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Comparison of Two Indicators of Perceived Egocentric Distance Under Full-Cue and Reduced-Cue Conditions

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It has not been established that walking without vision to previewed targets is indeed controlled by perceived distance. To this end, we compared walking and verbal report as distance indicators, looking for a tight covariation in responses that would indicate control by a common variable. Targets from 79–500 cm away were presented under dark and well-lit conditions. Both verbal reports and walking indicated overestimation of near targets and underestimation of far targets under dark viewing conditions. Moreover, the finding that verbally reported distance plotted essentially as a single-valued function of walked distance and vice versa is evidence that both indicators were responding to the same internal variable, ostensibly perceived distance. In addition, binocular parallax, absolute motion parallax, and angular elevation were evaluated as distance cues, and only angular elevation exerted a large influence on perceived distance.

When people are asked to view an object in a well-lit environment and then attempt to walk over to it with eyes closed, they do so, on average, without large systematic error. This finding has been documented by several researchers (Corlett, Patla, & Williams, 1985; Elliott, 1986, 1987; Loomis, Da Silva, Fujita, & Fukusima, 1992; Rieser, Ashmead, Talor, & Youngquist, 1990; Steenhuis & Goodale, 1988; Thomson, 1980, 1983) and is easy to demonstrate informally. This task is representative of a class of spatial behaviors that has been variously referred to as "locomotor pointing" (Laurent & Cavallo, 1985), "visually directed action" (Foley & Held, 1972; Loomis et al., 1992), and "open-loop action" (Philbeck & Loomis, 1993); the latter term reflects the fact that one does not receive visual feedback about positional error after initially seeing the object. In simple closed-loop spatial behavior, the behavior is begun and carried out under the intermittent or continuous control of vision and other sensory inputs. Thus, information about positional error "loops back" and becomes an input to the mechanism that plans and executes the motoric behavior and consequently may act to modify or correct the motoric response as it is carried out. Without such feedback, this loop remains incompleted, or "open," and under these circumstances the response is arguably more reflective of the initial visual input (assuming that other sensory inputs specifying the goal state are unavailable).

A primary goal of this research was to investigate the factors that might support the highly accurate performance observed in open-loop walking to targets seen in well-lit conditions. As we discuss, one issue that must be confronted when one uses any direct response to distance is how best to separate the perceived distance signal from transformations of that signal by subsequent processing. Although it is likely that the perceived distance signal is transformed to some extent both before and during the planning and execution stages of the walk, there are reasons to suspect that these transformations may be minimal. If so, open-loop walking would be an accurate indication of the controlling signal (perceived distance) on which the motoric behavior (walking) is planned and executed. Open-loop walking does have a certain degree of face validity. First, it exploits the natural connection between perception and action. From an ecological perspective, perceived distance acquires meaning solely in terms of the body-scaled spatial actions that it controls (Lee, 1980; Warren, 1988). Second, other open-loop actions, such as continuous blind pointing while walking past a previewed target, provide evidence of the target's perceived location consistent with that indicated by open-loop walking (Fukusima, Loomis, & Da Silva, 1997; Loomis et al., 1992). Finally, the introspective experience that one is approaching a previously viewed target with eyes closed is compelling, at least in the introspective reports communicated to us by our observers.

However, if it is true that people walk to where they actually see a target when they use the open-loop walking response, the accurate performance would seem inconsistent with the conclusions of several previous studies indicating that the further reaches of perceptual space are increasingly foreshortened with increasing physical distance, even in well-lit outdoor viewing (Baird, 1970; Da Silva,

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1985; Gilinsky, 1951; Harway, 1963; Toye, 1986; Wagner, 1985). One possible explanation is that the accurate open-loop walking performance seen in full-cue conditions reflects the influence of some internal variable other than perceived distance (which is assumed to be in error). For instance, accurate performance could be accomplished by knowledge, implicit or explicit, of the usual number of paces or units of walking time it takes to reach objects resting on the ground at the observed angular elevation. (Angular elevation is more generally referred to as "height in the visual field" or just "height in the field"; Cutting & Vishton, 1995; Epstein, 1966; Sedgwick, 1986.) Thus, even if angular elevation does not determine perceived distance, it may act through some other internal variable to regulate accurate open-loop walking. It is not known to what extent angular elevation influences distance responses through perceived distance. At the neuroanatomical level, there is evidence of some degree of dissociation of the motor control system from that which determines conscious perception (e.g., Goodale & Milner, 1992). Although perception and motor control may be processed to some degree in parallel and make use of distinct spatial representations, the research we present in this article was intended to investigate the variables relevant for controlling spatially directed behaviors at a more functional level. Are the effects of such a dissociation discernible for a spatial behavior such as open-loop walking?

To investigate whether open-loop walking is influenced by some other internal variable, we obtained verbal and open-loop walking distance estimations to targets seen under a variety of viewing conditions, ranging from well-lit to dark environments. The restriction of distance cues created by presenting targets in the dark typically produces perceptual errors (e.g., Gogel, 1961; Künnapas, 1968), with the distance to targets less than about 2–3 m distant tending to be overestimated and the distance to targets beyond that tending to be underestimated. If open-loop walking is found to be subject to the typical pattern of errors, such results would argue that walking does indeed respond to perceived distance under these conditions. In our three experiments, we evaluated the relative effectiveness of angular elevation, absolute motion parallax, and binocular parallax as distance cues. In addition to these, monocular parallax was available as a cue in all conditions. *Binocular parallax* and *monocular parallax* are the terms Foley (1980) suggested using instead of *convergence* and *accommodation,* respectively, emphasizing the informational content of these cues rather than the oculomotor signals that frequently carry the information. One of the goals of this research, then, was to assess the effectiveness of several potential distance cues and in so doing add to the considerable literature (see Baird, 1970; Ittelson, 1960; Sedgwick, 1986).

The other goal, as stated earlier, was to determine whether open-loop walking, as a representative of open-loop actions, is indeed responsive to perceived distance. For this, we depend heavily on the research of Foley (1977, 1980, 1985), who developed a theory of binocular distance perception and provided considerable evidence for it. Relevant to our work is his theoretical analysis of how to test whether candidate measures of perceived distance are indeed linked to perceived distance.

Most theorists accept the notion of visual space (or visually perceived space) as an important construct in understanding spatial behavior, but the problem of how to measure perceived distance, one aspect of visual space, is a formidable one. Perceived distance, like all psychological constructs, is an internal variable that can be accessed only by way of behavior. In the context of space perception, any single behavioral measure is referred to as an indicator. Because some indicators are influenced by variables other than perceived distance (e.g., instructions to the observer; Carlson, 1977), one needs a theory connecting the two to infer perceived distance from an indicator.

Even without such a theory, tight covariation of two or more such indicators when stimulus cues to distance are varied is evidence that each of the indicators is responsive to perceived distance (Foley, 1977). One would not expect any two indicators (e.g., verbal report and open-loop walking) to yield identical values of indicated distance. This being the case, one would not wish to argue that either indicator should be taken as the true measure of perceived distance. However, if the two indicators vary essentially in one-to-one correspondence whenever stimulus cues to distance are varied, one has good reason to suppose that the variation in each indicator is linked to variation in perceived distance.

Foley (1977; Foley & Held, 1972) presented observers with single points of light in an otherwise dark room and then asked them to place the tip of the index finger on the underside of a horizontal board at a point just under the target. Using this method, Foley found that pointing with an unseen hand exhibited large, reliable errors, with overreaching being the typical error. Foley (1977) also obtained verbal reports of target distance. When he compared verbal reports with distances indicated by pointing, he found that the reciprocals of the responses for the two indicators were related linearly.[1] This relation remained fairly constant as the number of available distance cues was increasingly restricted from a multicue situation to reduced-cue monocular viewing, suggesting that the two indicators were responding to a common underlying variable, ostensibly perceived distance.

