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A comparison of methods for estimating directions in egocentric space

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Abstract. A central issue for researchers of human spatial knowledge, whether focused on perceptually guided action or cognitive-map acquisition, is knowledge of egocentric directions, directions from the body to objects and places. Several methods exist for measuring this knowledge. We compared two particularly important methods, manual pointing with a dial and whole-body rotation (body heading), under various conditions of sensory or memory access to targets. In two experiments, blindfolded body rotation resulted in the greatest variability of performance (variable error), while the manual dial resulted in greater consistent bias (constant error). The variability of performance with body rotation was no greater than that of the dial when subjects' memory loads for directions to targets was reduced by allowing them to peek at targets in between trials, point to concurrent auditory targets, or point with their eyes open. In both experiments, errors with the manual dial were greater for directions to targets that were further from the closest orthogonal axis (ahead, behind, right, left), while errors with body rotation with restricted perceptual access were greater for directions to targets that were further from an axis straight ahead of subjects. This suggests that the two methods will produce evidence of different organizational frameworks for egocentric spatial knowledge. Implications for the structures and processes that underlie egocentric spatial knowledge, and are involved in estimating directions, are discussed, as is the value of decomposing absolute errors into variable and constant errors.

1 Introduction

An important component of spatial knowledge is knowledge of directional relationships between objects or places in the world. When one of those objects is one's own body, the directions may be termed *egocentric* directions. Knowledge of egocentric directions is especially important for guiding behaviors such as reaching or locomotion that occur in local space (eg Loomis et al 1992; Warren 1995). When combined with knowledge of one's own location, knowledge of directional relationships stored in cognitive maps is also critical for way finding in more extensive spaces not immediately accessible to perceptual – motor systems (eg Kozlowski and Bryant 1977; Kuipers 1978; Tversky 1981). Several studies of egocentric directional knowledge have been reported in the literature (eg Attneave and Pierce 1978; Hardwick et al 1976; Hintzman et al 1981; Rieser et al 1986; Sadalla and Montello 1989). Thus it is important that behavioral scientists have well-developed and understood methods for measuring knowledge of directions.

There are a wide spectrum of methods available from which to choose when studying directional knowledge, particularly when adult humans are the subject of study. Although a full description and characterization of these possibilities has not yet been published, an examination of existing literature like that cited above suggests many examples. Research subjects may point with their hands, turn their heads or eyes, rotate their bodies to some heading, or even turn and walk along some course. Body methods such as these require videotaping or some other instrumentation or technology in order to measure the angle of the body movement. Alternatively, a circular dial with a rotating pointer or a sighting tube may be used, with measurements generated and recorded manually or electronically. Another possibility is map sketching or angle drawing.

Last, subjects can explicitly provide angular measurements via a forced-choice or direct verbal report.

One study that specifically compared methods of directional estimation was reported by Haber et al (1993). They compared the accuracy (absolute value of error from correct) of pointing to auditory targets by blind adults; target directions were thus concurrently perceived rather than recalled. Pointing methods involving body parts (pointing with the nose, index finger, or chest) or extensions of body parts (long cane, short stick) resulted in the best accuracy. Methods involving a rotating pointer attached to a square dial, resting either on a table or on a board attached to the waist, resulted in significantly lower accuracy, about 4° less, than the body-part and extension methods (about 11° as compared with about 7°). Drawing a vector on a piece of paper or providing a verbal estimate in clock-face terms fared the worst; accuracy was nearly 3° less than the dial methods (about 14°).

We report two experiments in this paper that add to the literature on directional-estimation methods. Two estimation techniques are examined: (1) rotating one's body to face in a particular direction or 'heading', and (2) manually rotating a pointing wire or rod attached to a circular dial held in front of subjects. We compare body rotation with a manual dial because these are among the most widely used techniques, and their relative efficiency for collecting data with humans is quite different. Furthermore, there is a suggestion in the literature that whole-body movement measures egocentric knowledge that is relevant to behaviors such as locomotion through an environment in a more ecologically valid manner than some other methods (see below).

Experiment 1 focuses on four important issues. The first involves the motor system that is involved in the estimation procedure. Studies of directional knowledge with nonhuman subjects, many of which are reviewed in a recent special issue of the *Journal of Experimental Biology* (Wehner et al 1996), virtually always examine whole-body locomotion as an indicator of directional knowledge (von Frisch's 'dancing' bees are a famous exception). Because egocentric knowledge of directions in the environment typically serves a purpose of guiding travel, an examination of heading or course during actual locomotion makes some sense as a preferred method for measuring directional knowledge. In fact, one author in the special issue mentioned above (Bennett 1996) has implied that there is almost no relevant human literature on spatial cognitive abilities because observations of actual locomotion course directions are so rarely used as data by researchers of human behavior.

Contrary to this, as we cited above, there is a great deal of research with humans that employs one or more of the other methods for estimating directions. It is likely that methodological decisions were made out of convenience or feasibility; according to the situation of the research, having human subjects actually walk to target destinations is time-consuming, and difficult to record and score (see Klatzky et al 1990 for a convincing example). If one feels that body locomotion is a more valid indicator of directional knowledge, one could simply ask subjects to rotate their bodies to face particular target headings. As a measure of directional knowledge, actual locomotion toward a goal presumably adds to body rotation only the error of straight-line walking (and the potential to measure distance knowledge).

A second important issue examined in experiment 1 involves the question of visibility. In many studies of directional knowledge, interest is in the recall of directions from memory rather than from the perception of immediate directional relationships via vision or audition. This is typically because subjects have sensory disabilities such as blindness (eg Hollins and Kelley 1988; Rieser et al 1980), or because of the long distances and structures characteristic of large-scale environments (eg Montello 1991; Thorndyke and Hayes-Roth 1982). For these reasons, it is frequently necessary or desirable to study research subjects who have their sensory access to the environment partially or completely blocked, including their vision and audition. A critical point is that sensory blockage may obscure not only the targets to which directions are being estimated but an immediate visual context provided by the floor or walls of the testing room or instruments such as a pointing dial used to collect estimates. Foley and Held (1972), for instance, found some deterioration of pointing accuracy with the hand when it was obscured from vision but the target was not (see also Lovelace and Anderson 1993). An important concern, therefore, is with the performance of various estimation methods under conditions of either complete or partial vision restriction. In our first experiment, we compare performance while vision is completely restricted with a blindfold with performance while vision is partially restricted with a hood; in the latter case, subjects can see their feet, the floor surface around their feet, and the face of a pointing dial.

A third issue addressed in experiment 1 involves the way errors are calculated on directional data. According to Spray (1986), absolute error is the best overall index of 'accuracy' insofar as it most strongly relates to the probability of a person pointing within a range around the correct answer on any given trial of performance. However, Schutz and Roy (1973) pointed out many years ago that absolute error in fact confounds constant and variable error, and can be misleading unless there is little or no constant error (in which case it is equivalent to variable error). Constant error is the difference between the mean answer for a particular item and the correct answer. It reflects consistent bias in estimation across responses, such as a consistent tendency to point clockwise of the correct direction. Variable error may be calculated in different ways; for each item, we average the absolute values of the differences between each subject's response and the mean direction for all subjects on that item within a given condition (ie the mean angular deviation). Other possibilities include angular variance, standard deviation, and range measures. Variable error reflects inconsistency or disagreement across responses, essentially a measure of precision of estimation across trials.

