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Visual Space Perception and Visually Directed Action

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The results of two types of experiments are reported. In 1 type, Ss matched depth intervals on the ground plane that appeared equal to frontal intervals at the same distance. The depth intervals had to be made considerably larger than the frontal intervals to appear equal in length, with this physical inequality of equal-appearing intervals increasing with egocentric distance of the intervals (4 m–12 m). In the other type of experiment, Ss viewed targets lying on the ground plane and then, with eyes closed, attempted either to walk directly to their locations or to point continuously toward them while walking along paths that passed off to the side. Performance was quite accurate in both motoric tasks, indicating that the distortion in the mapping from physical to visual space evident in the visual matching task does not manifest itself in the visually open-loop motoric tasks.

The question motivating this work is whether natural environments viewed binocularly from a stationary vantage point are perceived correctly. It might be thought that visual space perception, having been the focus of study for a number of decades, would be properly understood in functional terms if not in terms of the underlying mechanisms as well. Yet a proper understanding, even of function, remains elusive, in part, because of the diversity of theoretical approaches and empirical findings that exist without any serious attempt at integration. In this article we focus on the seemingly contradictory results of two quite different approaches to the problem, one dealing with the properties of visually perceived space and the other with visually directed action.

Veridicality of Visual Space

The more traditional approach to the study of visual space perception has been to first assume that an observer has an internal representation of surrounding physical space, referred to as *visual space* or *visually perceived space,* and then to attempt to measure properties of visual space using a variety of psychophysical procedures, with one goal being to establish how well various properties of physical space are preserved in the mapping to visual space. Almost all of this work has dealt with the visual space of an observer viewing from a more or less fixed station point. Gibson (1979) and Haber (1985) have criticized viewing from a fixed location as atypical of ordinary viewing, where the observer is free to assume different vantage points and to obtain motion parallax information while moving about. Nevertheless, there are at least two good reasons for studying fixed location viewing. First, much of one's viewing and control of motoric behavior (e.g., reaching, throwing) is in fact from a location that is fixed or nearly so. Second, there are systematic distortions of visual space accompanying such viewing that provide important clues about the visual process that ultimately must be part of the understanding of both stationary and dynamic viewing.

Most of the work dealing with viewing from a fixed location has been concerned with the perception of egocentric (absolute) distance, exocentric (relative) distance or depth, and size. Laboratory studies using controlled but impoverished stimuli have contributed much to a functional description of visual space (e.g., Baird, 1970; Foley, 1980, 1991; Gogel, 1990; McCready, 1985; Sedgwick, 1986) as well as to the understanding of some of the underlying mechanisms (binocular vision: e.g., Julesz, 1971; depth from motion parallax: e.g., Rogers & Graham, 1982); however, these laboratory studies have been criticized for being unrepresentative of viewing in natural environments, in which there is generally an abundance of visual cues (Brunswik, 1956; Gibson, 1950, 1979; Haber, 1985). Although we believe that knowledge gained from laboratory studies does generalize to natural viewing situations, we choose here to concentrate on experiments involving binocular viewing in natural multicue environments.

Even with such a narrowed focus, it is apparent that no consensus on the veridicality of visual space perception exists, for the experimental results depend strongly on both the criterion of veridicality and the psychophysical method used

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(Baird, 1970; Da Silva, 1985). One criterion for veridicality is linearity of the function relating perceived egocentric distance to physical distance. Gilinsky (1951) constructed scales of perceived egocentric distance using the method of equally appearing intervals; in this procedure, a succession of intervals, each appearing 1 ft (0.3 m) in length, was marked on a grassy field in a direction extending away from the observer. More distant physical intervals had to be made larger to appear of constant apparent length, with the result that the constructed scale of perceived egocentric distance was strongly negatively accelerated with physical distance. Gilinsky found that the data were well fit by the hyperbolic function

$$D' = A \times D/(D + A), \quad (1)$$

where D is physical distance, D' perceived distance, and A the asymptotic perceived distance, in this case averaging 28.5 m for 2 adult subjects. The corresponding best fitting power function has an exponent of 0.73 (for Gilinsky's stimulus range). Subsequent work by Harway (1963) and Kuroda (1971) replicated her basic result. However, as will be argued later, the reliance of this method of scale construction on judgments of exocentric distance casts doubt on the validity of the resulting scale.

In contrast to Gilinsky's results, the direct scaling methods of verbal report, magnitude estimation, and ratio production yield scales of perceived egocentric distance that on average approach linearity much more closely for the same range of physical distance (Da Silva, 1985; Sedgwick, 1986). The exponents of the best fitting power functions are generally greater than 0.9 and often close to 1.0 (linearity) for distances out to 50 m. However, the use of direct scaling methods to provide pure measures of perceived distance has also been questioned, because adult observers are generally cognizant of the perceptual foreshortening of far distance intervals and have been hypothesized to correct their judgments (Baird, 1970; Carlson, 1977; Gogel, 1974; Gogel & Da Silva, 1987).

If direct scaling measures of perceived distance should in fact be contaminated by cognitive correction, is there any way to obtain uncontaminated measures? One proposal has been to have subjects report on apparent distance rather than objective distance (Carlson, 1977), the thought being that subjects will refrain from correcting their judgments. However, even if the use of "apparent" instructions does diminish the degree of cognitive correction, one cannot know how pure the resulting measure is without independent evaluation or a theory of the effect of instructions (see Sedgwick, 1986). A different tack has been to obtain responses for which subjects are less likely to make corrections and to then compute measures of perceived egocentric distance from these responses by way of theory. Gogel (1982, 1990) has demonstrated that the apparent motion concomitant with head translation can be used to provide uncontaminated measures of perceived distance for relatively short physical distances but has yet to show the efficacy of the method for measuring the perceived distances of distant targets in full-cue environments. Foley (1980, 1985) has provided compelling support for his theory stating that errors in stereoscopic depth intervals for small disparities are not the consequence of the misregistration of binocular disparity but are primarily the consequence of errors in perceived egocentric distance. Thus, according to the theory, one should be able to use stereoscopic depth judgments to infer perceived egocentric distance. Up to this point, however, the efficacy of this method has also not been demonstrated for use in large-scale outdoor environments.

A second criterion for veridicality of visual space perception is the perceptual equality of equal physical intervals (Haber, 1985; Wagner, 1985). In two experiments involving the estimation of visual intervals defined by targets on the ground plane (Toye, 1986; Wagner 1985), intervals lying in depth were consistently reported as shorter than equal frontal intervals. In particular, Wagner (1985) observed a systematic perceptual foreshortening that increased as the judged intervals approached the observer's sagittal plane, with frontal intervals appearing roughly twice the length of sagittal intervals. This is clear and direct evidence of nonveridicality of visual perception in natural environments having an abundance of visual cues.

Visually Directed Action

Quite a different approach to the problem of visual space perception is to focus on visually guided action, such as reaching, throwing, and locomotion, the goal being to determine which aspects of visual stimulation control the action and the process by which they do so. Some advocates of this approach (Gibson, 1958; Lee, 1980; Turvey & Remez, 1979; Warren, 1988) have eschewed the notion of an internal perceptual representation as a necessary construct in any explanation of visually controlled action and prefer instead to look for optical variables in the static or dynamic optic array that might be tightly linked to aspects of the controlled action. For example, theoretical studies (Lee, 1976, 1980; Lee, Lishman, & Thomson, 1982) have shown how the locomotor flow line in the optic flow field and the optical invariant specifying time to contact could be used to control steering and approach to a surface, respectively. Given the effectiveness of visually controlled behavior in such organisms as birds and insects (Gibson, 1958; Lee, 1980; Turvey & Remez, 1979; Warren, 1988), there is good reason to question the need for visually perceived space as an explanatory construct of the locomotory behavior of such species. However, in the human and other higher organisms for which the concept of visual space has greater cogency, it remains to be seen under what conditions the nonveridical aspects of visual space manifest themselves in visually guided behavior.

Of particular relevance here is that subset of visually guided behaviors that are initiated with visual input but, once under way, are performed without further visual input specifying the goal state. These are referred to as *visually directed actions* and are to be distinguished from visually guided actions that are carried out under continuous control of visual information (Foley & Held, 1972). The important question here is whether such behaviors exhibit the errors that might be expected should they be under the control of the observer's visually perceived space. Certainly it is the case that when the stimulus situation is highly impoverished, errors in visually directed action must reflect errors in perception. Foley (1980, 1985; Foley & Held, 1972), for example, has shown that subjects attempting to position the unseen hand beneath a binocularly viewed point of light make systematic distance errors consistent with errors of perceived distance as determined by other methods. Of greater interest to us here is whether visually directed action, such as walking, exhibits any error that can be traced to the nonveridicality of visual space that is known to occur for even full-cue environments (e.g., Wagner, 1985).