Foley based this interpretation on the following logic. Consider the model of space perception depicted in Figure 1A. Here, four distance cues, chosen only for illustration, codetermine perceived egocentric distance; their values can be conceived of as a four-dimensional "cue vector." Perceived egocentric distance, in turn, is a one-dimensional internal variable (scalar), which then controls the two indi-

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[1] Although we adopt the common usage of referring to a straight-line function between two scalars as *linear,* the more appropriate term is *affine.* The term *linearity* in connection with signal-processing systems refers to a system satisfying the properties of superposition and scale invariance. If the input (x) and output (y) of such a system are both scalars, the affine relation $y = k_1 * x + k_2$ ($k_2 \neq 0$) satisfies neither superposition nor scale invariance and thus is nonlinear. (Linearity also is much more general because the inputs and outputs can be vectors.)

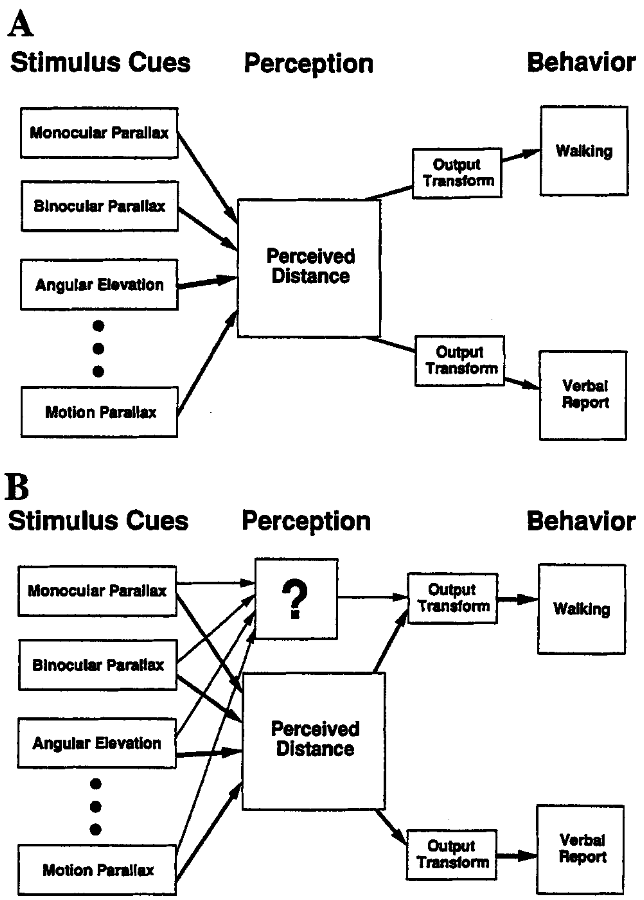

Figure 1. A model of visual space perception. A vector of stimulus cue values codetermines perceived distance, which determines behavioral indicators of perceived distance via output transformations. A: Case in which stimulus cues influence behavior through a common internal variable: perceived distance. B: Case in which the motoric response (walking) is influenced by an additional internal variable, which weights the stimulus cue vector differently than does perceived distance.

cators (verbal report and walking) via output transforms. The only restriction on the output transforms is that they map onto one-dimensional indicators. Other internal variables, such as the response unit (e.g., feet or meters) used in making verbal reports, also might influence the two indicators, but the assumption here is that the stimulus cues exert their influence only through perceived distance. This means that two different cue vectors that produce the same value of perceived egocentric distance will produce the same value of Indicator 1 (verbal report) and the same value of Indicator 2 (walking), provided that other inputs to the two indicators are held constant. This will be true even if the value of Indicator 1 is much different from the value of Indicator 2 to the same cue vector because there are differences in the output transforms. Consequently, when cues are varied to produce changes in perceived distance, Indicator 2 will plot as a single-valued function of Indicator 1 (and vice versa).

Figure 1B represents a situation in which one of the two indicators, walking, is controlled not only by perceived distance but also by some other variable. This variable also is linked to the stimulus cues but weights them differently than does perceived distance. The result is that two cue vectors that result in the same value of perceived distance could result in unequal values of the other internal variable (and vice versa). In this case, a dissociation of the two indicators would result; when verbal report is the same for the two cue vectors, walking would take on distinct values. Evidence for such a dissociation between a perceptually driven indicator and a motoric response comes from several studies. Goodale and Milner (1992) reported an experiment involving a patient with neurological damage induced by carbon monoxide poisoning. In one task, the patient was unable to orient her hand to match the orientation of different lines in the frontoparallel plane. By contrast, she could quickly and accurately insert cards into slots that varied in orientation. Bridgeman, Kirch, and Sperling (1981) found dissociation of a different sort: one between perceived motion and pointing. In one condition, they used a moving frame to induce perceived motion in a stationary target. Observers reported perceived motion that was much greater than the change in pointing direction obtained during the cyclical motion of the frame.

As stated earlier, if one indicator is controlled by a stimulus-driven variable other than perceived distance, there is no reason to expect the relation between the two indicators in Figure 1B to stay constant as the stimulus cues are varied. In fact, a change in this relation across cue conditions would be good evidence for an additional controlling input to one of the indicators. The stability of the mapping between verbal report and blind pointing found by Foley (1977) across conditions varying in cue availability suggests that the two indicators are responsive to the same underlying variable. A similar line of reasoning was used by Gogel, Loomis, Newman, and Sharkey (1985) in comparing two perceptual indicators of perceived distance: perceived size and perceived motion concomitant with motion of the head.

Our comparison of open-loop walking and verbal report as distance responses was modeled after Foley's (1977) comparison of verbal report and open-loop pointing. Using open-loop walking as a distance response not only extends the range of possible responses beyond arm's reach, but it also applies the open-loop walking distance estimation paradigm to targets seen under reduced-cue conditions. This application is important because it is not yet known what effect a reduction of distance cues might have on the accuracy of open-loop walking responses. If open-loop walking responses are found to diverge from the typical pattern of errors under reduced-cue conditions (e.g., to be more biased toward veridicality), this could be taken as evidence that verbal report and open-loop walking are not controlled by a common "perceived distance" variable. Conversely, tight covariation of these responses as the stimulus cues are manipulated would suggest that open-loop walking may indeed be considered an indicator of perceived distance.

Experiment 1

For a comparison of verbal and walked responses to be most diagnostic, there needs to be several different cue conditions, in each of which the cues induce variation in the observer's distance responses as the physical distance to the target changes. There should be enough variation to obtain reliable parameter estimates of the function that describes the relation between the two indicators. We chose to provide several cues in combination because the addition of distance cues typically has the effect of increasing the range of responses (Epstein & Landauer, 1969; Foley, 1977; Foley & Held, 1972; Gogel, 1977; Gogel & Tietz, 1973; Künnapas, 1968).

The physical distance to the target varied between 79 and 500 cm in Experiment 1. Monocular parallax was present as a distance cue in each condition. Monocular parallax induces not only an accommodative response but also a vergence response when targets are sufficiently luminous; this accommodative convergence accompanies even monocular viewing (Gogel & Sturm, 1972). Because of this, researchers who evaluate either monocular or binocular parallax as distance cues take pains to dissociate the normal covariation of the two oculomotor mechanisms. Accommodation with convergence held constant is a weak distance cue and is particularly poor for extended (i.e., nonpoint source) targets (Biersdorf, 1966; Foley, 1977; Gogel & Tietz, 1973; Heinemann, Tulving & Nachmias, 1959; Morrison & Whiteside, 1984; Owens & Leibowitz, 1976). We did not attempt to hold convergence constant during our monocular trials and assumed that accommodative convergence was present to some degree during all trials in the experiment and might have influenced distance responses as monocular parallax was varied.