The first step in the separation of variable and constant errors is to calculate the mean direction or vector of the responses to a particular item. The mean vector for a set of directions is appropriately calculated by using circular statistics (Batschelet 1981). Called *phi*, the mean vector is calculated by decomposing each estimate into its sine and cosine, averaging those separately, and then retransforming them back into a vector. It is appropriate whenever one works with directional or circular data, such as vectors in space or cyclic occurrences in time. A circular-analytic approach to a directional variable deals with such ambiguities as the fact that 5° and 355° are very far numerically but very close in space (an arbitrary definition of the latter as -5° does not solve this problem either). Mean directions calculated as if the variable was actually linear are incorrect (that is, calculating a standard arithmetic mean on untransformed angles)—slightly if the vectors are fairly close together, dramatically if the vectors are widely distributed around the circle of egocentric space. An extreme example of the latter would be averaging two vectors of 90° and 270°: the mean is 180° by standard linear averaging, but there is no mean direction according to circular averaging, clearly the correct mean.

It is instructive to consider the results of Haber et al (1993) with respect to how error is calculated on directional data. Their analyses were based almost entirely on absolute error from correct. They did present variability analyses as well, but these were based on the variability of absolute errors, not the variability of actual estimated directions (variable error as described above). Calculating variability in this way, Haber et al found that methods with higher absolute error also had greater absolute variability. This is not particularly informative; a positive correlation of means and variability is generally to be expected whenever one is working with a variable that is free to vary in only one direction (eg cannot be less than 0). Response time is another common example of such a variable, and it is usually subjected to a transformation to help overcome this correlation.

Haber et al did report constant errors for their methods, but only for trials in which the correct answer was straight ahead. Furthermore, it does not appear that they calculated constant errors with circular statistics, though given the apparently high concentration of their estimates around mean directions, this miscalculation would produce only a small distortion in their results.

A fourth and final issue addressed in experiment 1 concerns the issue of the underlying reference system used to organize egocentric directional knowledge. We previously (Sadalla and Montello 1989), for instance, found clear support for an orthogonal system as an organizer of egocentric space. That is, estimates of directions traveled were most accurate near the orthogonal directions of 0°, 90°, 180°, and 270°. Franklin and her colleagues (Franklin et al 1995; Franklin and Tversky 1990) have proposed a 'spatial-framework' model that incorporates the idea of an orthogonal egocentric reference frame but assigns a special role to the importance of the forward direction. Because we ask subjects to estimate directions to ten different items in experiment 1, the correct directions varying more or less evenly around subjects' bodies, we will be able to examine pointing accuracy as a function of the angular distance of the correct directions from certain theoretically important 'framework' directions such as orthogonal and forward–back axes.

The four issues of motor system involved in a technique, visibility, treatment of errors, and direction relative to an organizing framework, are examined in the first experiment we report below. Subjects are asked to estimate directions to a set of items in each of four conditions resulting from crossing the factors of Technique and Visibility. Directions are estimated by one of two techniques: either a radius pointer mounted on a circular dial is manually turned, or subjects rotate their bodies in the direction of the heading of an item. In two of the Technique conditions, subjects have their vision completely blocked with an opaque blindfold; in the other two, they are partially vision restricted with an opaque hood that limits vision to a view down toward their feet.

2 Experiment 1

2.1 *Methods*

2.1.1 *Subjects.* Twenty-four students participated in the experiment, twelve males and twelve females (mean age = 18.4 years). Subjects were undergraduates in an introductory psychology class at the University of California, Santa Barbara, and received course credit for their participation.

2.1.2 *Design.* Technique and Visibility were independent variables in this experiment. Direction estimates were collected with one of two techniques, either by using a pointing dial or allowing the subjects to indicate a heading by rotating their bodies to face in the desired directions. There were two levels of Visibility: subjects either wore a blindfold which blocked out all visual input or wore a vision-restricting hood which allowed them to see the pointing dial and their feet. The design was completely within subject; all subjects estimated directions to all target items within each condition.

2.1.3 *Materials.* A circular pointing dial was used to collect directional estimates for half of the trials. It was made of smooth cardboard with a single radius line and rotatable radius wire on the top face; the wire could be rotated to indicate direction. The reverse side of the dial had three-hundred-and-sixty degree tick marks numbered in every 5° around the edge. The line on the top of the dial corresponded to the 0° mark. For the other half of the trials, estimates were collected with a KVH Azimuth 100 digital compass which was mounted in a square-angled metal bracket. The bracket was held against subjects' lower backs by a firm-fitting waist pack worn by the subject. The compass could be reliably mounted on subjects in this way and easily read by the experimenter. The compass was precise to single degrees.

A vision-restricting hood was used to limit visibility in half of the conditions. This hood consisted of a piece of opaque cloth worn over the head which allowed subjects to see straight down around their feet. Subjects stood on a large piece of short-pile carpet throughout the experiment that had no patterned marks or rectilinear texture of any kind on it. Subjects wore either the hood or a pair of swimming goggles which had the lenses made opaque with paint, completely occluding vision when worn. In all conditions a pair of thick shooter's earmuffs was worn by subjects to deaden sound cues (sound-protection factor 30).

To examine the generality of the findings, subjects pointed to ten different target items grouped into three classes, including items within the lab room (the orange cone, whale poster, black case, overhead projector), items outside of the lab on campus (the 'Arbor' ticket office, flagpole, and east-gate entrance to the campus), and cardinal directions (north, southeast). These items were chosen in part so that correct directions were spread fairly evenly around subjects' bodies; figure 1 shows the correct directions to each item from subjects' starting orientation. Correct directions were established through careful repeated measurement separately for each measuring device (the compass and the manual dial). The square lab room measured 7.6 m on a side, and all lab-room items were placed against or on the walls. Last, a questionnaire was created with 7-point scales to assess how well subjects knew the locations of the north direction and of the campus landmarks tested, prior to the study (1 = not at all, 7 = perfectly well). Subjects also wrote down the number of months they had attended the University.

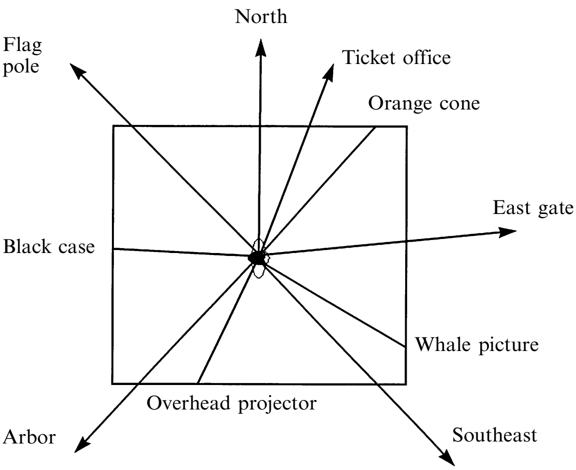

Figure 1. Names and correct directions from subjects' starting orientation for ten target items, experiment 1.

2.1.4 *Procedure.* Subjects were tested individually. They were taken from the lab to a location where three of the outside items were visible. These were pointed out to subjects, along with the direction of a fourth outside item that was not visible from that spot. The direction north was also pointed out. Subjects were told that they would have to point in the directions of the items. After returning inside the lab, subjects were asked to learn the locations of four more items within the room. These items, clearly visible, were pointed out and named while the subject viewed them from the center of the room. After this was done, subjects were asked if they still remembered the outside items. If not, they were taken outside and these items were pointed out to them again.