Consider the common experience of viewing the layout of a room, extinguishing the lights, and then walking without vision to a location across the room. Performing such visually directed walking well is something one takes for granted, even when it involves negotiating obstacles, but there is much import in performing such tasks for the understanding of visual space perception (Loomis, 1973; Thomson, 1980). Thomson (1980) and Laurent and Cavallo (1985) have shown that subjects can walk blindly to previewed targets around obstacles with quite high accuracy. In a more systematic investigation, Thomson (1983) had subjects walk without vision to targets placed on the ground at distances ranging from 3 m to 21 m following a period of preview with binocular vision from a fixed origin. He reported virtually zero mean signed error for each distance, indicating very high mean accuracy (and thus linearity) in the response. This is surprising in light of the findings discussed above indicating some systematic departures from veridicality in the visual perception of spatial layout. However, Thomson's primary concern was more with the precision of the response, as given by the average variable error. He reported that variable error remained small and constant for walking responses completed in less than 8 s but increased precipitously to large and constant values for responses taking longer than 8 s; he interpreted these precision results in terms of some memorial representation of space that endured with high fidelity for 8 s. Unfortunately, none of the studies that have conducted the same or a similar experiment have replicated this aspect of his data (Corlett, Patla, & Williams, 1985; Elliott, 1986, 1987; Rieser, Ashmead, Talor, & Youngquist, 1990; Steenhuis & Goodale, 1988); instead they have found that precision of the response decreases monotonically with target distance and is more or less independent of the time to complete the response. Because our concern here is with the mean accuracy and linearity of the response, as indicated by the mean walked distance to each target, the question arises whether these aspects of his data are replicable. The linearity is strongly confirmed by the exponents for the best fitting power functions for five walking experiments (Elliott, 1986, Exp. 1: 1.05; Elliott, 1986, Exp. 2: 1.11; Elliott, 1987: 1.02; Rieser et al., 1990: 0.98; Steenhuis & Goodale, 1988: 0.98), with a mean exponent of 1.02. The linearity is clearly apparent in Figure 1, which plots the results of the five published studies (note the vertical displacement of some data sets for clarity); however, the mean accuracy falls short of what Thomson reported in most of these experiments. Nonetheless, the accuracy observed is remarkable inasmuch as walking to a target more than 8 m away with the eyes closed is probably not something that any of the subjects had performed prior to the experiment.

When considering the results of the visual perception and visually guided tasks at the same time, one is struck by the apparent inconsistency. Whereas the evidence from visual psychophysics suggests some distortion of visual space in natural rich-cue environments, especially in connection with the comparison of depth and frontal intervals, the results of visually directed walking indicate no systematic errors in localization. Although it may be tempting to dismiss one or the other class of results as irrelevant to one's purpose, an encompassing theory of human spatial perception and action must reconcile the two.

We report the results of three experiments involving judgments of visual space and visually directed action. As will become evident, they do not lead to definitive conclusions about the veridicality of visual space perception and its connection with action, but they do suggest some possible ways of reconciling the seemingly conflicting results. The purpose in juxtaposing these different results is to illuminate the scope of the larger problem and thus point to the need for a broader synthesis.

Experiment 1

There were two tasks in Experiment 1. The first involved blind walking to single targets following a period of visual preview; targets were positioned on the ground surface at various distances from the observer. The second task involved the subject's adjusting the length of a frontal interval defined by two markers on the ground surface so as to appear equal in length to a second fixed interval lying in depth and perpendicular to the first. The first task is essentially that used by Thomson (1983), whereas, the second bears some similarity to the direct scaling task employed by Wagner (1985) and Toye (1986) to investigate the visual perception of spatial layout.

Method

Experimental Setting

The experiment was conducted at one end of an open field of dimensions 300 m × 30 m that has been used in numerous previous studies by José A. Da Silva (e.g., Da Silva, 1985). A rectangular grid was laid out using nails visible only to the experimenter and his assistants. As shown in Figure 2, there were three parallel lines extending in distance from the line at the origin and cross lines at the five egocentric distances used in the experiment (4, 6, 8, 10, and 12 m). For the walking task, a target could be positioned at any of the 10 positions indicated by the open circles in Figure 2; at each egocentric distance two target locations were used—1 m to the left of midline and 1 m to the right of midline. For the interval matching task, the fixed interval was defined by targets placed symmetrically about the midline along one of the cross lines; the two targets adjusted by the subject defined an interval along the midline that the subject judged to be objectively equal to the frontal interval. The walking task was conducted prior to the matching task, but they are presented in reverse order in what follows.

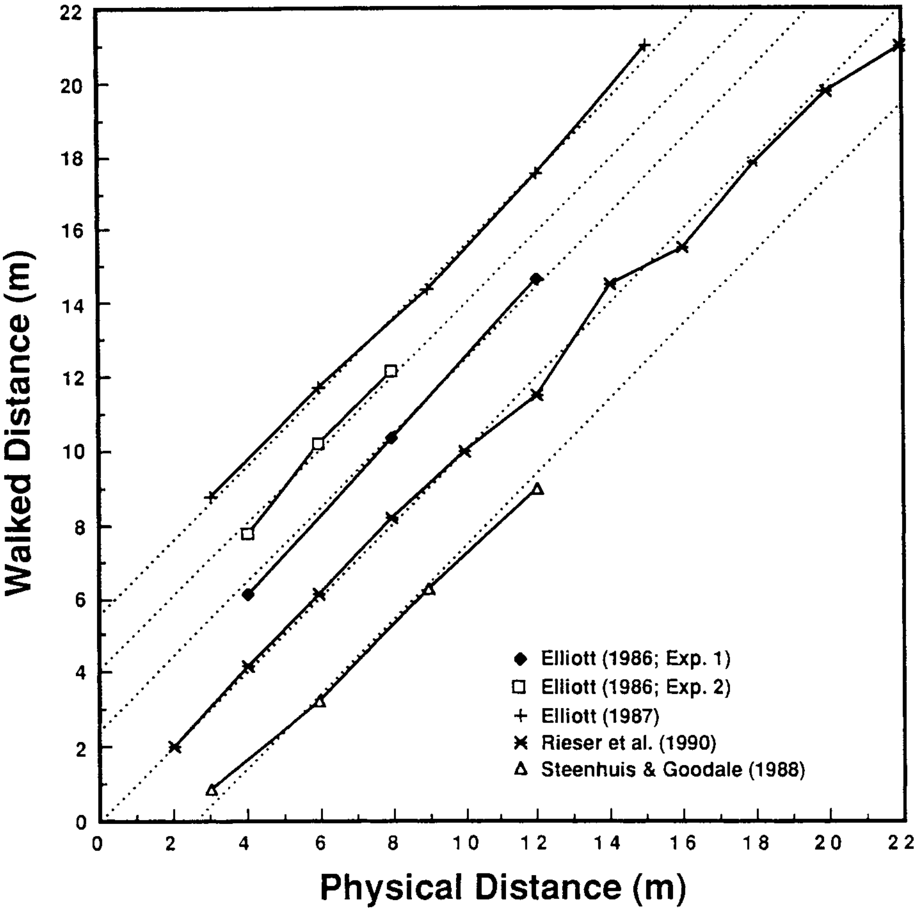

Figure 1. Summary of five experiments on visually directed walking. (Mean walked distance is plotted against target distance. For purposes of clarity, the data for four of the five experiments have been displaced vertically. In each case, the dotted line shows what perfectly accurate responding would have been.)

Apparatus

The targets were white steel rods, 16 cm high and 1 cm in diameter. They were sharpened to a point at one end and were attached to two strings, each measuring 150 cm, at the other. On some occasions the targets were suspended vertically just above the ground by two assistants standing well to both sides; on other occasions, the targets were fixed in position by sticking them into the ground.

Subjects

Ten men ranging in age from 20 to 33 years participated voluntarily as unpaid observers. They were students at the University of São Paulo at Ribeirão Preto and were screened for visual acuity of at least 20/20 with or without correction. The other criterion for inclusion was that the subject be an active nonprofessional player of soccer, volleyball, or basketball. None had participated in experiments like this before.

Procedure

Matching task. In this task two targets were stuck into the ground, thus defining a frontal interval at one of the cross lines 4, 6, 8, 10, or 12 m from the origin. The two targets created an interval of 1.0, 1.5, or 2.0 m symmetrically positioned about the central axis of the grid. The subject faced away during placement of the fixed targets.