Angular (retinal) size information also was always present, although it was held constant for all target distances. Gogel (1969) found that distance estimates of extended targets presented successively in reduced-cue conditions tended to increase as the targets' angular size increased; the first presentation data, however, showed no effect of angular size on reported distance. Thus, although angular size does not appear to be a cue to absolute distance, the information can be integrated over successive trials and subsequently influence distance responses to targets having the same projective shape. This being the case, the constant angular size information that we present in this research may be considered a cue that across trials conflicts with the information from the other cues, which otherwise specifies that the targets vary in distance.

In addition to these cues, we manipulated binocular parallax and absolute motion parallax, yielding four cue conditions: stationary head with monocular viewing, stationary head with binocular viewing, lateral head motion with monocular viewing, and lateral head motion with binocular viewing. When convergence is dissociated from accommodation, the binocular parallax of extended targets is a somewhat more reliable distance cue than is monocular parallax, although some observers apparently do not make use of either source of information (Epstein & Landauer, 1969; Gogel, 1961; Künnapas, 1968; Oyama, 1974; Richards & Miller, 1969; Swenson, 1932). When monocular parallax and binocular parallax are simultaneously present and mutually consistent, they can serve as fairly reliable egocentric distance cues up to a distance of about 2 m (Gogel, 1961, 1977; Wallach & Floor, 1971). Although monocular parallax is a weak cue when considered in isolation, it does exert considerable influence by way of accommodative convergence, even when viewing is monocular. Gogel and Sturm (1972), in fact, found little difference between distance judgments made under monocular and binocular viewing when convergence was allowed to covary normally with accommodation. Apparently, binocular parallax has little additional influence on distance judgments above and beyond the already considerable influence of monocular parallax and the accommodative convergence that it regulates. With regard to absolute motion parallax, results of several studies have shown it to be a weak cue (Beall, Loomis, Philbeck, & Fikes, 1995; Gogel & Tietz, 1973, 1979).

Although we followed Foley's (1977) analysis, that we presented extended targets at distances beyond arm's reach made our experiment more similar to those of Künnapas (1968) and Epstein and Landauer (1969). In those two studies, however, a relative distance task (magnitude estimation relative to a simultaneously presented standard with nearly the same visual direction) was used, whereas we obtained egocentric distance judgments of single targets in isolation. The perceived distance of a target, when seen in isolation, is subsequently altered by the addition of a second target, presumably because of the powerful influence of the binocular disparity between the two (Foley, 1980).

Verbal reports of distance under reduced-cue conditions generally are consistent with those of other response indicators, showing increasingly inaccurate responses as distance cues are restricted (Biersdorf, 1966; Da Silva, 1985; Epstein & Landauer, 1969; Foley, 1977; Gogel, 1961; Gogel & Tietz, 1973, 1979; Künnapas, 1968; Morrison & Whiteside, 1984). If open-loop walking and verbal report are responsive to the same internal variable (perceived distance), walking responses also should follow the same pattern and the relation between walking and verbal report should remain stable across cue conditions, as predicted by Foley (1977). A substantial change in this relation would indicate that the stimulus cues exert their influence on one of the two indicators through an interval variable other than perceived distance.

Method

Observers

Observers were 7 men and 2 women from the university community. They were aged 19–28 years (M = 24 years). All observers were paid $8 per hour for a single session, which lasted an average of 1.5 hr. All had acuity of at least 20/20, corrected if necessary. Stereoacuity was 25 s of arc or better for all observers, as measured with the Keystone (Meadville, PA) Orthoscope. All observers were within normal limits of near and far lateral phoria. Two observers had participated in a previous open-loop walking experiment but were naive about the stimulus distances used in this experiment.

Design

We used a 2 (verbal report and open-loop walking) × 2 (motion parallax and no motion parallax) × 2 (binocular and monocular) × 5 (distance) factorial design. The presentation order was fully randomized.

Stimuli

The stimuli were luminous rectangles presented at eye height in the frontoparallel plane and at 0° azimuth. The apertures used to produce these rectangles were scaled in physical size by photoreduction so that they each subtended a visual angle of 1.03° (horizontal) × 1.60° (vertical) when seen at the appropriate target distance. Five target distances in geometric progression were used: 79, 126, 199, 315, and 500 cm. The luminance of the stimuli was constant at 0.51 cd/m^2.

Apparatus

Laboratory. Experiment 1 was conducted in a carpeted hallway, 1.8 × 18.1 m, with the chin rest apparatus (described later) at one end. There were numerous tape markers on the floor used for positioning the stimuli. The observers could see these markers before the experiment began, but, to minimize the possibility that the observers' distance responses might be biased by seeing the tape, we put other pieces of tape unrelated to target positions on the floor. These extraneous markers were placed at locations out to 11 m into the hall, well beyond the farthest target distance.

A string of small, white lights were strung along the floor, extending from just behind the viewing position to about 13 m on the left side of the hall. The individual lights were spaced 12 cm apart. These lights were illuminated just after the observer closed his or her eyes before initiating an open-loop walking response. They provided dim illumination during the response to allow the experimenter to safely remove the target and to provide lateral information to the observer while walking. Because the observer saw the lights only with eyes closed, he or she experienced only a diffuse glow sufficient for lateral guidance but inadequate for specifying lengthwise position within the hallway.

All verbal instructions during the experiment were made by the experimenter from a location about 1.5 m from the observer. Several measures were taken to minimize potential auditory distance cues: Direct sound was attenuated by approximately 20 dB with tight-fitting hearing protectors worn over both ears. To introduce masking sounds that were unrelated to target distance, the observer also wore small earphones beneath the hearing protectors. The earphones in turn were connected to a wireless microphone system (Telex [Minneapolis, MN] models AAR-1 and TW-6). The microphone of the wireless system was placed on a table immediately to the observer's right near the loudspeaker of a detuned radio to introduce broadband masking noise. The microphone signal was amplified and delivered to both ears, making localization of the amplified sound impossible. Verbal instructions to the observer were audible through the microphone.

Chin rest. The chin rest used to immobilize the head in the stationary head trials was mounted on a hinged gate in a freestanding, doorframe-like apparatus. It was adjustable to the observer's standing chin height and could be swung out of the way by the observer using a familiar door-opening motion during walking trials. A floodlamp was attached to the doorframe and directed at a piece of white posterboard on the wall behind the apparatus. Between trials, the lamp was illuminated and the observer viewed the posterboard binocularly to ensure approximately equal light adaptation in both eyes. The luminance of the illuminated posterboard was 310 cd/m^2.

Light box. The light box consisted of an electroluminescent panel housed in a wooden frame. A groove in the frame 7 mm in front of the panel held two pieces of polystyrene that diffused the light from the panel. Cards with different-sized apertures could be slid in front of the diffusers and removed easily. There was no visible grain in the stimulus at any target distance. The light box was mounted on a camera tripod and could be adjusted to the observer's eye height. The placement of the tripod and light box was determined by positioning the legs of the tripod so that they were in register with the appropriate floor markers.

Procedure

Instruction and training phase. Preliminary equipment adjustments and vision tests were conducted in the laboratory in which the experiment took place. Instructions for the verbal report trials asked observers to verbally estimate the distance to the target, in feet, inches, or a combination thereof "as if there were a tape measure running between your eyes and the object" (objective instructions). Instructions for the open-loop walking trials asked observers to walk quickly and decisively to where the target was, stopping when they felt that their eyes were where the target was.