Testing then began. Each subject did four blocks of testing corresponding to the four different possible combinations of Technique and Visibility. Block order was counter-balanced. All ten items were pointed to four times, once within each block. Item order within each block was completely randomized for each subject. Subjects faced the east wall of the lab as they were asked about each item (see figure 1). In the Body-rotation conditions, subjects were turned back to face east before each trial. In the Dial conditions, the dial was held horizontally directly in front of the subject, with the radius line and pointer facing the subject. The dial was returned to this starting orientation before each trial. Between blocks, the lab door was opened, and the blindfold or hood was removed. Subjects were asked to look out in order to make sure they remained oriented to the outside items. After finishing, subjects completed the questionnaire about their previous knowledge of item locations.

2.2 *Results*

Errors in directional estimates were first analyzed as absolute errors from correct directions (absolute value of difference from correct). These were analyzed in a mixed repeated-measures MANOVA with Technique and Visibility as repeated-measures factors and Sex as a between-subjects factor. Mean error was virtually identical for males and females ($F_{1,22} = 0.00$) and Sex did not significantly interact with either of the other variables. Of primary interest is a comparison of errors as a function of the Technique and Visibility factors. Figure 2a presents mean absolute errors for the four conditions. Absolute error is low compared with chance (90°) in all conditions. It is especially low in the Hooded Body-rotation condition but especially high in the Blindfolded Body-rotation condition. This pattern is confirmed by the MANOVA; the interaction of Technique and Visibility is statistically significant ($F_{1,22} = 9.17$, $p < 0.01$).

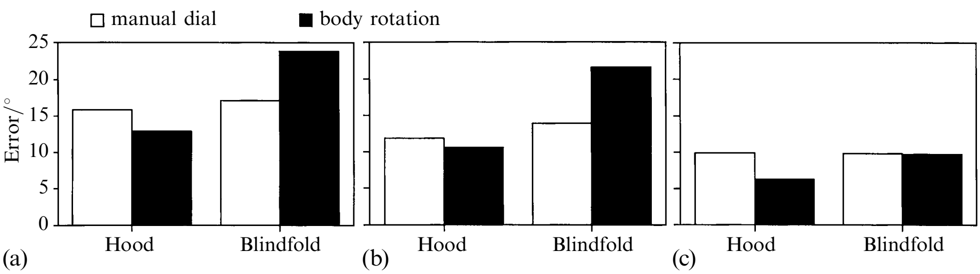

Figure 2. Errors for the four conditions, experiment 1: (a) absolute, (b) variable, (c) absolute constant. Absolute errors are based on absolute values of differences between estimated directions and correct directions. Variable errors are based on absolute values of differences between estimated directions and the directional mean for each item within each condition. Absolute constant errors are based on absolute values of constant errors, differences between the directional mean and correct directions, for each item within each condition. Absolute constant error thus reflects only the magnitude of constant error within each condition, not its direction.

To understand the nature of the interaction between Technique and Visibility, simple-effects tests were conducted. The simple effect of Technique was significant within the Vision-restricting Hood condition ($F_{1,22} = 4.42$, $p < 0.05$) and within the Blindfolded condition ($F_{1,22} = 5.18$, $p < 0.05$). When the hood was worn, error was about 3° higher when using the manual dial than when rotating the body; when the blindfold was worn, error was about 7° lower when using the dial than when rotating the body. From the perspective of Visibility, the dial was used equally accurately whether subjects were hooded or blindfolded ($F_{1,22} = 0.77$, ns). Body rotation, however, was about 11° less accurate when subjects were blindfolded as compared with wearing the hood ($F_{1,22} = 10.83$, $p < 0.005$).

It was of interest to determine if this pattern of pointing accuracy held for each of the three classes of items to which subjects estimated directions. Items were grouped into room, campus, and cardinal direction classes. Item class was entered into a repeated-measures MANOVA, along with Technique and Visibility. The three-way interaction was not significant ($F_{2,23} = 0.53$), confirming that the two-way interaction of Technique and

Visibility described above was replicated within each class of items. However, the two-way interactions of Item class with Technique ($F_{2,23} = 7.28$, $p < 0.01$) and with Visibility ($F_{2,23} = 4.12$, $p < 0.05$) were significant. Examination of figure 3a suggests that the dial resulted in less error than body rotation most clearly in the case of the room items. Only when pointing was to room items was the difference between the two techniques significant ($F_{1,23} = 8.84$, $p < 0.01$). Error was not significantly different for either the campus items ($F_{1,23} = 1.24$) or the cardinal directions ($F_{1,23} = 0.96$). Similarly, figure 3b indicates that pointing while wearing the vision-restricting hood was more accurate than while blindfolded, most clearly again in the case of the room items. The difference was significant, however, for both the room items ($F_{1,23} = 13.93$, $p < 0.001$) and the campus items ($F_{1,23} = 4.18$, $p < 0.05$). Apparently because of the larger variability in the data, the difference was not significant for the cardinal directions ($F_{1,23} = 1.26$).

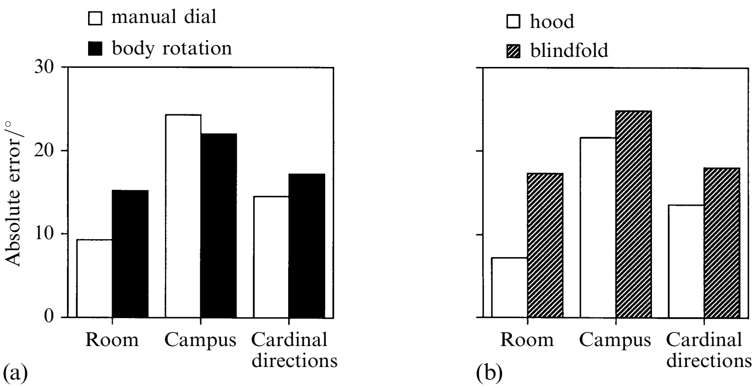

Figure 3. Absolute errors for the three item classes within conditions, experiment 1: (a) Technique conditions, (b) Visibility conditions.

We next investigated whether pointing accuracy varied as a function of block order, and whether the effects of the Technique and Visibility conditions depended on block order. In fact, though mean error (M) did drop a little across blocks of trials as would be expected ($M_1 = 20.4°$, $M_2 = 17.4°$, $M_3 = 16.9°$, $M_4 = 14.7°$), this drop was not significant ($F_{3,21} = 1.27$). Between-subjects comparisons of Technique and Visibility carried out separately within the four blocks of trials (first, second, third, fourth) showed that the effects of Technique and Visibility were strongest for the first block of trials. Keeping in mind that these analyses are much less powerful because they do not take advantage of within-subject comparisons, they did reveal that the interaction of Technique and Visibility approached significance only within the first block of trials ($F_{1,20} = 3.20$, $p = 0.09$). Main effects of neither Technique nor Visibility reached statistical significance in any block of trials taken separately.

A last analysis involving absolute errors examined their relationship to the various self-report questions. The mean number of months subjects reported having attended the University was 5.1, with a minimum of 2 and a maximum of 24. Unexpectedly, this did not correlate with mean error in pointing to all of the outside campus items combined ($r_{22} = 0.06$). However, mean error in pointing to most of the campus items did correlate in the expected negative direction with self-reported prior knowledge of the location of that item (values of r were: arbor −0.32, flagpole −0.41, ticket office −0.40, east gate −0.01, north 0.17).