With the fixed targets in place, the subject turned to view them binocularly. The subject's task was to construct an interval in the sagittal plane at ground level (referred to as a *depth interval*) that he thought to be equal in length to the frontal interval, under objective rather than apparent instructions (Carlson, 1977). He accomplished this by giving commands to the two assistants, who could move either of the targets along the central axis of the grid. Following the subject's instructions, the assistants eventually placed the two targets so as to define an interval that the subject judged objectively equal to and symmetrically positioned about the frontal interval. Two adjustments were made at each combination of egocentric distance and interval length. The first of these used an ascending method of adjustment in which the two targets both started out at the line used to define the frontal interval and were gradually increased in separation about this line. During the second of the two adjustments, appearing later in the random sequence of all trials, the two targets started from positions more extreme than the terminal positions of the first adjustment and were moved closer, at least initially. During both adjustments, the assistants moved first one target and then the other to positions indicated by the subject. They would then stick the targets into the ground and stand away to allow the subject to see the targets in isolation. The subject could then ask for readjustment if desired. After the subject was satisfied with his response, the experimenter measured

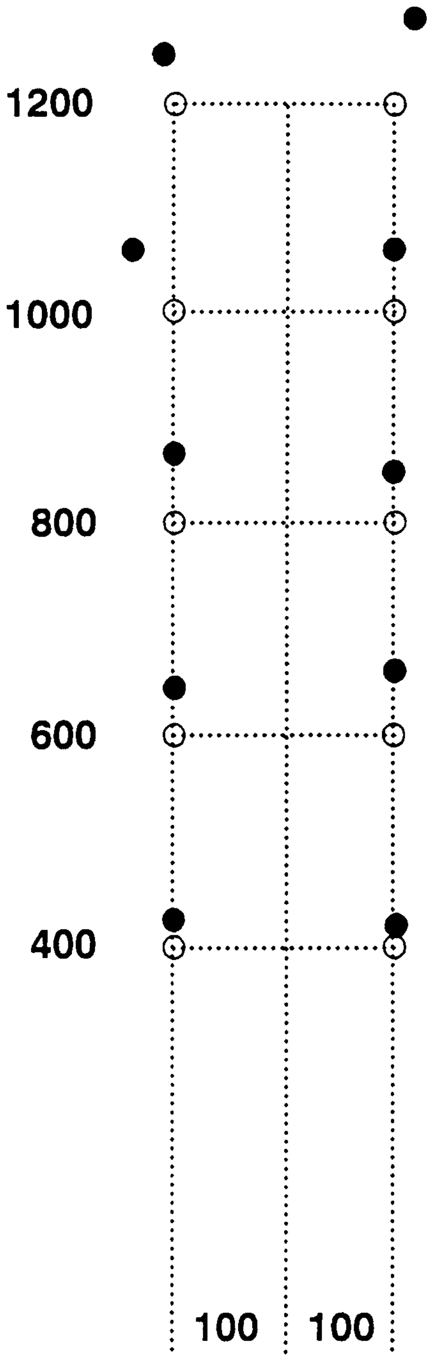

Figure 2. Arrangement of the 10 target locations relative to the origin of locomotion. (Each target location is indicated by an open circle. The values at the left represent distances of the cross lines from the origin in cm; those at the bottom represent distances of the targets from midline. Each solid circle is the centroid of all responses, averaged over subjects and trials, to the corresponding target.)

the length of the constructed interval. The entire task, consisting of two matches at each of the 15 combinations of 5 distances and 3 intervals, took about 2 hr.

Walking task. Prior to the main walking task, the subject received practice with blind walking to develop some facility and confidence. To the side of the rectangular grid of targets, the subject was shown a target at a distance of 7 m directly in front; it was stuck into the ground with an assistant holding the two strings from a position off to one side. The subject viewed the target binocularly with fixed head position and, when ready, walked with closed eyes to where he thought the target was. During the traverse, the assistant silently pulled the target from the ground and moved quietly away from the target location. Upon completing the response, the subject kept his eyes closed and was led back to the origin. Each subject received four or five practice trials at this one distance. During the practice trials, the subject received feedback about walking speed to encourage him to walk quickly and confidently but none about position error.

Upon completing the practice trials, the subject walked with open eyes to the origin of the rectangular grid. The subject faced in the opposite direction while the two assistants positioned the target at one of the 10 locations indicated in Figure 2. When the target was in place, he turned around and viewed the target binocularly. Trials were conducted precisely as in the practice period except for the randomized placement of the target. Following each response, an assistant marked the location midway between the two feet positioned side by side. The subject's response was recorded in terms of the coordinates of the terminal point within the rectangular grid; from these could be computed both walked distance, the Euclidean distance between the origin and the terminal point, and response direction, the angular direction from the origin to the terminal point. Each of the 10 target locations was tested twice, with complete randomization of all 20 trials. The subject received no feedback during the entire task, which lasted about 45 min. Recall that the walking task was done prior to the matching task.

Results

Matching Task

Figure 3a gives the results of the interval matching task. The abscissa is the egocentric distance of the frontal interval (measured from the origin at ground level). The ordinate is the ratio of the sagittal (depth) and frontal (width) intervals judged by the subjects to be equal. The three curves represent the three lengths of the standard frontal interval. The ratios are all well above 1.0, indicating that the depth intervals had to be made much larger in order to be judged equal to the width intervals, even under "objective" instructions. A three-way repeated-measures analysis of variance (ANOVA) (5 distances × 3 intervals × 2 adjustments) carried out on the ratios indicated a significant effect of egocentric distance, $F(4, 36) = 18.88$, $p < .001$; a significant effect of interval, $F(2, 18) = 16.36$, $p < .001$; and a significant effect of adjustment, $F(1, 9) = 10.74$, $p < .009$, the latter reflecting the slightly higher mean ratio obtained with the descending adjustment than with the ascending adjustment (1.61 vs. 1.58). What appears to be a Distance × Interval interaction in Figure 3a failed to reach significance because of large intersubject differences; furthermore, none of the other interactions attained significance either.

Walking Task

For each trial in the walking task, the subject's walked distance was taken as the distance between the origin and the

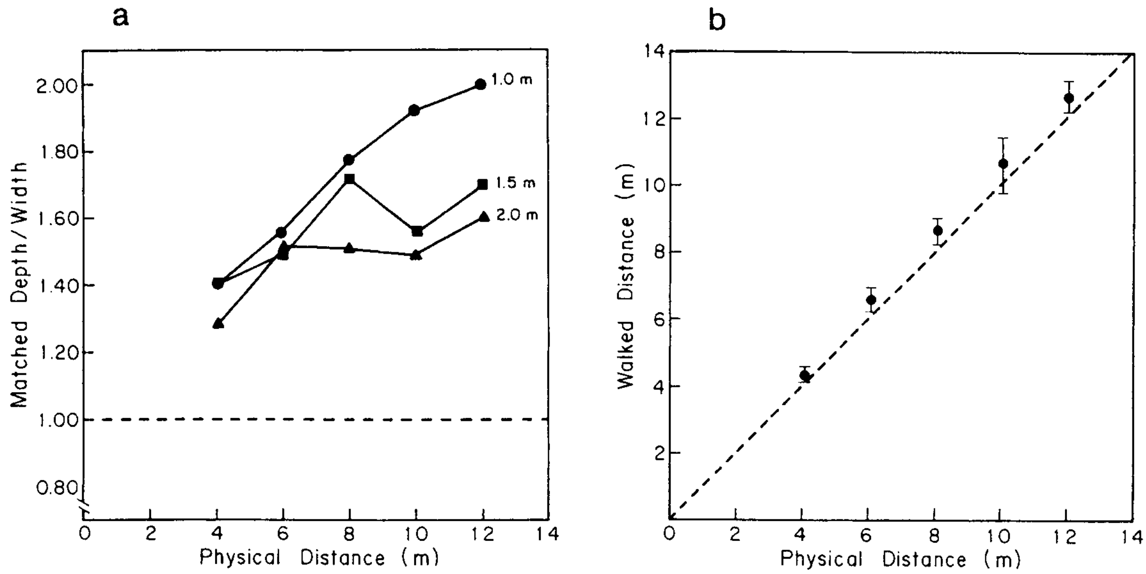

Figure 3. Results of the interval matching task (Panel a) and the visually directed walking task (Panel b) in Experiment 1. (Panel a: The length of the matching depth interval divided by the length of the standard frontal interval is plotted against the egocentric distance of the frontal interval. The parameter gives the length of the standard width interval. The dashed line represents the expected results if there were no error in matching depth to width intervals. Panel b: The mean walking response, averaged over subjects and the four trials to that distance, is plotted against target distance. The error bars represent standard deviations of the four responses to each target distance, averaged over the 10 subjects.)

terminal point, thus ignoring any curvature in the walked path. Distance error was then defined as the difference between walked distance and target distance (the straight line path between origin and target); note that distance error could be zero despite a nonzero angular error. The mean signed distance error for all subjects and targets was 55 cm, indicating an overshoot on average; the mean absolute distance error was 92 cm. The best subject showed a mean overshoot of 20 cm and a mean absolute error of 40 cm, whereas, the worst showed a mean overshoot of 189 cm with an equivalent mean absolute error. The centroid of all responses to each target is depicted by the corresponding solid circle in Figure 2.