After reading the instructions, observers were given training in how to walk without vision in a smaller hallway (1.71 × 9.87 m) nearby. We did this to minimize walking variance that might accompany unfamiliarity with walking with the eyes closed. Also, by using a different hallway for the practice phase, observers did not have the opportunity to learn nonvisual characteristics of the walking space in which they would be tested. Observers walked back and forth in the hall six times, stopping and turning when the experimenter signaled them to do so, with their eyes kept closed throughout this training session. Verbal feedback about veer was given in an effort to minimize subsequent veering in the experimental phase. Measurements of walked distance in the experimental phase did not take into account veer, but in practice observers did not veer substantially for most of the experimental trials.

After this training, observers were given four practice trials in the main laboratory to familiarize them with the procedure. No feedback about distance-related error was given. Unlike the stimuli in the experimental trials, the practice stimulus was a luminescent sphere, 13 cm in diameter, held on a black stick by the experimenter. Two of the four practice trials were conducted with the ball held at approximately 1.5 m from the observer and two with it held at approximately 2.5 m. Observers practiced using each of the four stimulus conditions once; two of these practice trials used the verbal response, whereas the other two used the walking response.

Experimental phase. The observer viewed the adapting surface binocularly between trials. When ready, the experimenter announced the conditions for the trial (e.g., "head motion, both eyes, verbal") and extinguished the adapting light, making the room dark. The observer turned around and signaled when she or he was in position. The experimenter illuminated the stimulus, which extinguished automatically after approximately 10 s. For open-loop walking trials, the experimenter moved the light box out of the way and gave a verbal signal to begin walking. The observer closed her or his eyes, swung the chin rest and door away, and began walking. The experimenter illuminated the string of lights when the door swung open and placed a marker at the observer's feet when she or he stopped walking. The observer then was led back to face the posterboard, where he or she opened both eyes (raising the eye patch if necessary) to view the adapting surface. For verbal report trials, the observer simply gave a verbal judgment of the distance to the target and then turned around to face the adapting surface again. The time between stimulus onsets, including the observer's response, averaged about 1 min. The experimenter attempted to make the trials approximately equal in duration.

Monocular trials were conducted with an eye patch placed over the nonpreferred eye. Compliance with the use of the eye patch was not strictly monitored, but casual observation indicated that observers used the patch appropriately. Stationary head trials were conducted with the observer's chin in the chin rest. Head motion trials were conducted by sliding the feet back and forth laterally between two blocks of wood, which were placed 52 cm apart at the observer's feet. This procedure resulted in approximately sinusoidal lateral head motion with a peak-to-peak amplitude of about 30 cm at a frequency of about 0.5 Hz. The exact rate of translation was paced by the observer.

Results

The data for the four conditions, averaged across the 9 observers, are shown in Figure 2. Mean verbal reports are plotted along with the mean open-loop walking responses; the error bars represent 1 *SEM*. In general, the variations in the values of the two indicators were similar, with the walked distances being uniformly larger than verbally reported distances. In all four conditions, observers tended to overestimate near distances and underestimate far ones, which is consistent with previous reduced-cue results (Epstein & Landauer, 1969; Gogel, 1961; Gogel & Tietz, 1973; Künnapas, 1968; Morrison & Whiteside, 1984; Owens & Leibowitz, 1976). When the head was held fixed, average performance did not vary much between monocular and binocular observation; the mean responses varied by only about 100–150 cm despite a range of physical target distances of more than 400 cm. Performance in the motion, monocular condition followed the same trends. The motion, binocular condition resulted in slightly more accurate performance for near targets, but the range of indicated distances remained compressed, with the average near-target responses differing from far-target responses by only 200 cm.

Many distance cues (e.g., monocular parallax, binocular parallax, and motion parallax) exhibit decreasing gain (i.e., a change in cue value for a constant increment in physical distance) as physical distance increases. Recognizing this fact, and assuming internal noise in the visual system, one may predict that the signal-to-noise ratio of the signals representing these cues ought to decrease with target distance. Consequently, many theories would predict increased

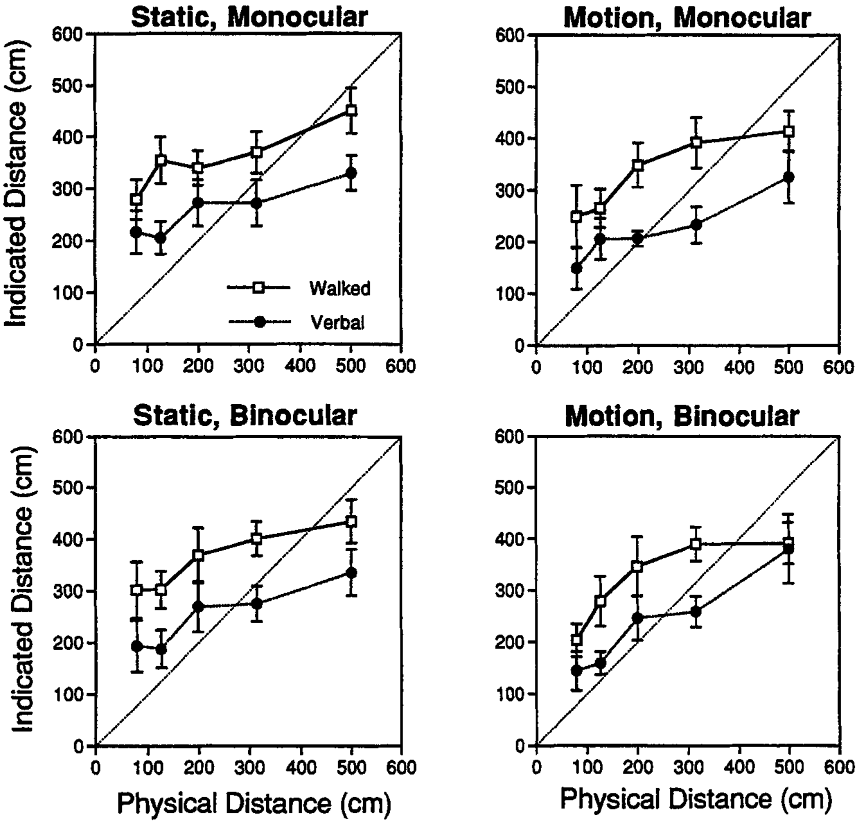

Figure 2. Mean indicated distance as a function of target distance for the four conditions of Experiment 1. Error bars denote ±1 *SEM.*

variability in any indicator of perceived distance with increasing target distance. By taking the reciprocal of the response measure, one obtains a new measure that should have roughly equal variability at different distances. Moreover, Foley (1977) transformed both stimulus and indicator values and found a linear relationship between them. Taking reciprocals of the response values has other desirable effects in addition to linearizing the data and equating response variance: Least squares linear fits to the transformed data consequently give more or less equal weight to the data for the different target distances, and the homogeneity of variance assumption for analysis of variance (ANOVA) is more nearly satisfied after this transformation. In the current experiment, however, the standard deviations of the untransformed distance judgments across observers showed little if any systematic change with distance for either indicator. Therefore, we performed the statistical analyses on the untransformed data. Separate analyses on the reciprocal data yielded similar results but are not reported here.