2.2.1 *Constant and variable errors.* The nature of the major error patterns described above can be understood more fully by separating errors into constant and variable errors. Figures 2b and 2c present mean constant and variable errors for the four Technique × Visibility conditions. Constant errors are calculated for each item within each condition, by using circular statistics as described above; that is, constant error is the difference between phi and the correct direction for each item. It would be meaningless to average these as directional (signed) errors across the ten items within a condition because the items are spread around the 360° field, and averaging would result in clockwise and counterclockwise biases in different parts of space canceling each other out (unless there is a consistent bias in only one direction around the entire field, which is not the case in any condition). Therefore, figure 2c presents *absolute constant errors*, in which we take the absolute values of directional constant errors for each item and calculate the arithmetic mean of them within each condition. Absolute constant errors thus reflect only the magnitude of constant error within each condition, not its direction.

Removal of the constant errors from the absolute errors, leaving variable errors, is informative. The pattern of variable errors in figure 2b is similar to that found with absolute errors but even clearer: low and nearly equal error in all four conditions, except the Blindfolded Body-rotation condition, which is considerably higher. This is again confirmed by a significant interaction between Technique and Visibility ($F_{1,22} = 7.88$, $p < 0.01$). As was the case with absolute error, males and females performed nearly identically on variable error ($F_{1,22} = 0.06$) and Sex does not significantly interact with any other variable. The simple effect of Technique is significant only when subjects were blindfolded ($F_{1,22} = 6.93$, $p < 0.05$), not when they wore the vision-restricting hood ($F_{1,22} = 1.05$, ns). When the blindfold was worn, variability was about 8° lower with the dial than when rotating the body. From the perspective of Visibility, the dial was used with equal variability whether subjects were hooded or blindfolded ($F_{1,22} = 2.15$, ns). Body rotation, however, was about 11° more variable when subjects were blindfolded as compared with wearing the hood ($F_{1,22} = 10.45$, $p < 0.005$).

The greater clarity in the pattern of variable errors, as compared with absolute errors, is due to the fact that constant errors are not equivalent in all four conditions. Figure 2c shows that absolute constant error was nearly 10° in all conditions except Hooded Body Rotation, where it was a little over 6°. This explains the fact that absolute error was actually lowest in this condition: hooded subjects estimating directions by rotating their bodies showed a smaller consistent bias but equal variability compared with when they used the pointing dial, whether hooded or blindfolded. We do not use a significance test to compare constant errors, however, because they reflect a property of a sample of estimates, not individual estimates. There is only one constant error within each condition, averaged across items, with no variation in constant error across subjects to use as an estimate of error variance.

2.2.2 *Framework analyses.* As described in section 1, correct directions to the ten different items were distributed more or less evenly around subjects' bodies, allowing us to examine biases in pointing accuracy as a function of the possible influence of a 'framework' for organizing egocentric spatial knowledge. We assess the influence of organizing frameworks by examining absolute errors for each item as a function of the angular distance of the correct directions from certain theoretically important framework directions. Three frameworks are examined (figure 4): orthogonal axes (straight ahead, straight behind, to the left, to the right), forward–back axis (straight ahead, straight behind), and forward half axis (straight ahead only). With items treated as the unit of analysis ($n = 10$), correlations were computed between the mean absolute error on each item (averaged over all subjects) and the absolute angular distance between the correct direction to an item and the closest axis of the particular framework in question. For example, the correct direction to the orange cone was 36° from straight to the left (nearest orthogonal axis), and 54° from straight ahead (both forward–back and forward axes). These correlations thus allow us to investigate whether error in pointing to items is

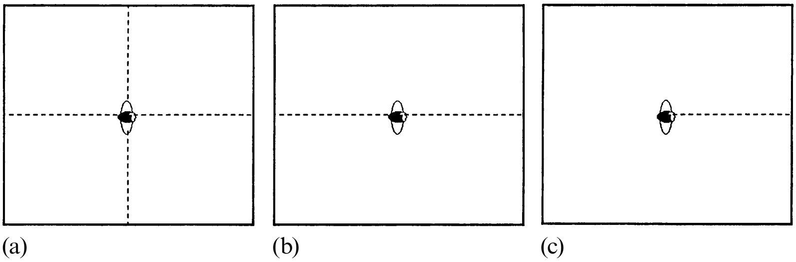

Figure 4. Three directional 'frameworks' for organizing knowledge of egocentric directions: (a) orthogonal, (b) forward – back, (c) forward.

greater as the correct direction to the items gets further from a framework axis. The correlations are calculated separately within each of the four Technique × Visibility conditions, resulting in a total of twelve correlation coefficients.

Results are shown in table 1. Although only one correlation reaches significance with only ten data points, the pattern is clear. When directions were estimated with the manual dial, error increased as the direction to the item differed more from the closest orthogonal axis. Whether subjects could see the dial or not had little effect on this pattern (recall that there was only a single radius line drawn on the face of the dial, not an orthogonal cross). There was no such orthogonal pattern when directions were estimated by rotating the body. Instead, error increased significantly as the direction to the item differed more from straight ahead (ie approached directly behind). However, this pattern held only when subjects were completely blindfolded; it was absent if they could see their feet and the surrounding floor nearby (ie were wearing the hood). The lack of a relationship between error and any of the framework axes in the Hooded/Body-rotation condition suggests, as was intended, that the textureless carpet effectively provided no systematic linear or orthogonal cues to direction.

Table 1. Relationship of absolute pointing error within each condition to distance of correct direction from possible framework axes, experiment 1. Correlations were computed over items ($n = 10$). Positive correlations indicate greater error associated with greater distance from closest framework axis.

Condition	Orthogonal axes	Forward – back axis	Forward half axis
Hood – Dial	0.39	0.06	0.05
Hood – Body	0.08	−0.23	−0.18
Blindfold – Dial	0.54	−0.03	−0.18
Blindfold – Body	−0.14	−0.21	0.73*

*$p < 0.05$.

2.3 *Discussion*

Results of experiment 1 indicate that the use of a manual pointing dial is as good a technique for measuring directional knowledge in humans as is the use of body heading (rotation), even though the latter is sometimes posited to be a more direct and ecologically relevant measurement technique. In fact, blindfolding research subjects so that they are completely without visual access to the surrounds does not impair the performance of the manual-dial technique, while the performance of body heading is significantly degraded by blindfolding subjects. Analysis of constant and variable errors indicates that these patterns are a function of the greater variability in performance associated with estimating directions by body rotation when vision is completely occluded. To interpret this, it is critical to note that performance of the body-rotation method is as good as the manual dial when subjects can see the area down around their feet. In fact, body rotation results in less bias (constant error) in pointing under these circumstances. The relatively good performance of body rotation by hooded subjects indicates that nothing about the specific way in which we calibrated or attached the digital compass precludes performance by blindfolded subjects from being just as good as in the other conditions. Analysis of block order further suggests that patterns of error are most pronounced during early trials of data collection and may be attenuated by practice effects reflected in later repeated trials.

Consideration of our results points to some of the process factors that may have contributed to the error patterns reported here. Subjects can estimate directions quite well by rotating their bodies to target headings, as long as they can see their feet and the surrounding floor. During blindfolded rotation, once subjects begin to turn, they have to rely on a short-term vestibular memory trace to keep track of how far they have turned. If they falter, they have no access to their initial heading. When rotating with sight, on the other hand, optic flow from the carpet may produce a stronger and more accurate memory trace for the initial heading. The correlations presented in table 1 also suggest that at least some subjects use the sight of their feet at the beginning or during body rotation in order to maintain orientation with the body-heading technique.