The angular error of the response was defined as the difference between the target direction (from the origin) and the response direction. The mean signed angular error was 0.2° for all subjects and targets; the mean absolute angular error was 1.9°. As is evident in Figure 2, there was little evidence of systematic directional error over the group of subjects.

Figure 3b plots the mean walked distance against target distance and indicates virtually perfect linearity of the walking response, thus adding to the evidence provided in Figure 1 and confirming the original result obtained by Thomson (1983). The error bars indicate the average subject's precision in performing the task at each distance. For each subject, the standard deviation of the four walked distances to each target distance was computed, and these values were then averaged across the 10 subjects to give the mean within-subject variability for each distance. The error bars clearly show a monotonic increase in response variability until the last distance, at which the variability drops. These variability data are generally in accord with the results of those other studies (Elliott, 1986, 1987; Rieser et al., 1990; Steenhuis & Goodale, 1988) reporting a monotonic increase in response variability with distance, in contrast with the results reported by Thomson (1983), wherein response variability was small and constant for targets between 3 m and 9 m (at normal walking speeds) and much larger for targets more distant.

Discussion

The results of the walking task, in agreement with previous studies (Elliott, 1986, 1987; Rieser et al., 1990; Steenhuis & Goodale, 1988; Thomson, 1983), show that visually directed walking is almost perfectly linear in distance, there being no indication whatsoever that incrementing target distance from 10 m to 12 m produces any less of an increment in walked distance than incrementing target distance from 4 m to 6 m. Moreover, in view of the fact that the average terminal position was close to the target in both direction and distance, one can conclude that subjects are able to locomote blindly to any previously seen target within 12 m without much systematic error.

Under virtually identical viewing conditions, the interval matching task shows that, even with "objective" instructions, subjects do not judge equal frontal and sagittal intervals to be equivalent. This perceptual inequality of frontal and sagittal intervals, also observed by Wagner (1985) and Toye (1986) using direct scaling methods, indicates an anisotropy in the mapping from physical to visual space. The increasing depth-to-width ratio (Figure 3a), especially for the 1.0 m standard, indicates that this perceptual anisotropy increases with egocentric distance, as might be expected if depth intervals are increasingly perceptually foreshortened with distance (Baird, 1970).

We mention here that we have also informally demonstrated the two tasks to many of our colleagues using cardboard targets placed on the ground. Whereas they can generally walk blindly to any target with good accuracy, albeit with some variability from trial to trial, they consistently adjust the depth interval to be between 1.5 and 2 times the width interval and express considerable surprise when seeing the degree of their error. Given the robustness of these two results, it is most unlikely that they are artifacts of the particular manner in which the experiment was conducted.

In considering the results of the two tasks together, one is struck by the apparent inconsistency, for subjects exhibit systematic errors in perceiving visual space yet are able to walk blindly to any previously seen target with very little systematic error. Some possible ways of reconciling these seemingly conflicting results will be considered later.

Experiment 2

Because the matching task of Experiment 1 required the subject to respond to exocentric intervals while the walking task involved responding to an absolute position in space, Experiment 2 was conducted with tasks considered more comparable. The interval matching task was the same as before, but the walking task required the subject to walk to two targets in quick succession, with the two targets defining either a frontal or a sagittal interval. With this procedure, the subject created intervals in the two directions that allow an assessment of the isotropy of visually directed walking.

Method

Experimental Setting

The experiment was conducted in the same section of the field as before, and the interval matching task was conducted in identical fashion. For the walking task, the field was laid out with markers just visible to the experimenters, as shown in Figure 4a. The open symbols represent the locations of the white cylindrical target toward which the subject first traveled; these were always directly in front of the subject at 4, 6, 8, 10, or 12 m from the origin. The second target could then be positioned 1.0, 1.5, or 2.0 m from the first, being either more distant along the central axis of the grid or off to the right or left on a line perpendicular to the central axis.

Subjects

As before, the 10 subjects were male students at the University of São Paulo at Ribeirão Preto and ranged in age from 18 to 33 years.

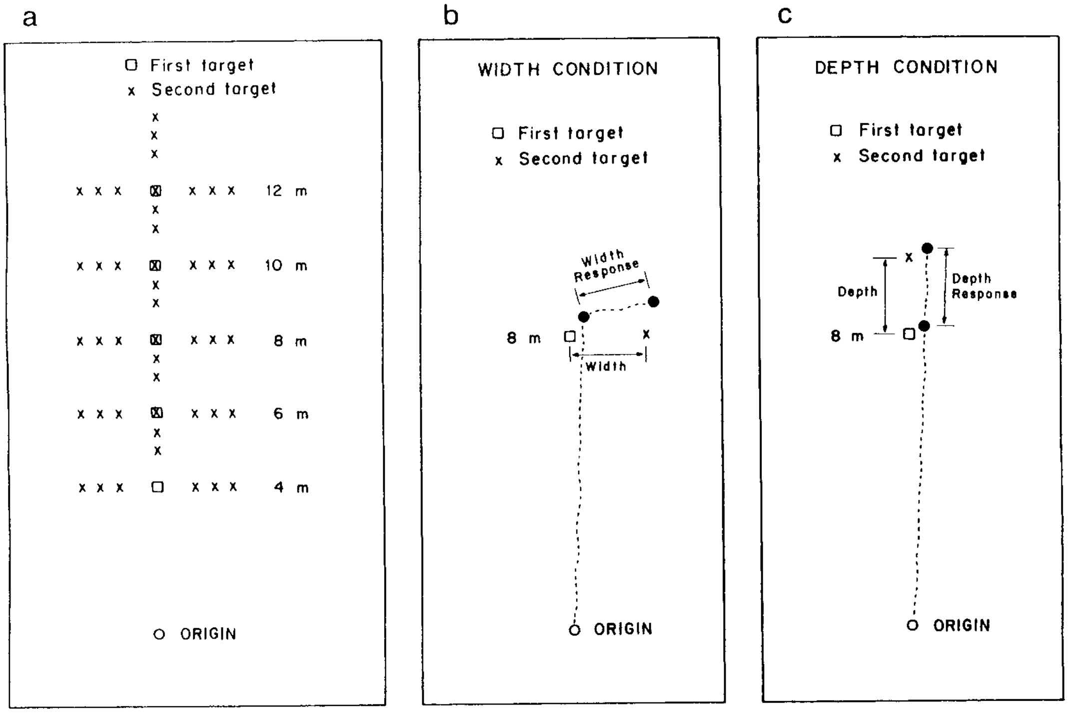

Figure 4. Depiction of stimulus layout and some representative responses in Experiment 2. (Panel a: The arrangement of locations for the first and second target in the walking task of Experiment 2. The first target was always directly in front of the origin of locomotion. In the depth condition, the second target was always in the same direction and beyond the first. In the width condition, the second target was to either the right or left of the first. Panel b: Schematic representation of a response in the width condition and how the response interval was measured. Panel c: Schematic representation of a response in the depth condition and how the response interval was measured.)

All satisfied the visual acuity and athletic skill criteria used previously and participated voluntarily without pay. None had participated in experiments of this type before.

Procedure

The interval matching task was unchanged. In the walking task, two targets were fixed in the ground to define a frontal interval or depth interval of 1.0, 1.5, or 2.0 m; the frontal interval and the first target of the sagittal interval were located at 4, 6, 8, 10, or 12 m from the origin. For each target, an assistant stood to one side holding the strings attached to the target so that when the subject began walking, the targets could be removed. The subject was instructed to view the two targets binocularly and, when ready, to walk toward the first. Upon placing the left or right foot at its judged position, the subject said "here" and then continued without stopping to the judged position of the second target, whereupon he stopped. The assistants marked the center of the first footstep and central location between the two feet at the terminal point. The subject was led back to the origin with eyes closed, and measurements were made of the locations of the two responses with respect to the rectangular grid; Figures 4b and 4c depict typical responses for the frontal (width) and sagittal (depth) conditions. As before, subjects received no feedback about their performance. In the depth condition two trials were run for each pair of targets (3 intervals × 5 distances), giving a total of 30 trials. In the width condition, one trial was run for each pair of targets involving a left turn (3 intervals × 5 distances) and one for each pair involving a right turn, giving a total of 30 trials. The depth trials were run first, then the width trials, and then the interval matching task, each segment taking about 2 hr. Within each segment, stimulus trials were completely randomized.