The four-way repeated measures ANOVA (Distance × Motion Parallax × Binocular Parallax × Response Indicator) performed on the response measures revealed main effects of distance, $F(4, 32) = 20.31$, $p < .01$, $MSE = 15{,}136$, and response type, $F(1, 8) = 15.90$, $p < .01$, $MSE = 57{,}053$, with no significant interactions. On the basis of this analysis, we concluded that manipulating the availability of absolute motion parallax and binocular parallax had no statistically reliable effect on the perception of distance. To assess the influence of these cues in still another way, we performed two multiple regression analyses, one for each indicator, using the reciprocal of physical distance (as monocular parallax values), the values of motion parallax, and the average values of binocular parallax across observers as predictors of the average verbal reports and walked distances. For both analyses, the regression equations provided a good fit of the data: verbal, $F(3, 16) = 15.05$, $p < .01$, $MSE = 1{,}326.61$; walked, $F(3, 21) = 43.56$, $p < .01$, $MSE = 562.31$. The squared multiple correlation coefficient was high in both cases (verbal = .738, walked = .891). For verbal reports, the standardized partial regression coefficients were −.67, −.27, and −.06 for monocular parallax, motion parallax, and binocular parallax, respectively. Two-tailed t tests revealed that both monocular parallax, $t(19) = -4.21$, $p < .01$, and motion parallax, $t(19) = -1.88$, $p < .01$, were significant predictors of verbal reports. For walking, the coefficients were −.72, −.33, and −.05, with monocular parallax, $t(19) = -7.01$, $p < .01$, and motion parallax, $t(19) = -3.52$, $p < .01$, again being significant predictors. Monocular parallax (i.e., accommodation and accommodative convergence), then, was weighted most heavily in determining distance responses, with motion parallax contributing somewhat less and binocular parallax contributing little. The significance of motion parallax as an egocentric distance cue, however, should be viewed in light of the small difference in the means across all the trials with head motion and no head motion (280 vs. 308 cm, respectively).

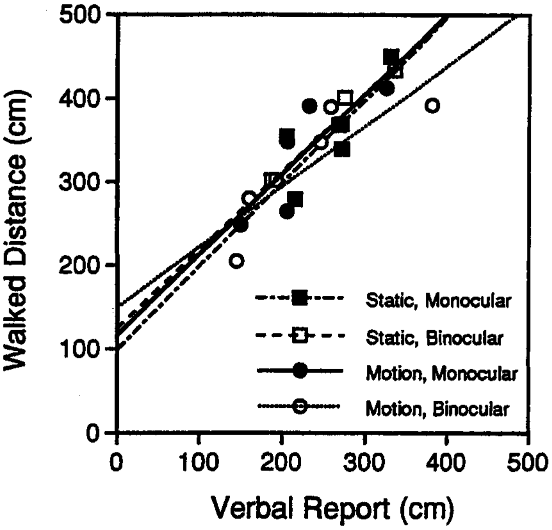

Figure 3. Mean walked distance as a function of mean verbal report for the four conditions of Experiment 1. Lines show the best-fitting straight lines through the average data.

Figure 3 shows the average walked responses as a function of the average verbal responses for each of the four conditions. Plotting the data this way provides a visual indication of the extent to which the mapping between verbal and walked responses remained constant across the different cue conditions. Even though the verbal reports were uniformly lower than the walked distances (see Figure 2), Figure 3 shows that the mapping between one indicator and the other is roughly constant across stimulus conditions. The mapping is well fit by a linear function for each cue condition. The slopes for the static monocular, static binocular, motion monocular, and motion binocular conditions were 1.00, .94, .96, and .73, respectively; the corresponding intercepts were 99.10, 124.72, 116.70, and 149.24. To assess whether the variations in slopes and intercepts were reliable, we conducted separate ANOVAs. The analysis of the slopes of the walked distances versus the verbal reports showed no significant effects. The analysis of the intercepts of these functions showed only a marginal main effect of head motion, $F(1, 8) = 5.57$, $p = .046$, $MSE = 260{,}413$.

The product–moment correlation between the average verbal reports and the average walked distances, incorporating all 20 points in Figure 3, was .853. This correlation indicated that the relationship between the two indicators was approximately a fixed one-to-one mapping (across the four cue conditions) and that the mapping was nearly linear.

Discussion

The limited and highly variable data obtained in Experiment 1 do not allow strong conclusions to be drawn, but our results are generally consistent with the findings of Foley (1977) and suggest that the stimulus cues have their effect on the two indicators solely through a common variable (i.e., perceived distance). When the data were smoothed by averaging across observers, verbal reports and open-loop walking responses were related linearly, with a similar function fitting the data for each of the four cue conditions. Both indicators showed overestimation of near targets and underestimation of far ones. Indirect measures such as the head motion and size matching procedures (which are assumed to be less susceptible to cognitive influences) have shown this pattern of errors under reduced-cue conditions (Gogel & Tietz, 1973, 1979; Holway & Boring, 1941; Wallach & Floor, 1971). On the basis of the covariation we found between verbal reports and walking, we tentatively concluded that open-loop walking is indeed responsive to perceived distance. In Experiment 3 we more rigorously tested this hypothesis.

The results of previous studies have suggested that when single, extended targets are seen in isolation, binocular parallax and absolute motion parallax are both weak beyond about 2 m (Beall et al., 1995; Epstein & Landauer, 1969; Gogel, 1961, 1977; Gogel & Tietz, 1973, 1979; Künnapas, 1968; Oyama, 1974). We found little effect here of either cue, even within 2 m, although the significant effect of distance presumably reflects the influence of accommodation and accommodative convergence. The weak effect of binocular parallax indicates that the additional effect of fusional convergence is minimal. (Recall that in the current experiment, the constant angular size over trials did constitute a weak cue specifying constant target distance.) In all conditions, there was unmistakable overestimation of near distances and underestimation of far distances for both indicators (see Figure 2). The suggestion is clear that had all distance information been eliminated, observers would have responded with some nonzero value, roughly 3.5 m for walking and 2.5 m for verbal report. According to Gogel (1969), these default-indicated values ought to correspond to a default value of perceived distance (in the absence of distance cues) that he referred to as the "specific distance tendency."[2]

Because we obtained only one measurement per condition per observer, we were able to assess only response variability between subjects. In contrast to the results of open-loop walking experiments conducted in full-cue conditions, which showed approximately linear increases in between-subjects standard deviations of about 10% of the target distance (Steenhuis & Goodale, 1988), we found little if any systematic change in variability with distance, perhaps because of the small range of target distances.

Experiment 2

Targets in open-loop walking experiments typically have been presented on the ground. Because ground-level targets vary systematically in angular elevation as egocentric distance increases, angular elevation uniquely specifies the distance of such targets and thus could serve as a useful cue to egocentric distance. It is well established that when two targets are presented simultaneously in an otherwise dark environment, their relative heights in the visual field can influence judgments of their relative distance (Bruno & Cutting, 1988; Bugelski, 1967; Dunn, 1969; Dunn, Gray, & Thompson, 1965; Epstein, 1966). Wallach and O'Leary (1982) manipulated angular elevation with an optical device and investigated the influence angular elevation had on absolute size judgments of paper rectangles in a well-lit room. They found that its influence on size perception (and thus indirectly on distance perception) was highly susceptible to the effect of expectation and concluded that it could not be a strong cue to distance. To our knowledge, however, no one has manipulated the angular elevation of a single target seen in an otherwise dark environment to evaluate its effectiveness as an egocentric distance cue. We did this in Experiments 2 and 3 to determine whether angular elevation would influence distance responses only through perceived distance.

In Experiment 2, observers used open-loop walking to indicate the egocentric distance of targets seen in the dark, either at eye level or on the floor, and with either one eye or two. Because angular elevation uniquely specifies the distance of floor-level targets, we expected that responses to floor-level targets would be more accurate than those to eye-level targets. Even though the results of Experiment 1 and others (Epstein & Landauer, 1969; Gogel, 1961, 1977; Künnapas, 1968) suggest that for our range of target distances there would be little effect of manipulating binocular parallax on perceived egocentric distance, we wanted to test check this again.

Method

Observers

Six men and 2 women from the university community served as observers. They were aged 21–31 years ($M = 24.5$ years). All had normal or corrected-to-normal acuity, as measured by the Keystone Orthoscope, and stereoacuity of at least 25 s of arc. Observers were paid $8 per hour, and the experiment lasted about 1 hr. One observer had participated in a previous open-loop walking experiment but was naive about the stimulus distances used here.

