Allocentric and Egocentric Spatial Representations: Definitions, Distinctions, and Interconnections

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Abstract. Although the literatures on human spatial cognition and animal navigation often make distinctions between egocentric and allocentric (also called exocentric or geocentric) representations, the terms have not generally been well defined. This chapter begins by making formal distinctions between three kinds of representations: allocentric locational, egocentric locational, and allocentric heading representations. These distinctions are made in the context of whole-body navigation (as contrasted, e.g., with manipulation). They are made on the basis of primitive parameters specified by each representation, and the representational distinctions are further supported by work on brain mechanisms used for animal navigation. From the assumptions about primitives, further inferences are made as to the kind of information each representation potentially makes available. Empirical studies of how well people compute primitive and derived spatial parameters are briefly reviewed. Finally, the chapter addresses what representations humans may use for processing spatial information during physical and imagined movement, and work on imagined updating of spatial position is used to constrain the connectivity among representations.

1 Reference Frames and Spatial Representations

Put simply, a reference frame is a means of representing the locations of entities in space. An entire chapter could be devoted to frames of reference, and several excellent ones have been (see, e.g., Berthoz, 1991; Brewer & Pears, 1993; Levinson, 1996; Soechting, Tong & Flanders, 1996). Nor is the literature deficient in discussions of allocentric and egocentric representations. In fact, the contrast between those two

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terms abounds in discussions of spatial perception, spatial cognition, and spatially directed action. Not everyone treats these terms equivalently, however. Allocentric is sometimes used synonymously with "exocentric" or "geocentric." To Paillard (1971) the geocentric reference frame was gravity-based and subsumed both allocentric and egocentric representations. Pick (1988) has pointed out that although allocentric implies reference to another human, the term has assumed more general use.

Exceptions notwithstanding, there is general understanding that in an egocentric reference frame, locations are represented with respect to the particular perspective of a perceiver, whereas an allocentric reference frame locates points within a framework external to the holder of the representation and independent of his or her position. While the general distinction between allocentric and egocentric representations is commonly made, it is far less common to see a specific proposal for what is represented in each.

2 Some Basic Definitions

In this section, I define critical parameters that are conveyed by spatial representations. It is important to note that the parameters are being defined independently of the nature of the representation that conveys them. For example, the egocentric bearing of a point in space will be defined as an angle that is measured with respect to an object, ego, within the space. The egocentric bearing is a particular numerical value that could be derived from an egocentric or allocentric representation, given relevant input information. It is the parameter definitions, rather than processes that derive the parameters, that are specified in this section.

2.1 Spatial Parameters

The parameters of a spatial representation are values that can be assigned to individual points (e.g., location of one point) or multiple points (e.g., distance between two points). *Primitive* parameters are those that the spatial representation conveys directly for all entities that are included in the representation. *Derived* parameters are those that can be computed from primitives, possibly in several computational steps. A *locational* representation is one that has primitives conveying the locations of points in space. A *heading* representation is one that has primitives conveying the heading of objects in space.

2.2 Points and Objects

A "point" refers to a spatial location for which the values of the primitive parameters in a locational representation are known. An "object" comprises multiple points that are organized into a coherent entity.

2.3 Axis of Orientation of an Object

The axis of orientation of an object is a line between points on the object that defines a canonical direction in space. Not all objects have an axis of orientation; for example, an object that is radially symmetrical has none. The axis of orientation of a person within a space is aligned with the sagittal plane. One can differentiate between the axis of orientation of the head vs. the body, but for most of the present paper, that distinction is irrelevant.

2.4 Heading of an Object

An object's heading in space is the angle between the object's axis of orientation and some reference direction external to the object (see Figure 1). The heading of a moving object can be differentiated from its *course*, or direction of travel as defined over the past few locations that were occupied. Because the reference direction is external to the object (a heading that was defined relative to its own axis of orientation would always be zero), heading will sometimes be referred to as *allocentric heading*.