As in Experiment 1, subjects received practice in the walking task to build confidence. First they were given about five practice trials walking to one target at 7 m. Then they were given about five practice trials walking to targets lying in depth, the first at 7 m and the second at 8.2 m. Prior to the width trials, they then received five more trials involving two targets defining a frontal interval at 7 m. Subjects did not receive information about the accuracy of their responses but were told to walk more quickly and confidently if they appeared hesitant while walking. Practice trials were conducted off to one side of the area used for the experiment proper.

Results

Matching Task

Figure 5a gives the results of the matching task. As before, the abscissa is the egocentric distance of the frontal interval and the ordinate is the ratio of the lengths of the constructed sagittal interval and the standard frontal interval. The results are very much like those in Figure 3a, except that the increase in ratio with egocentric distance is more apparent for all three intervals than before. A three-way repeated-measures ANOVA (5 distances × 3 intervals × 2 adjustments) showed a significant effect of egocentric distance, $F(4, 36) = 8.43, p < .001$; a significant effect of interval, $F(2, 18) = 29.37, p < .001$; and a significant Distance × Interval × Adjustment interaction, $F(8, 72) = 2.09, p = .047$.

Walking Task

The accuracy of the walking response to the first target, averaged over all subjects and conditions, was even better than in Experiment 1. In the width condition, the mean

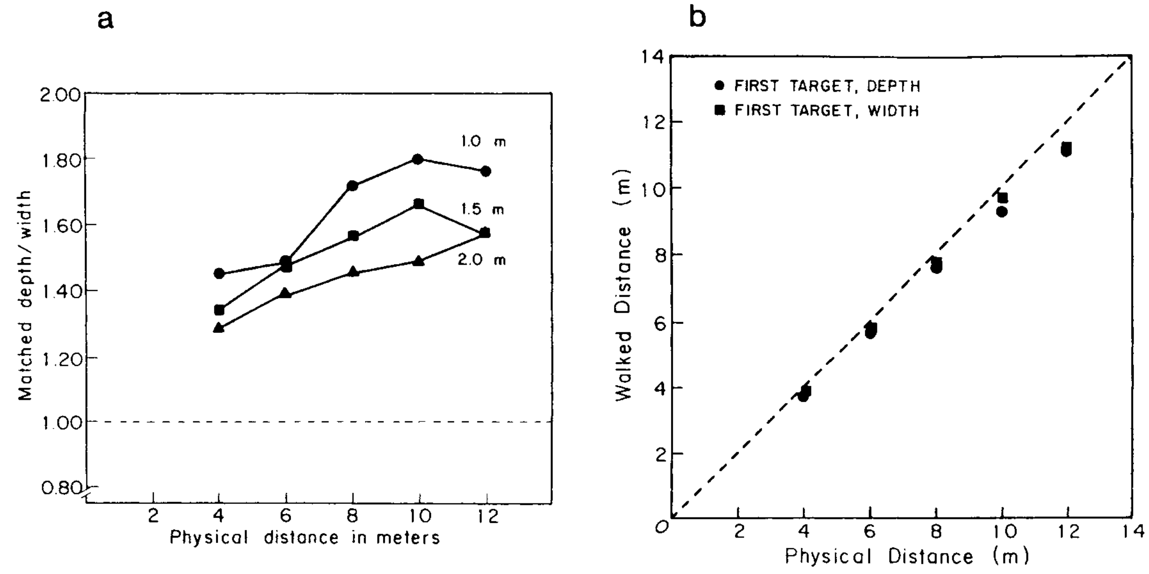

Figure 5. Results of the interval matching task (Panel a) and partial results of the visually directed walking task (Panel b) in Experiment 2. (Panel a: The length of the matching depth interval divided by the length of the standard frontal interval is plotted against the egocentric distance of the frontal interval. The parameter gives the length of the standard width interval. The dashed line represents the expected results if there were no error in matching depth to width intervals. Panel b: The mean walking response to the first target in both the width and depth conditions, averaged over subjects and the two trials to that target, is plotted against target distance.)

signed error was −27 cm (undershoot) and the mean absolute error was 57 cm; in the depth condition, the mean signed error was −50 cm (undershoot) and the mean absolute error was 74 cm. Figure 5b gives the mean walked distances to the first target in the two conditions. The corresponding power function exponents were .98 and .96, indicating near-linearity of the responses.

Of greater interest here are the lengths of the intervals between the positions marked by the subjects in both the frontal and sagittal interval conditions. Each response interval was calculated as the direct distance between the footstep marking the response to the first target and that marking the response to the second position (the terminal position). Figures 6a and 6b give the mean width and depth responses, respectively, to each of the three intervals for each of the five egocentric distances. One obvious result is that the mean intervals were on the average about 50 cm larger than the corresponding physical intervals, indicating some inaccuracy in the walking response. We have no explanation for this systematic overestimation of the intervals. More important, though, is the relative constancy of the response intervals across conditions. Figure 7 gives the ratio of the width response divided by the corresponding depth response. If the anisotropy of visual space perception and its increase with egocentric distance, manifest in Figures 3a and 5a, were reflected in the walking responses, one would expect the ratio to be greater than 1 and to increase with distance. It is obvious in Figure 7 that despite the perceptual foreshortening of depth intervals relative to width intervals and the increasing foreshortening with distance, walking to two targets does not manifest this anisotropy, although there is some anisotropy in the reverse direction for the smallest interval size.

Discussion

Whereas our subjects consistently perceived depth intervals to be smaller than physically equal width intervals on the ground plane, confirming the results of Wagner (1985) and Toye (1986), they showed absolutely no tendency to indicate smaller depth intervals than width intervals with visually directed walking. Admittedly, blind walking to one target and then another following visual preview need not be an exocentric response, for the subject might simply guide his locomotion to each absolute position in succession. Thus, one can correctly argue that this experiment, like the first, is comparing responses that may not be strictly comparable inasmuch as the matching task involves the perception of exocentric intervals whereas walking to two targets might involve responding to two absolute locations. Nonetheless, it is interesting that walking to two targets is as accurate as it is, given the nonveridicality of visual space perception, both in terms of its anisotropy and the increase in anisotropy with egocentric distance.

How might we reconcile the accurate walking in Experiments 1 and 2 with the apparent distortion of visual space? The following hypotheses represent different ways of thinking about the question.

Hypothesis 1: Accurate Egocentric Distance Perception

Under this hypothesis, subjects on average perceive egocentric distance correctly under the conditions of this experiment and use visually perceived distance to initiate open-loop walking, with the result that they are able to walk without systematic error to the location of one or more targets within the range of distances studied. If this hypothesis should be correct, the optical information most likely affording correct perception of distance in our stationary viewing situation is that provided by angular elevation (height in the visual field), texture gradient, binocular parallax, and binocular disparity (see Foley, 1980, 1991; Gibson, 1950; Purdy, 1960; Sedgwick, 1986; Warren & Whang, 1987). However, given the obvious physical inequality of equal-appearing spatial intervals demonstrated in the matching task, this hypothesis would then

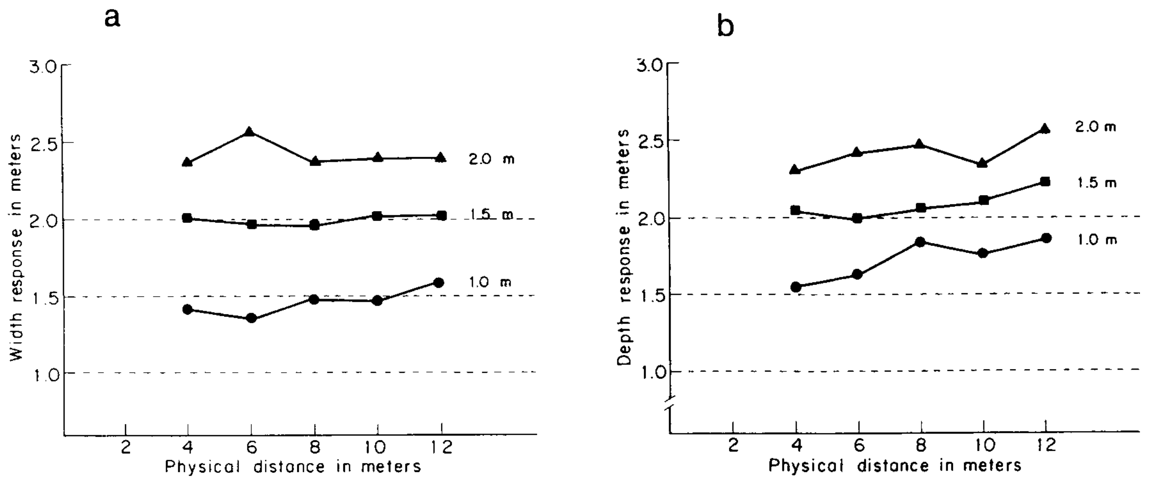

Figure 6. Average response interval in the width condition (Panel a) and in the depth condition (Panel b) as a function of the distance of the first target and the physical interval between the first and second targets. (Dashed lines represent correct responding.)