Subjects also estimate directions well with the manual pointing dial. Whether blindfolded or not, subjects apparently can maintain orientation to the four headings of an orthogonal reference frame at all times during pointing trials. For instance, if subjects want to point just past 90°, they can flip the pointing wire very close to 90° and then check that the angle is indeed greater than 90° quite accurately. Because visual access to the dial (and feet and floor) does not facilitate or impede accurate pointing, it appears that subjects can maintain orientation to the dial tactually as they turn the radius pointer. It bears noting that the orthogonal framework that operates when estimating with the dial is apparently imaginary and not directly perceived from any cues actually on the dial or in the environment.

The pattern of error associated with the Technique and Visibility conditions replicates across three classes of target items: room items, campus items, and cardinal directions. However, differences between the two Technique conditions, and between the two Visibility conditions, are most pronounced when subjects point to room items. These items were the closest to subjects and the only items whose locations were not known to subjects at all prior to the study. The room items are pointed to with the lowest error overall, which might mean they are simply more sensitive to method manipulations (they did result in lower variance). Although the cause of these patterns is ambiguous, they do suggest that the nature of the testing items used in a study may have implications for a researcher's decision as to which pointing method to use.

Of course, material objects and landmarks have width; they subtend several degrees of azimuth in some cases. This could contribute error to directional estimates, most likely from a little increased variability. We did not explicitly instruct subjects to indicate the direction *to the center* of an item, though we did demonstrate it. In general, we believe that subjects performing directional estimation implicitly understand that their task is to estimate the direction to the center of a target, though we have no direct evidence for this. In any case, such a contribution to error is not relevant for narrow or distant items that subtend less of an angle than the error found under optimal estimation conditions (at least three or four degrees, as reported below in experiment 2). Most importantly, any such confusion about estimating directions to the center of an item would operate equivalently in all conditions in our experiments; in particular, it should operate in the same way whether subjects use a manual dial or rotate their bodies.

Our finding that blindfolded adults indicate directions with a manual dial more accurately than by body rotation apparently contradicts the results of Haber et al (1993) reported above. However, all of their targets were in the front half of egocentric space, spread across 180°, while ours were spread around the entire 360° field of egocentric space. The framework analyses indicate that blindfolded body rotation degrades with angular distance from straight ahead. Furthermore, there are several additional differences between their methodology and ours that may be relevant. Their subjects were blind rather than blindfolded; the possibility that experience with blindness influences the way direction methods are used is intriguing and has implications for research such as that by Loomis et al (1993), cited above. Probably most importantly, the targets used by Haber et al were concurrently perceived auditory targets rather than visual targets recalled from memory. Many of the process issues we considered above, such as a demand on working memory, do not apply when concurrent sensing of targets can occur. Furthermore, subjects in Haber et al stood with their backs against a wall at the start of each trial but were "told they could move their body as needed during each trial" (page 40). Given that their auditory targets were played concurrently during trials, this is not clearly a study of directional estimation. Instead, subjects could simply rotate their heads until they perceived the target in the midline of their bodies, a perceptual task which humans are known to carry out very precisely and accurately without the need for actual knowledge of direction.[1] Experiment 2 was carried out to address these issues and provide data to compare with the results of Haber et al.

3 Experiment 2

Experiment 2 was conducted in order to replicate our findings from experiment 1, particularly the finding that blindfolded body rotation results in greater pointing variability than does the use of a manual dial. Our second experiment also allowed us to examine possible explanations for the patterns in our first experiment, and allowed us to account for some of the differences between our results and those of Haber et al (1993). We once again had subjects estimate egocentric directions either by rotating their bodies or by using a manual pointing dial. Unlike experiment 1, the vision-restricting hood was not used in experiment 2, and only room items were used as targets. In one condition, the two techniques were compared under Blindfolded Visibility conditions, replicating part of experiment 1. In a second condition, subjects wore the blindfold but responded to concurrently perceptible auditory targets, replicating Haber et al. In a third condition, the role of working-memory demand was examined by allowing blindfolded subjects to lift the blindfold between trials, affording a 'peek' at the room, the dial, their feet, and the floor area. This should have reduced memory load, providing a test of the hypothesis that errors are greater during blindfolded body rotation because of a demand caused by having to remember the locations of target items relative to one's starting orientation throughout a block of trials. Last, in a fourth condition, subjects pointed to the room items without wearing a blindfold. This established baseline levels of performance for each technique under conditions of unrestricted visibility, essentially producing evidence of the optimal performance possible with each technique.

3.1 *Methods*

3.1.1 *Subjects.* Twenty-four students participated in the experiment, nine males and fifteen females (mean age = 19.2 years). Subjects were undergraduates in an introductory geography class at the University of California, Santa Barbara, and received course credit for their participation.

[1] Acknowledgements to Jack Loomis for pointing this out to us.

3.1.2 *Design.* Technique and Modality were independent variables in this experiment. Direction estimates were again collected with one of two Techniques, either by using the manual dial or allowing subjects to indicate a heading by rotating their bodies to face in the desired directions. There were four levels of Modality: (1) Blindfold—subjects wore a blindfold that blocked out all visual input during a block of trials, which replicates a condition in experiment 1; (2) Auditory—they wore the blindfold and responded to auditory targets; (3) Peek—they wore the blindfold but got to peek at the room objects between each pair of trials; or (4) Eyes open—they estimated directions with their eyes open throughout the session. As in experiment 1, the design was completely within subject; all subjects estimated directions to all target items within each condition.

3.1.3 *Materials.* The circular pointing dial and digital compass were again used in this experiment. In the Auditory condition, 6-inch-diameter speakers were hung from the ceiling right above or in front of the corresponding visible target, thus equating the actual directions across conditions. Each speaker was suspended 1 m above the floor, pointing up toward the ceiling. The speakers emitted a 1000 Hz pure tone (as in Haber et al 1993). The vision-restricting hood was not used in this experiment, but the same blindfolding goggles were used. The shooter's earmuffs were not used in this experiment; subjects in the Auditory condition had to be able to hear, and we wanted to keep the conditions equivalent in this respect.

In this experiment, subjects pointed only to items in the lab room. In addition to the orange cone, whale poster, black case, and overhead projector used in experiment 1, subjects also estimated directions to a plant and a map, bringing the total number of items (and number of trials within each block) to six. Again, the correct directions to these six items were spread fairly evenly around subjects' bodies; figure 5 shows the correct directions to each item from subjects' starting orientation.

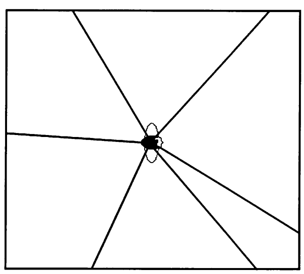

Figure 5. Names and correct directions from subjects' starting orientation for six target items, experiment 2.

