1. Mean egocentric-distance and exocentric-distance judgments when targets were separated by 135°. Standard errors for exocentric-distance estimates are given in parentheses. Violations of triangle inequality (where the exocentric distance between two posts is judged larger than the sum of the egocentric distances to the two posts) appear in bold.

d_{T_1}	d_{T_2}	d_{exo}	$d'_{\mathrm{T}_1} + d'_{\mathrm{T}_2}$	d'_{exo}
5	5	9.2	**7.2**	**7.76 (0.24)**
5	10	14.0	**10.4**	**12.21 (0.28)**
5	15	18.9	13.9	13.54 (0.33)
5	20	23.8	**17.3**	**20.01 (0.67)**
10	10	18.5	13.7	12.14 (0.38)
10	15	23.2	**17.2**	**22.34 (1.21)**
10	20	28.0	**20.6**	**22.38 (1.60)**
15	15	27.7	**20.7**	**24.67 (1.30)**
15	20	32.4	24.1	22.99 (0.72)
20	20	37.0	**27.5**	**29.15 (1.77)**

of non-Euclidean geometry by analyzing perceived triangles in both large-scale and small-scale space (Battro et al 1976; Blank 1961; Norman et al 1996). In the current study, the violation of triangle inequality is a result of the discrepant slopes from the egocentric-distance and exocentric-distance functions (figures 8 and 9). Anytime the exocentric-distance slope is larger than the egocentric-distance slope, there will exist some separation angle at which triangle inequality will fail.

The data show little effect of angular separation on perceived exocentric distance. As is evident in figure 9, frontoparallel extents (filled circles) were not judged larger than non-frontoparallel extents (open circles) of the same physical size. The exact values of the slopes for the non-frontoparallel and frontoparallel functions are 0.80 and 0.79, respectively. Prima facie, this appears to conflict with other studies that do show an effect of stimulus visual angle on perceived exocentric extent (Foley et al 2004; Levin and Haber 1993; Toye 1986; Wagner 1985). A likely reason for this discrepancy is that all of the exocentric intervals in this experiment had angular separations of 45°, 90°, or 135°. In the other studies cited above, angular separations were often quite small (close to 0°), and the model of Foley et al (2004) predicts that the biggest effects of line orientation occur with exocentric intervals of small angular size.

5 Discussion

Work by Cuijpers et al (2000b) on visual parallelism sheds some light on the negative bias seen in the body-pointing task. In their task, observers were shown a reference bar at a fixed orientation and a test bar whose orientation could be controlled remotely by the observer. By asking observers to set the test bar parallel to the reference bar, the authors found a pattern of errors consistent with the negative bias found here: when the test bar was to the right of the reference bar, observers erred in a clockwise direction and when the test bar was to the left of the reference bar, observers erred in a counterclockwise direction. In the body-pointing task, the two posts can be construed as the reference direction and the observers' task was to orient their bodies parallel to this reference. When they performed this task to the right, judgments were biased in a clockwise direction, and when they performed the task to the left, judgments were biased counterclockwise. The body-pointing data, it seems, reflects errors both in judging exocentric direction (seen in the quasi-sinusoidal error pattern in figure 4) as well as errors in judging parallelism (seen in the constant negative bias in figure 4). The body-pointing bias should not be considered as a bias in the perception of the stimulus direction, but rather a bias in producing a parallel response. If observers were asked to face in a direction perpendicular to the stimulus, this bias ought to disappear, since there is no longer any directionality implied in the stimulus.

The similarity of the error patterns found with exocentric pointing in other studies (eg Cuijpers et al 2000a) and the collinearity and body-pointing responses presented here suggest that all three of these response types are tapping the same underlying judgment of exocentric direction. The direct comparison of these three methods in figure 4 allows for some reflection on their respective advantages and disadvantages. A primary advantage of the stimulus design and responses used in the current experiment is their simplicity: since single points define the stimulus locations, there is no need to discuss whether physical lines are perceived as straight or curved (this is a complication when a pointing device that extends in space is used). The negative bias associated with the body-pointing response is surely a drawback, and errors associated with judgments of parallelism may have unknown effects on the highly involved perceptual and sensorimotor tasks. In cases where distance perception is linearly scaled (eg under full-cue viewing conditions) the collinearity judgment seems the most promising response method of measuring perceived exocentric direction.

Previous studies of perceived exocentric direction have focused on small-scale space, with stimuli ranging from 50 cm out to 5 m (for an exception, see Kelly et al, in press). The closest target in the present study was 5 m and the farthest was 20 m. Given the close correspondence between the current large-scale data set and the small-scale data set from the literature, it seems that this dependence of angular error on relative target distance is scale invariant. On the basis of their small-scale data set, Cuijpers et al (2000a) draw the same conclusion.

One potential difficulty with the collinearity task involves the third, more distant point that observers judged to be collinear with the first two posts: since observers did not report the perceived distance to the third point of collinearity, we cannot assume that those distances were accurately perceived. There are, however, three arguments that mitigate this concern. First, the body-pointing task required no distant third location, and the highly correlated error patterns suggest that the third point in the collinearity task had little impact. Second, consider the case where the targets are equidistant from the observer. Here, the exocentric direction of that stimulus should be accurately perceived (since any misperception of the target distance will equally affect both targets), and collinearity judgments in fact show zero mean error. This implies that observers were able to extrapolate an imaginary line across large distances and correctly identify the third collinear point. This would only be possible if perceived egocentric distances were linearly related to the physical distances. Third, Johnston et al (2003) have shown that increasing the distance between the pointer and target in an exocentric pointing task has no effect on judgment errors. These three separate lines of evidence all suggest that errors in the collinearity task are reflective of errors in perceived exocentric direction.

Given that distances were underestimated by a constant factor, indicating a linear relationship between physical and perceived distance over the range of distances studied here (for a review of recent evidence, see also Loomis and Knapp 2003), the underlying cause of errors in perceived exocentric direction remains unclear. Recent findings by Loomis et al (2002) suggest a dissociation between certain perceptual properties of object shape and perceived object location. Specifically, observers' judgments of width and depth ratios changed with monocular and binocular viewing, but their estimates of the locations of the targets specifying those intervals remained unchanged. Thus, the two processes, shape perception and distance perception, are dissociable to some extent (for further examples of perceptual dissociations in space perception, see Baird and Biersdorf 1967; and Norman et al 1996, 2000). It is possible that exocentric-direction judgments are also dissociable from distance judgments and reflect errors more akin to shape perception. Another possibility is that errors in exocentric-direction judgments are attributable not to perceptual distortions per se but to distortions in the judgment process.

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