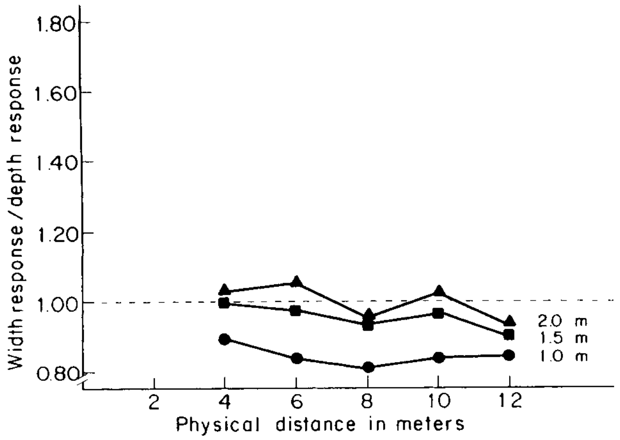

Figure 7. Ratio of the average response interval in the width condition (Figure 6a) divided by the average response interval in the depth condition (Figure 6b) as a function of the distance of the first target and the physical interval between the first and second targets. (The dashed line represents isotropic responding. If the anisotropy of visual space, indicated by the results seen in Figure 5a, were to be manifest in walking to two targets, the data here ought to lie above the dashed line.)

imply some degree of dissociation between perceived egocentric distance and perceived exocentric distance. That is, even though the observer correctly perceives the locations of two targets, this does not mean that he or she correctly perceives the distance between them.

Hypothesis 2: Correction of Misperceived Distance

As discussed earlier, there is some question as to whether direct scaling tasks (verbal report, magnitude estimation, etc.) provide pure measures of a subject's visual space, for the subject might modify his or her responses using some sort of cognitive correction (e.g., Baird, 1970; Carlson, 1977; Gogel, 1974; Gogel & Da Silva, 1987). A similar correction process can be hypothesized to underlie visually directed action. This putative correction process need not involve conscious thought but might simply reflect unconscious learning that allows the coordination of different responses. Foley (1980) has argued that no single response from a perception–action experiment can be taken as the "true" measure of perception; he has suggested instead that the goal in research on space perception is to develop a theory of perception, which, among other things, specifies the mappings between the constructs of the theory and the various response measures as well as the mappings between these measures. In this view, as long as there is a fixed mapping between physical and perceived space, however distorted, the subject can carry out visually directed action without systematic error, provided that experience has allowed a mapping between perceived space and action to develop.

Hypothesis 3: Separation of Systems

A third possibility is that the conscious perception of surrounding space and the control of motoric activity are served by partially or wholly independent processes. Whereas Hypothesis 2 asserts that conscious visual perception controls action through some fixed and possibly nonlinear mapping, the idea here is that action need not even be mediated by the same processes that underlie conscious visual perception (see Turvey, 1977). This hypothesis entails the possibility that variation in the perceived location of a target need not be accompanied by variation in open-loop action directed to that target. This very result has been demonstrated by Bridgeman and his colleagues (Bridgeman, Kirch, & Sperling, 1981; Bridgeman, Lewis, Heit, & Nagle, 1979; Stark & Bridgeman, 1983); in both eye-press and induced visual motion experiments, they have shown a degree of dissociation between the visually perceived direction of a target and the pointing direction of the hand toward that target. These results lend support to the notion of two distinct visual systems (Schneider, 1969; Trevarthen, 1968), one dealing with the focal perception of space and the other with visuomotor coordination.

Experiment 3

If subjects do indeed correctly perceive the egocentric distance of a target under the conditions of our experiments (Hypothesis 1), then one might expect them to be able to properly execute more complex visually directed tasks that demonstrate the subject's knowledge of the target's location from a variety of points in space during the traverse. An example of such a task would be blind walking to the target along curving paths, including ones that take the subject beyond the target and back. A second such task, the one used here, is continuous blind pointing toward a previously viewed target as the subject traverses a path that passes to the side of the target. The procedure we used is similar to that used by Böök and Gärling (1981) to study imaginal updating of a previously viewed target. In their study, they had subjects binocularly view a single target positioned on the ground in a completely darkened room; when the subject was ready, the target was extinguished and the subject walked along a straight path just behind a moving strip of light on the ground. At different stopping points indicated by the terminal position of the light strip, the subject then indicated verbally the distance and direction of the unseen target. Our procedure differed in that subjects had more visual information about spatial layout initially and responded by pointing continuously to the unseen target while walking without vision.

Method

Experimental Setting

The experiment was conducted within a lightproof warehouse 35 m × 20 m. Figure 8 depicts the experimental setup. A square workspace 1200 cm on a side was used. A red neon lamp was placed on the ground at the center of the workspace, and parallel straight paths, 6 m long, were marked on the ground with masking tape; they varied in the distance of nearest approach to the target, the values being 100, 200, and 400 cm. For each path two locations were used for the start of locomotion, one at one end of the path and the other

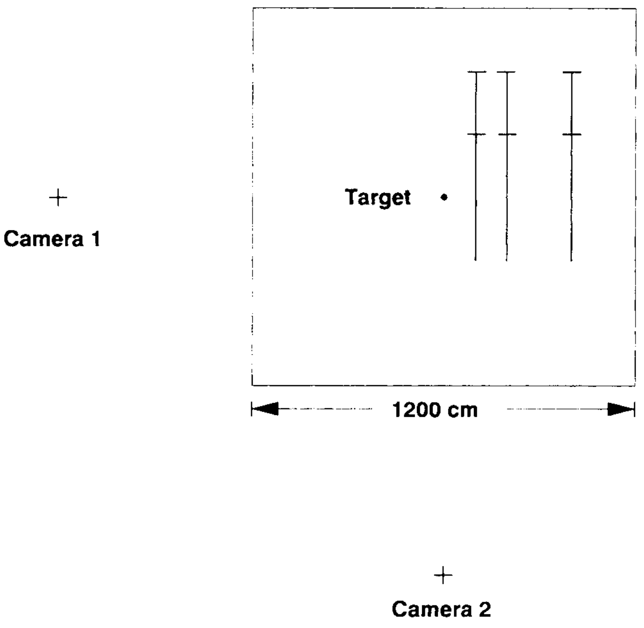

Figure 8. Experimental setup used in Experiment 3. (The 12 m × 12 m workspace is depicted by the grid. The walking paths are indicated by the heavy lines and the six starting points by the cross lines. The target light was positioned at the center of the workspace.)

200 cm from the end, giving a total of six starting locations; these are indicated by the horizontal line segments in Figure 8.

Apparatus

A computer measurement system based on signals from two video cameras was used to record the orientation of the arm as the subject pointed toward the target while walking. Two flashlight lamps were attached to the right arm of the subject, one on the lower arm and the other near the shoulder. The two lamps were driven by direct current and alternated at 4 Hz, the sampling rate at which the position of each lamp was measured.

The measurement system, as used in previous research (Klatzky et al., 1990; Loomis, Hebert, & Cicinelli, 1990), kept track of only one light; for this experiment, it was modified to permit measurement of the locations of two lights. The two cameras were positioned at right angles 6 m from the edge of the workspace as shown in Figure 8. They were mounted on tripods and rotated 90° from the normal orientation so that the video raster lines were vertical rather than horizontal. A signal from special video processing hardware provided the 12 MHz 80286 computer with the raster line corresponding to the image of whichever light was illuminated at that moment. Thus, the circuitry provided the horizontal angular direction of each light for each camera; this angular direction was unaffected by changes in the vertical position of the light within the workspace. A triangulation algorithm computed the horizontal position of each light within the workspace with an absolute accuracy on the order of 4 cm, as assessed during calibration of the system with targets at known locations. Because the lights alternated at a relatively low rate, the instantaneous projection of the arm was not given directly but was computed by calculating the midpoint of two successive pulses of one light and associating this with the intervening pulse of the other; the associated pair thus defined the orientation of the arm as projected onto the horizontal plane. Because the orientation of the arm varied with respect to the vertical, the projected length of the arm varied but the projected orientation, which was of interest, did not.