3.1.4 *Procedure.* Subjects were again tested individually. After meeting the experimenter in the lab, they were asked to learn the locations of the six items within the room. As in experiment 1, these items were pointed out and named while the subject viewed them from the center of the room. Testing then began. Each subject did eight blocks of testing corresponding to the eight different possible combinations of Modality and Technique. Block order was counterbalanced across subjects, with the exception that all subjects did the two Eyes-open conditions last (half using the dial during the seventh block, half using body rotation during the seventh block). All six items were pointed to eight times, once within each block. Item order within each block was completely randomized for each subject. As in experiment 1, subjects initially faced the east wall of the lab as they were asked about each item (see figure 5). In the Body-rotation conditions, subjects were rotated back to face east before each trial. In the

Dial conditions, the dial was held horizontally directly in front of the subject, with the radius line and pointer facing the subject. The dial was returned to this starting orientation before each trial. Both of these procedures were exactly as in experiment 1. Except in the Eyes-open condition (where no blindfold was used), the blindfold was removed between each block of trials. In addition, in the Peek condition, subjects were instructed to pull up the blindfold between each pair of trials and look at the room items.

3.2 *Results*

Errors in directional estimates were again analyzed first as absolute errors from the correct directions, in a mixed repeated-measures MANOVA with Technique and Modality as repeated-measures factors and Sex as a between-subjects factor. As in experiment 1, mean error was virtually identical for males and females ($F_{1,22} = 0.29$) and Sex did not significantly interact with either of the other two variables. Figure 6a presents mean absolute errors for the eight Technique × Modality conditions. Once again, absolute error is low compared with chance (90°) in all conditions. However, as indicated by a significant interaction between Technique and Modality ($F_{3,22} = 4.21$, $p < 0.05$), error is not equally low in all conditions. To understand the nature of this interaction, simple-effects tests were conducted. Unlike in experiment 1, absolute error was not greater when blindfolded subjects estimated direction by body rotation, as compared with using the dial ($F_{1,22} = 0.01$). In fact, error was much lower in the Body-rotation condition in this experiment than in our first experiment (13.9° versus 23.8°); error with the Dial condition was more similar in the two experiments (14.4° versus 17.0°).

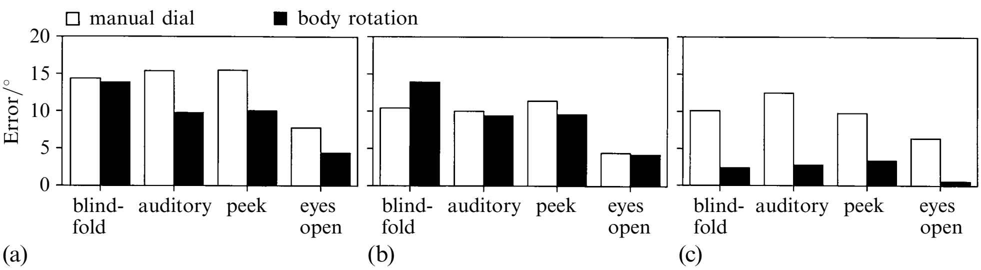

Figure 6. Errors for the eight conditions, experiment 2: (a) absolute, (b) variable, (c) absolute constant. Absolute errors are based on absolute values of differences between estimated directions and correct directions. Variable errors are based on absolute values of differences between estimated directions and the directional mean for each item within each condition. Absolute constant errors are based on absolute values of constant errors, differences between the directional mean and correct directions, for each item within each condition. Absolute constant error thus reflects only the magnitude of constant error within each condition, not its direction.

Simple-effects tests on absolute error also revealed that using the dial led to significantly more absolute error than did body rotation, for all of the other three Modality conditions: Peek ($F_{1,22} = 4.38$, $p < 0.05$), Auditory ($F_{1,22} = 19.63$, $p < 0.001$), and Eyes open ($F_{1,22} = 23.97$, $p < 0.0001$). From the perspective of Technique, absolute error was significantly different across the four Modality conditions for both the dial ($F_{3,22} = 29.24$, $p < 0.0001$) and body rotation ($F_{3,22} = 44.46$, $p < 0.0001$). With the manual dial, error was nearly equal when subjects were blindfolded, peeked, or pointed to auditory targets. It was about 7° less when subjects pointed with their eyes open, providing an estimate of optimal performance for the manual dial of 7.8°. In contrast, when body rotation was used to estimate directions, error was greatest when subjects were blindfolded, about equal when they peeked or pointed to auditory targets, and was lowest when subjects pointed with their eyes open. In the last condition, error was quite low, only 4.4° for an estimate of optimal performance possible when directions were measured with body rotation and a body-mounted compass as we did.

In this experiment, subjects pointed to six room items repeatedly in a series of eight blocks of trials. However, the two Eyes-open conditions were always conducted last (in counterbalanced order). Therefore, we next looked at the possible effects of block order for the first six blocks only. Mean error was quite constant across the blocks, actually rising a little in the later blocks, perhaps as a result of fatigue ($M_1 = 12.3°$, $M_2 = 12.6°$, $M_3 = 11.1°$, $M_4 = 13.7°$, $M_5 = 13.1°$, $M_6 = 16.3°$). As in experiment 1, however, these variations were not significant ($F_{5,19} = 0.88$). Between-subjects analyses of Technique and Modality were carried out separately within each of the six blocks of trials. The interaction of Technique and Modality was not significant in any block, and main effects of either variable reached significance only in the first and third blocks.

3.2.1 *Constant and variable errors.* The nature of the error patterns described above can once again be understood more fully by separating errors into variable and constant errors. Figures 6b and 6c present mean variable and absolute constant errors for the eight Technique × Modality conditions. This separation is especially informative here. Examining variable errors in figure 6b, we again find a significant interaction between Technique and Modality ($F_{3,22} = 4.11$, $p < 0.05$). Unlike for the pattern with absolute errors, we now replicate the finding from experiment 1 that variable error is greater when blindfolded subjects estimated directions by body rotation than when using the dial. This difference is only 3.5° in experiment 2, but it is clearly reliable ($F_{1,22} = 9.47$, $p < 0.01$). As was the case with absolute error, males and females performed similarly in terms of variable error ($F_{1,22} = 1.60$) and Sex did not significantly interact with any other variable.

Interestingly, variable error did not differ for the dial and body-rotation techniques for any of the other Modality conditions: Peek ($F_{1,22} = 0.58$), Auditory ($F_{1,22} = 0.69$), or Eyes open ($F_{1,22} = 0.33$). From the perspective of Technique, variable error was significantly different across the four Modality conditions for both the dial ($F_{3,22} = 50.41$, $p < 0.0001$) and body rotation ($F_{3,22} = 41.38$, $p < 0.0001$). This pattern is identical to that found for absolute error. With the manual dial, error was nearly equal when subjects were blindfolded, peeked, or pointed to auditory targets. It was about 6° less when subjects pointed with their eyes open. In contrast, when body rotation was used to estimate directions, variable error was greatest when subjects were blindfolded, about equal when they peeked or pointed to auditory targets, and was lowest when subjects pointed with their eyes open.

As in experiment 1, one can gain a greater understanding of the relationship of absolute errors to variable errors by examining the patterns of constant errors. These are quite different in the various conditions. As figure 6c reveals, the magnitude of constant error (as reflected by absolute constant errors) was greater in all conditions in which the manual dial was used. With the dial, constant error is approximately 10° in the Blindfold, Peek, and Auditory conditions, and about 6° in the Eyes-open condition. In strong contrast, constant error with body rotation is only about 3° in the first three Modality conditions, and a paltry fraction of a degree in the Eyes-open condition. To summarize, variable error is greater when using body rotation than when using the dial if subjects are blindfolded; otherwise it is equivalent. Constant error is greater when using the dial in all Modality conditions. Because constant and variable errors are conflated when data are analyzed as absolute errors, which they commonly are, this interesting pattern is typically obscured.