Design

We used a 2 (binocular parallax and no binocular parallax) × 2 (eye level and floor level) × 5 (distance) factorial design, with two measurements per condition. The presentation order was fully randomized.

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[2] An alternative view is that the default-indicated values reflect a more general psychological process. When stimulus information is degraded or must be remembered for some time, observers' responses reflect the range of stimulus magnitudes, in a type of regression to the mean (Fujita, Klatzky, Loomis, & Golledge, 1993; Pepper & Herman, 1970). Although range effects may be detectable in spatial perception data, the perceptual default tendency clearly is separate from these range effects because it is roughly constant at about 1–3 m, correlates highly with the resting state of convergence (Owens & Leibowitz, 1976), and is independent of context, as indicated by the analysis of first responses (Gogel, 1969).

Stimuli

The stimuli were luminous rectangles of the same luminance and visual angle as those used in Experiment 1. They were seen in an otherwise dark room and always were oriented to be normal to the line of sight through their centers. Five target distances were used: 199, 260, 315, 415, and 500 cm. These distances were measured from the observer's eyes to the target for both the eye-level and floor-level conditions. Thus, at each target distance, changes in angular elevation did not alter the monocular and binocular parallax cue values. Note that the distance of the floor-level stimuli (as measured along the floor) and their orientations with respect to the floor varied with the observer's eye height; the appropriate distances and orientations were computed for each observer before the experimental session.

Apparatus

Experiment 2 was conducted in a carpeted laboratory 7.3 × 4.3 m. A black curtain was hung about 1 m from the wall to provide a tactile warning in the event that the observer walked too close to the wall. In actuality, only 2 observers ever reached the curtain. As in Experiment 1, tape markers on the floor were visible before the experiment began, along with several extraneous markers. The same chin rest apparatus and light box were used as in Experiment 1. The light box could be removed from the tripod and positioned on the floor. The angle of the light box with respect to the floor was adjusted on each trial so that the luminous rectangle always was normal to the line of sight through its center. This was intended to eliminate systematic changes in retinal image shape with target distance, which could have conveyed distance information.

Procedure

The procedure was essentially the same as that used in Experiment 1, but with three changes: (a) Only open-loop walking was used to indicate target distance. (b) No walking practice with the eyes closed was given. However, as before, observers were given four practice trials (without response error feedback) to familiarize them with the procedure. (c) To provide dim illumination while the response was being carried out, a small flashlight, rather than the string of small white lights, was illuminated on the floor to the observer's left.

Results and Discussion

Figure 4 shows the average walked distance as a function of the average physical distance (as measured along the ground) for each of the four conditions: monocular eye level, monocular floor level, binocular eye level, and binocular floor level. Error bars show 1 *SE* above and 1 *SE* below the mean, computed across the 8 observers, with the individual data being the means of the two measurements per condition collected per observer. Because each eye-level target distance mapped onto eight floor-level distances as measured along the ground (dependent on the observer's eye heights), we averaged the eight floor-level distances for each eye-to-target distance and plotted walked responses as a function of the resulting stimulus averages.

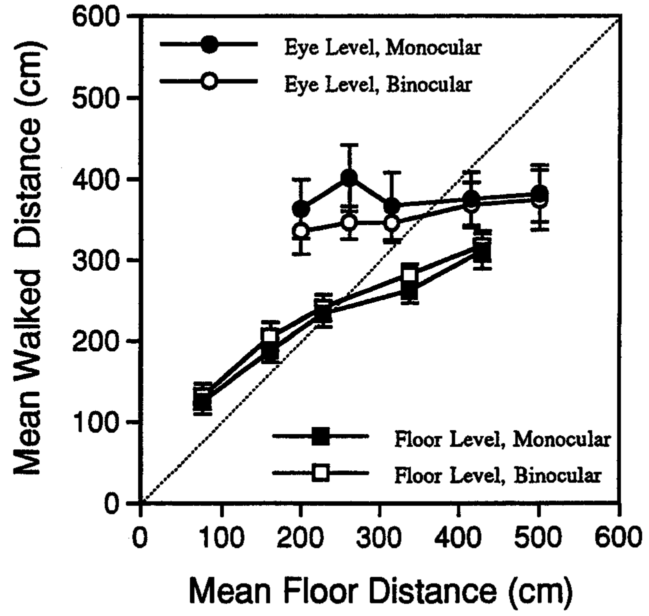

Figure 4. Mean walked distance as a function of target distance for the four conditions of Experiment 2. Error bars denote ±1 *SEM.*

As can be seen in Figure 4, the mean walked distances were virtually the same for both monocular and binocular conditions. Responses to eye-level stimuli were unrelated to target distance and tended to cluster around 350–375 cm. Responses to floor-level stimuli varied substantially with target distance but showed a pattern of errors similar to the binocular head motion condition of Experiment 1: The distance of near targets was overestimated, and the distance of far targets was underestimated. We did not directly contrast the two levels of the angular elevation manipulation in our statistical analysis because we thought that observers' walking responses to floor-level stimuli were not strictly comparable to responses to eye-level stimuli. For floor-level targets, the same distance walked by different observers necessarily differed in accuracy because the correct distance along the floor was determined by each observer's eye height. For eye-level stimuli, however, this was not the case. Instead, we performed separate two-way ANOVAs (Distance × Number of Eyes) on the eye-level conditions and floor-level conditions. The eye-level condition analysis showed no main effects, either of distance or number of eyes, and no interaction. The floor-level analysis showed a main effect of distance, $F(4, 28) = 123.46, p < .01, MSE = 36{,}876$, and a small but significant effect for number of eyes, $F(1, 7) = 17.98, p < .01, MSE = 2{,}113$, with no interaction. The responses under binocular observation and monocular observation, averaged across distances, differed little (295 vs. 301 cm, respectively).

Although we did not statistically evaluate the effect of manipulating angular elevation, we concluded that target distance had little if any effect on the responses in the eye-level conditions but that it did in the floor-level conditions. The variation in means relative to the standard errors in Figure 4 indicate clearly that adding angular elevation as a distance cue (in the change from eye level to floor level) greatly improved the accuracy of walked distance, although the mean response values still exhibited considerable overestimation at near distances and even larger underestimation at far distances. Thus, the results of Experiment 2 provide evidence for the efficacy of angular elevation as a cue to egocentric distance. Further support for this conclusion was adduced in Experiment 3.

Experiment 3

In Experiment 3, we again tested the proposal that open-loop walking is responsive to perceived distance, applying the same logic (Foley, 1977) used in Experiment 1. We compared open-loop walking responses with verbal reports using floor-level and eye-level targets. To allow a more direct comparison of responses in a controlled dark environment with those obtained within well-lit natural environments used in previous open-loop walking studies (Corlett et al., 1985; Elliott, 1986, 1987; Loomis et al., 1992; Rieser et al., 1990; Steenhuis & Goodale, 1988; Thomson, 1980, 1983), we also manipulated the context in which the stimuli were seen. Targets were seen either in the dark, as in Experiments 1 and 2, or with the overhead incandescent lights and the adapting light illuminated. The comparison of performance between dark and well-lit viewing conditions has precedents in several studies (Epstein & Landauer, 1969; Foley, 1977; Foley & Held, 1972; Gogel, 1977; Holway & Boring, 1941; Künnapas, 1968; Morrison & Whiteside, 1984). The results of those studies show that presenting targets in an environment rich in context produces large variations in responses as target distance increases and, in some cases, nearly accurate performance. Some researchers have emphasized that the relational structure of the visible environment under well-lit conditions provides a powerful source of continuous layout information (Gibson, 1979; Haber, 1985). Indeed, Corlett (1986) found that the consistency and accuracy are influenced by the richness of the visible environment. Reduced-cue conditions, in which a single target is seen in isolation, do not supply this relational information. There are cues common to both viewing conditions, however, and the degree to which responses to targets viewed in the dark approach those obtained in well-lit environments may be used to gauge the efficacy of these cues.