Subjects

Six subjects were run in the experiment, 5 graduate students at the University of California, Santa Barbara (ages 24–29 years), and 1 of us (Jack M. Loomis, age 43); 1 of the students (Subject 6) was female. Only Loomis had had experience with the pointing task. He and 1 other subject helped mark the floor and were thus familiar with the stimulus arrangement. The others were unfamiliar with the task and the experimental setup.

Procedure

The subject entered the warehouse at a position removed from the workspace and adapted to the reduced illumination of the warehouse; this illumination level permitted use of the measurement system while allowing the subject to see the floor texture and the three parallel paths marked on the floor with tape. After being told about the task, the subject was led with eyes closed to one of the six starting locations. There the subject binocularly viewed the neon target as well as the path to be followed. When ready to respond, the subject raised his or her right arm to point to the target. Shortly thereafter, the measurement lights began flashing and the subject then began walking with eyes closed along the path while attempting to point continuously in the direction of the target. Subjects were told to emphasize accurate pointing and not to worry about veering from the path. The target was not visible through the eyelids, for the flashing measurement lights were considerably more intense. In performing the task, subjects found it advantageous to turn their heads toward the target while walking by it, and a few subjects turned their upper torso as well. Because it was awkward for subjects to point much beyond an azimuth of about 120° (straight ahead = 0°), the termination point varied with each of the three paths; the experimenter told the subject when to stop. After completing a response, the subject was led with eyes closed to the next starting position. Three blocks of 6 trials were run; in each block, the subject was led to each of the starting positions in randomized order. During the entire testing period, lasting about 15 min, subjects kept their eyes closed except when at one of the starting positions. After completing this portion of the experiment, subjects went through an additional 18 control trials with the identical procedure, except that the subject pointed to the target with both eyes open during the traverse (vision condition).

Results

Because of an error in transferring data files, all of the data for Subject 6 and the visual trials for Subject 3 (Loomis) were lost. The analysis is thus based on all data for 4 subjects and the no-vision data for Subject 3. Because of initial pointing errors measured while the subjects pointed toward the target with eyes open at the starting positions, errors that are probably the result of imperfect placement of the lights on the arm or the subject's alignment criterion, we corrected the pointing responses in the following way. All of the initial pointing azimuths for the 18 trials of a given subject in a given condition (vision or no-vision) were compared against the correct azimuths (determined by the geometry of our experimental setup). The mean initial pointing error was then subtracted from all other arm orientations of that subject for that condition. Figure 9 depicts the corrected orientations of

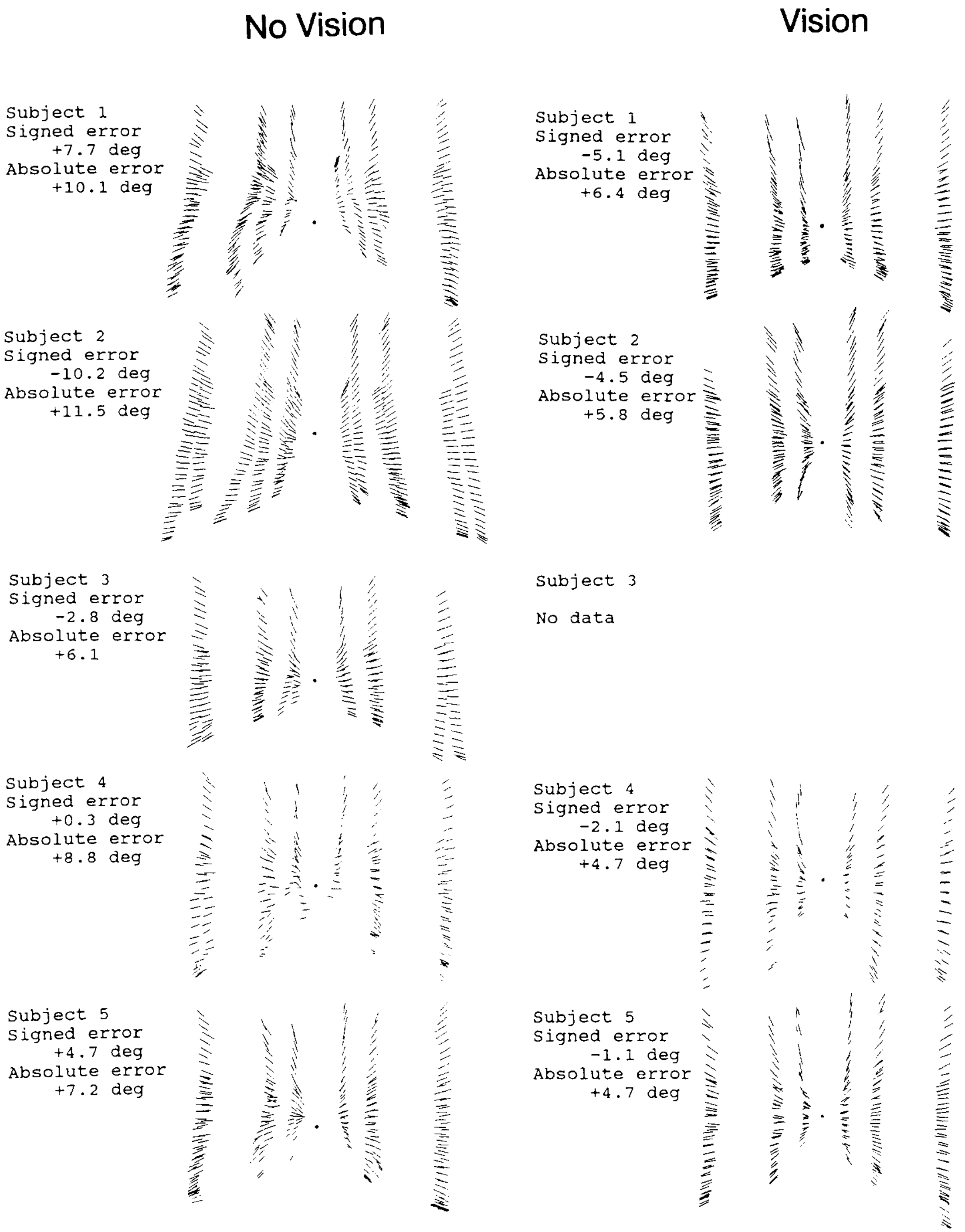

Figure 9. Some of the arm orientation data from Experiment 3. (The no-vision data are given on the left and the vision data on the right. For each subject in each condition, the corrected orientation of the right arm is shown at various positions during the subject's traverse [depicted here as from top to bottom]; the solid dot at the center of each panel depicts the target location. The trajectories for Trial 2 for each starting position are shown to the right in each panel and can be compared with the paths shown in Figure 8. The trajectories for Trial 3 have been reflected about the vertical axis in each panel for purposes of clarity. Trial 1 trajectories are not shown. The vision data for Subject 3 are missing.)

the right arm during the second and third trials for each of the six starting positions; the third trial trajectories have been reflected about the central axis of each panel for purposes of clarity. To the extent that subjects were pointing at the target correctly, all line segments should converge at the target location that is depicted as the solid dot in each panel. The degree of convergence is quite good even in the no-vision condition, despite the noticeably greater veer relative to that in the vision condition.

Figure 9 also gives the mean signed error and mean absolute error for each subject and each condition averaged over all corrected arm orientations within that condition; deviations of the subject's path from the path marked on the floor were not taken into account. Of the two measures, absolute signed error is a better measure of accuracy. It averaged 9.4° for Subjects 1, 2, 4, and 5 in the no-vision condition and 5.4° in the vision condition.

Because there is nonnegligible noise in the pointing response resulting from limitations in our relatively crude measurement procedure, we computed the mean pointing response, averaged over subjects and repetitions, for different positions along the three different paths. Because each trajectory consisted of discrete measurements, it was necessary to interpolate intermediate values in order to compute a mean response. For those trials starting at the endpoints of the three paths, pointing azimuth was computed as a function of position along the path (ignoring deviations to either side). For each trajectory, azimuths at intermediate positions were computed by linear interpolation. Figure 10 plots mean interpolated pointing azimuth in the no-vision condition as a function of path and distance from the end of the three paths (see Figure 8); each of the three solid curves was based on 15 interpolated trajectories (5 subjects × 3 repetitions). The dotted curves give the theoretically correct azimuth values.

Discussion

As seen in Figure 10, the mean pointing response in the no-vision task is quite accurate, indicating no systematic tendency to point to a position other than the target position.