3.2.2 *Framework analyses.* As in experiment 1, we examine biases in pointing accuracy as a function of the influence of organizing frameworks for egocentric spatial knowledge. Correlations were again computed between the mean absolute error on each item ($n = 6$) and the absolute angular distance between the correct direction to an item and the closest axis of the particular framework in question. The same three frameworks are examined (figure 4): orthogonal axes (straight ahead, straight behind, to the left, to the right), forward–back axis (straight ahead, straight behind), and forward half axis (straight ahead only). The correlations are again calculated separately within each of the eight Technique × Modality conditions, resulting in a total of twenty-four correlation coefficients. Results are shown in table 2. Even though each correlation is based on only six cases, the pattern of correlations is very clear and strongly replicates the pattern found in experiment 1. The largest positive correlations, which indicate greater error associated with greater distance from a frame axis, are found for the orthogonal framework when subjects used the manual dial. This is true in all Modality conditions. Conversely, when subjects used body rotation to estimate directions, error correlated most positively with the forward-half-axis framework. This is true except when subjects turned with their eyes open, in which condition there were no strong correlations with any of the three frameworks (it should be remembered that this was the only Modality condition in experiment 2 in which subjects had constant visual access to their feet, the floor, or any part of the room while rotating).

Table 2. Relationship of absolute pointing error within each condition to distance of correct direction from possible framework axes, experiment 2. Correlations were computed over items ($n = 6$). Positive correlations indicate greater error associated with greater distance from closest framework axis.

Condition	Orthogonal axes	Forward–back axis	Forward half axis
Blindfold–Dial	0.73	0.57	−0.94**
Blindfold–Body	−0.94**	−0.31	0.80*
Auditory–Dial	0.88*	0.54	−0.97**
Auditory–Body	−0.97**	−0.55	0.92**
Peek–Dial	0.93**	0.49	−0.91*
Peek–Body	−0.94**	−0.34	0.83*
Eyes open–Dial	0.81*	0.51	−0.96**
Eyes open–Body	−0.22	−0.16	0.20

*$p < 0.05$, **$p < 0.01$.

3.3 *Discussion*

In experiment 2, analysis of absolute error did not reveal a difference between body rotation and the manual dial when subjects were blindfolded, as it had in experiment 1. However, decomposing absolute error into variable and constant error reveals that we did replicate the finding from experiment 1 that the use of body rotation as a method for collecting directional estimates produces greater variable error than does the use of a manual dial, when subjects are blindfolded and pointing to targets from memory of their locations before the block of trials. Similarly, as in the first experiment, constant error is greater with the manual dial—this is true for all Modality conditions. These results hold in spite of the fact that error is several degrees less in this experiment than in experiment 1, especially for body rotation; the lower error is probably because only room items were used in experiment 2, and there were two more blocks of practice in its design.

Experiment 2 was intended to account for some differences between the results of our first experiment and those of Haber et al (1993). This comparison can only be approximate; Haber et al tested blind rather than blindfolded subjects, their targets were limited to the front half of egocentric space, and they did not use circular statistics to analyze constant and variable errors. In fact, when we have subjects point to concurrent auditory targets, even though still blindfolded, we do find that absolute error is greater with the dial than with body rotation, as Haber et al found. When analyzed as variable and constant error, however, it turns out that this difference is almost entirely due to the greater constant error resulting from use of the dial. Error pointing to auditory targets is about equally variable when using the dial or body rotation.

Experiment 2 has a Peek condition designed to shed light on one possible explanation for differences found in experiment 1 between blindfolded body rotation and pointing with a dial. The Peek condition allowed subjects to lift the blindfold between trials, intended to relieve some of the demand on working memory. Unlike pointing while blindfolded throughout the block of trials, this did result in greater absolute error for the dial than body rotation. As when subjects pointed to auditory targets, constant error is greater for the dial, and variable error is nearly equal for the dial and body rotation. The opportunity to peek at targets in between trials allowed subjects to point to targets less variably with body rotation, as compared with body rotation while blindfolded throughout. If one considers that variable error from body rotation was not inflated when subjects wore the vision-restricting hood in experiment 1, it appears that blindfolded body rotation produces extra variable error because of a demand on memory for a clear sense of one's initial heading before rotating on each trial, rather than a confusion or forgetting about the locations of target items.

In a fourth condition, subjects pointed to the room items with their eyes open throughout. This establishes baseline levels of performance for each technique under conditions of unrestricted visibility, essentially producing evidence of the optimal performance possible with each technique. Performance is quite good under these conditions. Absolute error is 7.8° with the manual dial and 4.4° with body rotation. This difference is again due to greater constant error with the dial, an average of 6.4° with the dial and only 0.6° with body rotation. Variable error is very similar with the two techniques, 4.4° and 4.2°, respectively.

Last, the frame analyses in experiment 2 replicate the findings from experiment 1. When using the manual dial, error is smallest for targets whose directions lie close to one of the four orthogonal directions of ahead, behind, right, or left. Conversely, when using body rotation, error is smallest for targets nearest straight ahead, except for when subjects point with their eyes open throughout. In experiment 1, it was also found that error did not correlate with any of the possible frameworks when subjects rotated their bodies while wearing the vision-restricting hood. This clearly suggests that blindfolded body rotation puts a demand on subjects to remember their initial heading as they attempt to rotate to target items. Confusion or forgetting of their initial heading as they engage in body rotation results in greater variable error for this technique. Allowing subjects to have visual access to their feet, the floor, or their surrounds (as in the Hood condition of experiment 1 or the Eyes-open condition of experiment 2) removes this confusion while subjects rotate, so that targets far from straight ahead are estimated just as accurately as those near straight ahead.

4 General discussion

Pointing with a dial or rotating one's body are behaviors that can be used to externalize people's 'knowledge of egocentric directions'. The latter is a construct hypothesized to underlie the behaviors that are actually quantified as part of the measurement process. Concerns about construct validity and measurement reliability thus require a careful consideration of the amounts and patterns of variance in directional data that result from the particular method used to generate data. The results of these two experiments make clear that different methods for externalizing people's knowledge of egocentric directions contribute error to directional data in different amounts and in different ways.

When accuracy is interpreted as absolute error from correct, it is evident that subjects' perceptual access to their surroundings has important implications for the performance of body rotation versus a manual dial. Perceptual access includes visual access to the room in which subjects estimate directions or at least the floor around one's feet, as well as visual or auditory access to the target items themselves. In experiment 1, absolute error was much worse for the body-rotation technique than for the dial when subjects were completely blindfolded throughout a block of trials. Experiment 2 did not replicate this difference in absolute error; performance by blindfolded subjects was virtually the same for body turning as for the dial. In both experiments, giving subjects some type of perceptual access between or during trials resulted in absolute error with body rotation equivalent to or lower than with the manual dial. It is clear from both experiments that complete blindfolding during blocks of trials impaired body rotation but had little or no effect on the performance of the manual dial.