Method

Observers

Six men and 2 women from the university community served as observers. They were aged 21–30 years ($M = 24$ years). All observers had normal or corrected-to-normal acuity, as measured with the Keystone Orthoscope, and stereoacuity of at least 25 s of arc. Observers were paid $8 per hour, and the experiment lasted about 1.5 hr. Four observers had been in previous open-loop walking experiments several months earlier but were unaware of the distances being used in this experiment.

Design

We used a 2 (verbal report and open-loop walking) × 2 (floor level and eye level) × 2 (dark and light) × 4 (distance) design, with one measurement per condition for each indicator. The presentation order was fully randomized.

Stimuli

Four eye-to-target distances were used in this experiment: 199, 260, 415, and 500 cm. The stimuli in the dark conditions were identical to the binocular conditions of Experiment 2, minus the 315-cm target distance. As in Experiment 2, all targets were oriented so that they were normal to the line of sight, and the distance from the observer's eyes to the targets was kept constant across the angular elevation manipulation. In the full-cue conditions, the overhead incandescent lights and the adapting light were illuminated while the observer viewed the stimuli. Thus, observers were exposed to not only the rectangular aperture in the light box but also the light box itself and the rest of the laboratory. Therefore, although angular size of the rectangular target was held constant in both the light and dark conditions, the angular size of the visible light box obviously varied when the lights were on. Also, because the stand supporting the light box in the light/eye-level condition was visible, angular elevation provided information about the distance of the stand even though the rectangular target itself remained at eye level; this meant that, in terms of the information available to the observer, the Floor-Level/Eye-Level × Dark–Light stimulus conditions were not strictly crossed with one another. Luminance of the rectangular target, as measured off the light box in the light trials, varied with the box's position in the hallway, ranging between 8.4 and 19.8 cd/m^2.

Apparatus

Experiment 3 was conducted in the same laboratory as Experiment 1 and used the same chin rest and light box apparatus.

Procedure

As in Experiment 1, observers practiced walking with the eyes closed in an adjoining hallway before the main experiment and then received several trials without feedback in the main hallway to familiarize them with the procedure. The experimental procedure was essentially the same as that followed in Experiment 1, without the head motion and monocular viewing manipulations. The main procedural difference was that just before the light trials in Experiment 3, the overhead incandescent lights were illuminated, and the adapting light was not extinguished while the observer viewed the stimulus. For light/open-loop walking trials, observers walked with both the string of small white lights and the overhead lights illuminated; for dark/open-loop walking trials, observers walked with only the string of white lights on.

Results

Figure 5 shows the means of the verbal and open-loop walking responses of the 8 observers for each of the four conditions. Error bars represent 1 *SE* above and 1 *SE* below the mean. In general, verbal responses increased somewhat more rapidly with physical distance than did the walked distances, although this difference was less apparent in the

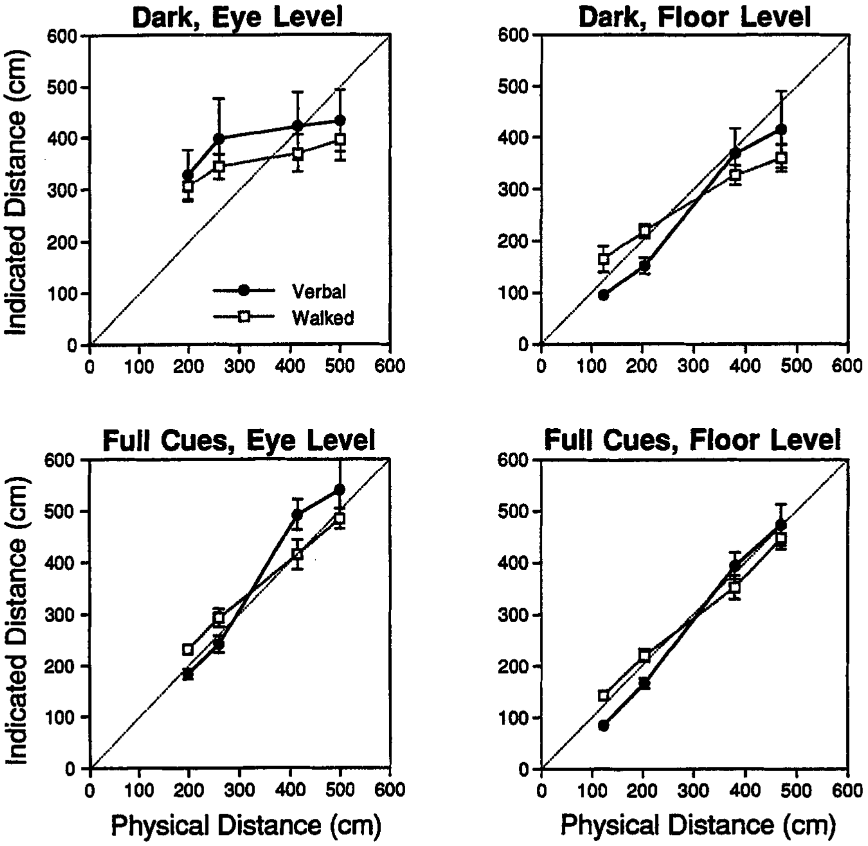

Figure 5. Mean indicated distance as a function of target distance for the four conditions of Experiment 3. Error bars denote ±1 *SEM*.

dark/eye-level condition. More important, despite this small difference, the two response indicators yielded similar patterns of results, as they did in Experiment 1. For both indicators, average distance responses were highly accurate in the two full-cue conditions. When targets were seen in the dark, the pattern of results depended more strongly on the angular elevation of the targets. When targets were presented on the floor, the distances of the two nearer targets were indicated accurately, whereas the two farther targets were slightly underestimated. Responses to eye-level targets seen in the dark showed a strong compression in the range of responses, with average values varying by less than 1 m to targets that varied in physical distance over a range of 3 m. The results agree well with those found under the similar stimulus conditions presented in Experiments 1 and 2, except that here verbal responses were marginally greater than walked distances, whereas in Experiment 1 the opposite was true.

Because the design was not strictly crossed, we performed four separate two-way ANOVAs (Distance × Response Type) when analyzing the data. The dark/eye-level analysis showed only a main effect of distance, $F(3, 21) = 4.71$, $p < .01$, $MSE = 6{,}133$, whereas the dark/floor-level analysis showed an effect for target distance, $F(3, 21) = 31.12$, $p < .01$, $MSE = 7{,}995$, as well as a marginal Response Type × Distance interaction, $F(3, 21) = 4.10$, $p < .05$, $MSE = 4{,}532$. The full-cue/eye-level analysis revealed only a main effect of distance, $F(3, 21) = 59.29$, $p < .01$, $MSE = 5{,}746$, whereas the full-cue/floor-level analysis showed both an effect for target distance, $F(3, 21) = 199.56$, $p < .01$, $MSE = 2{,}028$, and a Response Type × Distance interaction, $F(3, 21) = 6.24$, $p < .01$, $MSE = 1{,}734$.

The relation between walked responses and verbal reports is shown in Figure 6, with average walked response plotted as a function of the average verbal response for each of the four conditions. The straight lines provide a good fit to the averaged data, which is in agreement with the results of Experiment 1. The slopes for the dark/eye-level, dark/floor-level, light/eye-level, and light/floor-level conditions were .77, .57, .64, and .73, respectively; the corresponding intercepts were 47.80, 120.05, 123.85, and 85.84. Because there was little variation in mean responses as distance increased in the dark/eye-level condition, estimates of the straight-line parameters were less reliable for that condition.