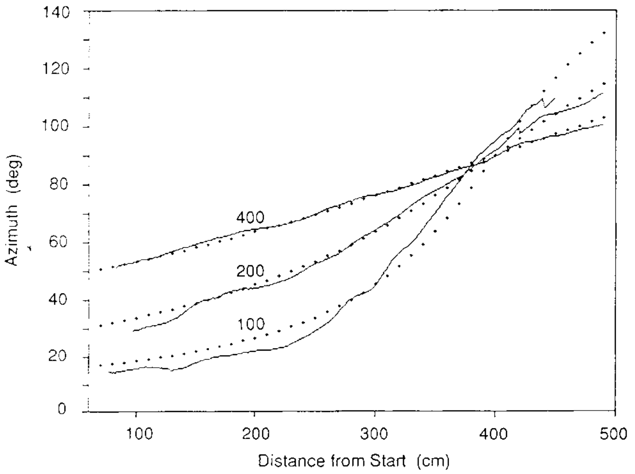

Figure 10. Mean interpolated azimuths of the arm during the traverses starting at the endpoints of the three paths shown in Figure 8. (Each solid curve is the mean of 15 interpolated curves, 3 for each of 5 subjects. The azimuths have been corrected for initial pointing error with eyes open. The parameter is the nearest approach [in cm] that each path makes to the target. The dotted lines represent the correct pointing azimuths along the three paths.

Accurate visually directed pointing, being an instance of triangulation, is consistent with Hypothesis 1, the accurate perception of egocentric distance. A more complete explanation consonant with Hypothesis 1 would postulate the following errorless stages of processing: (a) correct perception of initial target position, (b) correct perception of active self-locomotion, (c) correct imaginal updating of the egocentric location of the target during locomotion, and (d) correct pointing to the updated target location.

Though the results are readily interpretable under Hypothesis 1, they are also consistent with the two alternative hypotheses. In the case of Hypothesis 3, separation of systems, one would suppose that the subsystem controlling motoric activity correctly specifies the goal state of the visually directed action and properly executes a motor program for attaining that goal. This would constitute an explanation of the observed behavior; however, without more knowledge of the functional properties of the putative subsystem controlling action, the explanation is a rather empty one. Hypothesis 2, correction of misperceived distance, results in an explanation with a little more substance. For the sake of argument, suppose that the subject initially perceives the target half as far away as it actually is. A nearer stationary target that is half the distance of another stationary target in the same visual direction has an angular velocity twice that of the other when the observer translates (Nakayama & Loomis, 1974). Thus, in order for the subject to correctly point to the misperceived target during the traverse without vision, the subject must incorrectly represent the changing angular velocity of the target as half what it would be for a target at that distance. Thus, an explanation of the results of Experiment 3 under Hypothesis 2 requires that the subject's internal representation of the changing angular positions of targets be distorted in such as way as to allow correct pointing to the misperceived targets. This is not an unreasonable possibility if the mapping between physical and perceived distance in full-cue conditions has been sufficiently constant to allow the subject to associate the angular velocities of targets with their perceived distances. However, rather than assuming this additional distortion, we prefer to interpret correct performance in this triangulation task as signifying the subject's knowledge of the target location both during the period of visual preview and during the blind traverse. This knowledge could be in the form of correct visual perception and correct updating of the internal representation (Hypothesis 1) or error-free functioning of the putative subsystem controlling action (Hypothesis 3). We prefer the former and assume it in subsequent discussion.

With the experimental setup that we used, the range of initial target distances varied between 1.4 m and 5.7 m. Thus, assuming Hypothesis 1, the results do not speak to the accuracy of perceiving egocentric distances on the order of the larger distances studied in Experiments 1 and 2. However, work now being completed (Fukusima, Loomis, & Da Silva, 1991) suggests that egocentric distance is perceived quite accurately out to at least 15 m, as assessed by both pointing and another triangulation method based on visually directed walking. Even without these newer results, Experiment 3 is important, for it suggests that egocentric distances out to 5.7 m are perceived correctly even though the interval matching tasks of Experiments 1 and 2 show considerable error in perceiving the equality of exocentric intervals within 6 m of the observer.

In two quite similar experiments, Böök and Gärling (1981) observed subjects making large and systematic errors in judgments of direction and distance of an unseen target following blind walking past the target. Their results ostensibly conflict with our results showing accurate mean pointing. One possible reason is that their subjects perceived the targets as closer than they were, as a consequence of the reduced cue availability of the completely darkened room, as would be expected (Foley, 1980); indeed, the reported distances of the target from the starting location indicated some underestimation of its distance. Another possibility is that the procedure of having the subject follow just behind a moving light strip might have interfered with the subject's perception of self-motion and with the imaginal updating of the target location. Still another possibility is that their use of verbal responses gave results different from the motoric response used here.

General Discussion

Experiment 1 showed that subjects can walk accurately without vision to previously viewed targets, thus adding to the evidence of previous work showing that blind walking is accurate out to beyond 12 m (Elliott, 1986, 1987; Rieser et al., 1990; Steenhuis & Goodale, 1988). At the same time, the interval matching confirmed the results of Wagner (1985) and Toye (1986) showing that subjects consistently perceive sagittal intervals as much shorter than physically equal frontal intervals. Experiment 2 went a bit further and showed that subjects mark off nearly equal frontal and sagittal intervals with blind walking to the interval endpoints when the intervals are physically equal. This is a surprising result, given that the same frontal and sagittal intervals were judged as unequal from the origin of blind locomotion.

The purpose of Experiment 3 was to determine whether subjects can correctly indicate the instantaneous direction of a previously viewed target while blindly walking past the target. The evidence is that for the range of target distances studied (1.4 m–5.7 m), subjects can do so. Because visually directed pointing is a form of triangulation, the accurate performance favors Hypothesis 1, as argued in the preceding section.

If egocentric distances out to 6 m are perceived correctly, as suggested by the pointing task, then the results of the interval matching tasks of Experiment 1 and 2 are indeed puzzling, for they, along with the direct scaling results of Wagner (1985) and Toye (1986) and the equal-appearing interval results of Gilinsky (1951), suggest that physically equal intervals are often perceived as unequal, even when 4 m from the observer. As suggested earlier, one way to reconcile the two results is to assume that perceived exocentric distance is independent, to some extent, of perceived egocentric distance. This possibility is supported by the following observation. Viewing a scene alternately with one and two eyes produces obvious changes in the exocentric distance between objects lying in depth (as stereopsis is alternately brought into and out of play) but produces little change in their perceived sizes, which according to size–distance invariance (Gilinsky, 1951; McCready, 1985; Sedgwick, 1986) are a function of perceived egocentric distances. If confirmed in a formal experiment, this result would go a long way in making sense of the results of Experiment 2, for one could argue that the walking task involves responding to two egocentric positions in succession while the interval matching task involves the perceptual comparison of exocentric intervals.

Besides suggesting correct perception of the initial egocentric location of the target, the accurate blind pointing of Experiment 3 also suggests that subjects perceive their self-motion correctly and are able to imaginally update the target location correctly. A number of researchers (Attneave & Pierce, 1978; Böök & Gärling, 1981; Potegal, 1971, 1972; Rieser, 1989; Rieser et al., 1990; Thomson, 1980, 1983) have postulated the existence of and provided evidence for some nonperceptual spatial representation of nearby object locations that is updated during observer motion. Figure 10 indicates that as subjects walk blindly past a previously viewed target, the mean pointing direction nearly coincides with that of the target for all three paths (nearest approaches of 100, 200, or 400 cm). The results for the 100-cm path are especially interesting, for the angular velocity of the arm (given by the slope of the function) changes systematically during the traverse in accord with the true target azimuth. This means that subjects are not preprogramming an arm rotation of constant angular velocity, as might be argued for the path of 400 cm nearest approach. Thus, the hypothesis of imaginal updating of some internal spatial representation as postulated by those cited above is supported by the present results.

Last, the hypothesis that subjects form an internal representation on the basis of visual perception of a scene and update this representation while walking without vision makes the following prediction. If subjects perceive equal frontal and depth intervals as unequal from a distant vantage point but update the interval endpoints correctly in the internal representation during blind walking, the imagined intervals ought to be judged as more nearly equal the more closely they are approached, just as they would be if actually viewed. An experiment to test this idea is currently in progress. If supported, it would mean that, at the point of observation, subjects have implicit knowledge of interval equality that conflicts with their perceptual knowledge of interval inequality, and that mere locomotion without vision is sufficient to make this implicit knowledge explicit.

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Carr Appointed Editor of the *Journal of Experimental Psychology: Human Perception and Performance*, 1994–1999

The Publications and Communications Board of the American Psychological Association announces the appointment of Thomas H. Carr, PhD, Michigan State University, as editor of the *Journal of Experimental Psychology: Human Perception and Performance* for a 6-year term beginning in 1994. As of December 15, 1992, manuscripts should be directed to

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