This somewhat ambiguous picture of the relative accuracy of the two techniques is considerably clarified by separating absolute error into constant and variable error. In fact, our research shows that such a separation is essential to a complete understanding of patterns of error with different estimation methods. Analyzing spatial data in this way provides an important clarification of the meaning of our results relative to those of Haber et al, and it provides insight into the processes that underlie the estimation of egocentric directions and the operation of different methods for collecting these estimates. In general, body rotation, at least as we employed it in this research, suffers from the restricted perceptual access caused by a blindfold because of increased variability of performance. In both experiments, blindfolded body rotation resulted in significantly greater variable error than the use of the dial while blindfolded. Under all other conditions, which allowed greater perceptual access to the surrounds, variable error was nearly identical for body rotation and the manual dial.

The manual dial, however, resulted in greater constant error, or systematic bias, than did body rotation. This was evident in all but one condition in both experiments. The exception occurred when subjects wore the blindfold in experiment 1; in this condition, the amount of constant error from body rotation was the same as from the dial (though, as stated above, variable error was much greater for body rotation than for the dial in this condition). The increased constant error from the manual dial was particularly evident in experiment 2. In no condition was constant error greater than 4° with body rotation; it was around 10° in three of the four conditions with the manual dial. One reason that constant error may be greater with the dial is the parallax between the subject's location and the location of the center of the pointing dial. When the dial is held in front of the subject, about 30 cm from the body, a confusion about whether to point from the center of the dial or from the center of one's body could produce a constant error of over 5° for items 3 m away. This would of course be negligible for distant target items, or items near straight ahead or straight behind.

The framework analyses from both experiments indicate that subjects use the straight-ahead direction as a reference frame for keeping track of how far they have rotated their bodies under all conditions in which they cannot see their feet and the floor while rotating during trials. In these conditions, estimates further from straight ahead are made with greater error. No reference frame we examined accounts for patterns of error with body rotation when subjects have visual access to their feet and the floor during rotation. When using the manual dial, conversely, an orthogonal reference system of ahead, behind, left, and right is used to estimate egocentric directions under all conditions. Neither visual nor auditory access during or between trials affects this pattern. Estimates further from one of the orthogonal axes are made with greater error.

The framework analyses have implications for the processes involved in the generation of directional estimates. When using a manual dial, subjects apparently employ the four orthogonal directions as reference axes for their estimates. Directions are first estimated as being closest to one of the four axes, then an adjustment is made within the four quadrants of egocentric space in order to estimate the direction to a target within that quadrant (see Huttenlocher et al 1991). This adjustment process adds extra error to the estimate of any target direction not very near to one of the four orthogonal directions; we previously (Montello 1991) discussed this two-part process of 'quadrant' and 'metric' errors. This process apparently occurs even when there is no direct perceptual information to any orthogonal directions; that is, the orthogonal system operates without access to any orthogonal pattern on the dial, on the floor or in the surrounding environment. It is an internalized organizing system, one that does not require external cues for its operation.

When estimating directions by body rotation, on the other hand, subjects rely on a short-term memory trace of their initial forward-facing direction as they rotate to face in the estimated direction. Whenever subjects have visual access to their feet or the surrounding environment during rotation, they can constantly and accurately maintain a sense of their facing direction at any time relative to their initial facing direction. When visual access is blocked during rotation, orientation relative to straight ahead depends on a memory trace that is increasingly in error as one turns further from straight ahead. Knowledge of the initial straight-ahead direction is refreshed between trials, 'reorienting' the memory trace.

The framework analyses are thus relevant to discussions in the literature about underlying reference systems used to organize directional knowledge. We previously (Montello 1991; Sadalla and Montello 1989 for instance), found clear support for an orthogonal system as an organizer of egocentric space. Our data were collected with a manual pointing dial. Franklin and her colleagues (Franklin et al 1995; Franklin and Tversky 1990) have generated support for their 'spatial-framework' model with data generated by a variety of methods, including verbal response times, verbal labeling, body rotation, and cane pointing. The spatial framework incorporates the idea of an orthogonal egocentric reference frame but assigns a special role to the importance of the forward direction. Given that we find an orthogonal framework pattern for the pointing dial and a forward-half-axis pattern for body rotation, it appears that method variance contributes to the various patterns of data offered as support for one framework or another. In particular, body rotation does not produce results supportive of an orthogonal frame. As is generally true in the study of cognition [eg the analogue–propositional debate in mental imagery (Anderson 1978)], a complete model of a cognitive task must include ideas about both the knowledge structures and the processes that operate on these structures to produce external behavior. A model of the cognition of egocentric directions would specify both the structure of directional knowledge stored in long-term memory and effects of specific measurement techniques that operate on knowledge when it is activated into working memory.

Our results have important implications for research on knowledge of egocentric directions. For example, Loomis et al (1993) reported interesting data on the abilities of blind and blindfolded subjects to perform dead-reckoning 'path integration'. Body heading and course were used as measures of directional knowledge. Our results suggest that their data might contain extra variability due to the use of these body methods. Had the researchers used other methods for measuring directional knowledge, such as a manual dial, they might have found support for somewhat better path-integration abilities overall. Also, this methodological issue may have implications for comparisons between blind and blindfolded subjects.

Our data also provide some guidance for researchers choosing a method with which to measure knowledge of egocentric directions. Both a manual dial and body rotation produce satisfactorily low levels of error as long as one's research concerns effects on directional estimation on the order of 20° or more, which is common in research on large-scale or environmental spatial knowledge. Under optimal conditions of full perceptual access, either technique will add less than 10° of measurement error. When testing occurs with blindfolded (possibly blind) subjects, body rotation results in several additional degrees of variable error across trials. Conversely, a manual dial produces a few degrees of additional constant error. This becomes a concern when subjects are indicating directions to relatively close targets (such as inside a room). A remedy for excess constant error, whatever the measurement technique, would be to empirically establish baseline patterns of constant error in a particular research context, which can subsequently be used to correct estimates of directions gathered as data. Given the fact that constant error will not be equivalent in all directions of egocentric space, and any correction may not operate equally well in all directions, it is clear that performance should not be compared among conditions or individuals for which the actual directions of targets are not equated. For example, one should not conclude that performance is better in one condition rather than another, or by one individual rather than another, unless the target directions being compared are matched across the comparison trials. Alternatively, by analyzing variable errors instead of absolute errors, researchers would effectively be removing any effects of differential constant bias.

Of course, the choice of a method for collecting direction estimates can rarely be based solely on patterns of error data like those generated in this study. In most cases for which either a dial or body rotation could be used, the dial is to be preferred because it is less difficult and probably less costly to use. Setting up a system to automatically collect estimates with body heading or course is time-consuming and expensive, but once the system is in place, data collection is quite efficient. Conceptual factors may also play a deciding role; for example, a researcher may be specifically interested in patterns of locomotion to targets or in verbal expressions of spatial knowledge. In addition, any given data-collection effort involves situational factors that will favor some methods over others. Body rotation may be impractical to use in real-world situations, such as testing the spatial knowledge of pedestrians stopped on city sidewalks. Obviously, the distinction between a vision-restricting hood and a blindfold is eliminated when working with completely blind research subjects. Less obviously, subjects may have to remain stable during testing, disallowing the use of body heading or course as measures. Or they may have their hands otherwise occupied, disallowing the use of a manual pointing dial. Furthermore, it may be highly desirable to automate data-collection methods in order to increase the efficiency of data collection, decrease the human error introduced by manual data recording, and allow for accurate and precise timing of pointing responses. Thus, careful considerations of situational and resource factors, in addition to pattern of error performance like those reported above, need to be taken into account whenever research on directional knowledge is planned.

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