As in Experiment 1, we computed the product–moment correlation between the average verbal reports and the average walked distances for all 16 points in Figure 6; here it was .983. This high correlation indicates that the relationship between the two indicators was approximately a fixed one-to-one mapping (across the four cue conditions) and that the mapping was nearly linear.

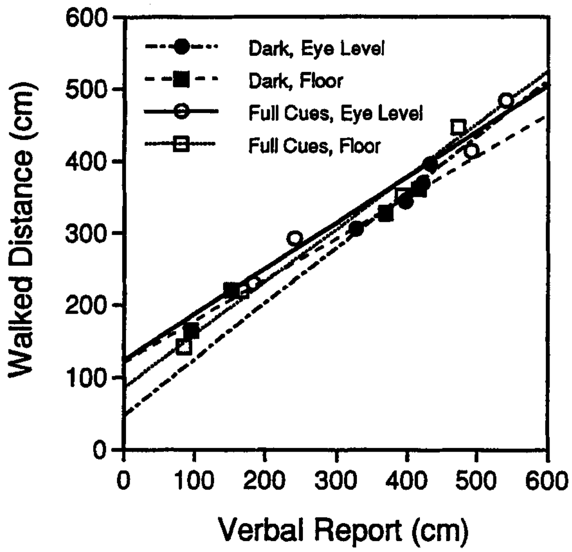

Figure 6. Mean walked distance as a function of mean verbal report for the four conditions of Experiment 3. Lines show the best-fitting straight lines through the average data.

We also fit linear functions to the walking versus verbal report data for each observer. The resulting parameters varied considerably from observer to observer because of the high intersubject variability in the data. An ANOVA carried out on the parameters of these functions did show reliable differences in the mean parameters across conditions: slopes, $F(3, 21) = 4.65$, $p < .05$, $MSE = 0.06$; intercepts, $F(3, 21) = 5.71$, $p < .01$, $MSE = 6{,}416$. The mean slopes across observers were .32, .65, .67, and .75 for the dark/eye-level, dark/floor-level, full-cue/eye-level, and full-cue/floor-level conditions, respectively. The dark/eye-level condition clearly contributed to the obtained statistical significance between the slopes across cue conditions, but one should be cautious in making much of this difference because the obtained slopes in this condition were less reliable, as noted earlier. The mean intercepts across the four conditions were 240.82, 114.44, 127.22, and 87.37, respectively.

Discussion

The test of the proposal that the two response indicators would be controlled by the same internal variable was much stronger in Experiment 3 than in Experiment 1 because our choice of conditions caused a much greater change in the range of the two responses in the change from one viewing condition to another (e.g., compare the dark/eye-level and light/floor-level trials in Figure 5). The tight covariation in the walked distances and the verbal reports of distance as stimulus cue availability was manipulated suggests that the cues exert their influence on the two indicators only through a single common variable: perceived distance. This provides further evidence that open-loop walking is responsive to perceived distance, the variable that presumably underlies verbal reports. In particular, the results support the conclusion that angular elevation affects walked indications of distance primarily through perceived distance without being weighted differently by some other variable that also controls walking.

Unlike the results of Experiment 2, target distance did reliably influence responses in the dark/eye-level condition, although the average responses to a 300-cm range of target distances varied by less than 100 cm and the responses themselves were far from accurate. This may reflect the memory of contextual cues, which were provided in the randomly interleaved, full-cue conditions. However, regarding the angular elevation manipulation, the pattern of results discussed earlier is clear given the size of effects relative to the standard errors, even without a direct comparison of the four conditions.

Walking performance in the two light conditions mirrored the results of previous open-loop walking experiments in showing highly accurate mean responses. Intersubject variability was generally low for both indicators in these two conditions. In the dark conditions, the variability of the walked response was again small, but that of verbal reports was noticeably larger (see Figure 5); note, however, that the two indicators were highly similar in terms of intersubject variability in Experiment 1.

General Discussion

The results of Experiments 1 and 3 provide strong evidence that open-loop walking is responsive to perceived distance. We found that open-loop walking is subject to the same pattern of errors in dark viewing conditions as is verbal report; this pattern of errors has been attributed in previous work to errors of perceived distance (Foley, 1977; Gogel & Tietz, 1973, 1979; Holway & Boring, 1941; Wallach & Floor, 1971). Following the analysis of Foley (1977), we found a tight covariation of these indicators as stimulus cues were manipulated, which suggests that they are both controlled by the same internal variable. If verbal report is indeed responsive to perceived distance, open-loop walking is as well.

In particular, this conclusion rules out the hypothesis that open-loop walking is responsive to a different set of cues or weighting of cues than is verbal report. According to this hypothesis, accurate full-cue walking performance might reflect the presence of a more accurate location signal that controls motoric actions but that is not available to perceived distance. As discussed earlier, there is evidence of dissociation of the motor system from systems that determine aspects of consciously perceived space (Bridgeman et al., 1981; Goodale & Milner, 1992; Goodale, Milner, Jakobson, & Carey, 1991). However, if there is even a partial dissociation between the signals controlling verbal report and those controlling visually directed action, we certainly did not detect it here using our methods and Foley's (1977) analysis. However, our conclusion might be limited in its generality because it is possible that a dissociation would have been observed under full-cue conditions for target distances well beyond 5 m, where perceptual error is larger.

In our experiments, we found that monocular parallax, binocular parallax, and absolute motion parallax all were relatively weak cues to egocentric distance, especially beyond 2 m. (Recall, however, that these were being evaluated against a backdrop of constant angular size, which over trials constituted a weak cue to target distance.) This result confirms the findings of previous studies investigating these cues (Beall et al., 1995; Gogel, 1961, 1977; Gogel & Tietz, 1973, 1979; Heinemann et al., 1959). Angular elevation, however, was found to be a strong cue to egocentric distance, producing much more variation in indicated distance than any combination of the other cues, whether the lights were on or off; when the lights were on, mean walked distance was highly accurate.

Our conclusion that both response indicators are controlled by perceived distance does not imply that both indicators are measures of perceived distance. Indeed, because the indicated values are generally different, both cannot be measures. Foley's (1977) analysis assumes that both indicators are linked to perceived distance by output transforms. Even if both transforms are nonlinear but monotone functions of perceived distance, one would expect the tight covariation observed here; the linear covariation of the two (see Figures 3 and 6), however, suggests that if the output transforms are nonlinear, they are of the same form. Thus, what can be said about a "true measure" of perceived distance?

We believe that walked distance is as close a measure of perceived distance as any that has been proposed. If one assumes that walked distance is linear in perceived distance and is properly scaled for near target locations (e.g., out to 2 m) under full-cue conditions by virtue of constant calibration by closed-loop visuomotor control, the supposed linearity of perceived distance with physical distance under full-cue conditions would extend visually directed walking out to the much farther distances that have been studied and result in the accurate responding at these distances that has been observed. Evidence that perceived distance is indeed linear in physical distance under full-cue conditions is supported by converging evidence that derives from two different triangulating responses, one involving pointing without vision to a previewed target while walking past it and the other blind walking along an oblique path and then a turn toward the previewed target (Fukusima et al., 1997). Our research complements the triangulation results in showing that systematic errors do occur with visually directed walking when distance cues are reduced. We recently extended these results by using a variant of the triangulation-by-walking method in which observers attempted to walk to the target after turning toward it (Philbeck, Loomis, & Beall, in press), thus defining an indirect path to the target. Both direct walking and indirect walking indicated approximately the same perceived target locations; this was true whether the perception was accurate (under full-cue conditions) or systematically in error (under reduced-cue conditions).

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