2.5 Bearing Between Two Points

Like heading, bearing is defined with respect to a reference direction. The bearing from point A to point B is the angle between the reference direction and a line from A to B. If the reference direction is aligned with the axis of orientation of an "ego" (i.e., an oriented organism in the space), the bearing from A to B will be called *ego-oriented*. If any other reference direction is used, the bearing from A to B will be called *allocentric*. The *egocentric bearing* of a point, B, is equivalent to a bearing from ego to B, using ego's axis of orientation as the reference direction. Thus the egocentric bearing is a special case of the ego-oriented bearing, in which ego's location is the source point. The egocentric bearing of B is numerically (but not conceptually) equivalent to the difference between B's allocentric bearing from ego and ego's allocentric heading, when both are defined with respect to a common reference direction. (See Figure 1.)

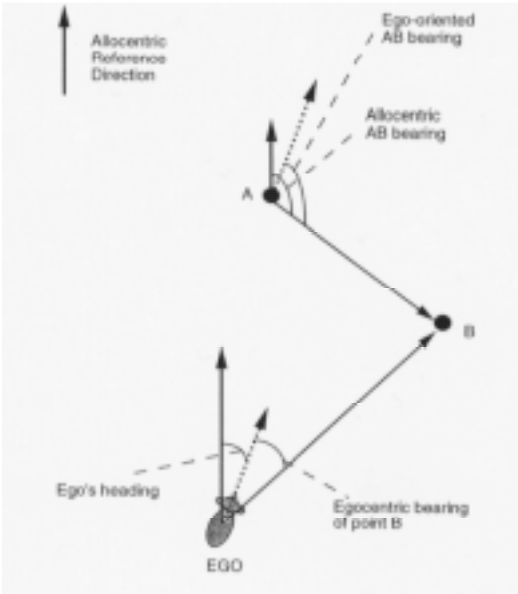

Figure 1. Illustration of basic terms introduced in text

2.6 Distance Between Two Points

The term distance is used here as it is commonly defined, i.e., as a metric relation between points corresponding to their separation in space (typically in this paper, Euclidean). It is sometimes useful to differentiate between egocentric and nonegocentric distance. The *egocentric distance* of some point P is the distance from ego to P; the distance between two points other than ego is called a *nonegocentric distance*.

3 Core Assumptions

This paper stipulates a core set of assumptions about representations of allocentric location, egocentric location, and allocentric heading, as follows.

i) Allocentric and egocentric locational representations convey the layout of points in space by means of an internal equivalent of a coordinate system (which may be distorted or incomplete).

ii) The primitives of allocentric and egocentric locational representations differ. The locational information provided by an allocentric representation is referred to space external to the perceiver; the information provided by an egocentric representation is referred to an ego with a definable axis of orientation. Specifically, the allocentric representation conveys the positions of points in the internal equivalent of Cartesian or Polar coordinates. The egocentric representation makes use of a special polar coordinate system in which the origin is at ego and the reference axis is ego's axis of orientation; it conveys the location of a point by egocentric distance and the egocentric bearing.

iii) In addition to the two types of locational representation, there is also an allocentric heading representation, which defines the angle of ego's axis of orientation relative to an external reference direction.

iv) What can in principle be computed from the primitives in the representations differs, as will be discussed further below. Point-to-point bearings are not stably defined with respect to the egocentric locational representation but can stably be computed from the allocentric one. To compute the heading of a unitary object other than the ego requires that the object be treated as multiple points (or point plus axis of orientation).

v) Connectivity among sensory systems and the different representations allows representations to be updated from sensory input. Sensory signals of changes in heading are input to the allocentric heading representation and from there are input to a locational representation (egocentric or allocentric) for purposes of updating. Signals of translatory changes of position are directly input into the egocentric and/or allocentric locational representation for purposes of updating.

vi) Connectivity between cognitive processes and the representations also allows representations to be updated from imagery -- apparently with limitations, as described below.

4 Primitives of Allocentric and Egocentric Representations

I will deal with primitives of representations in the context of a plane; generalization to three-dimensional space would be straightforward. For convenience, I will use a polar coordinate system to describe locations in the allocentric representation. The issue of Cartesian vs. polar coordinates was discussed by Gallistel (1990) in the context of updating during dead-reckoning navigation. He pointed out that computing within Cartesian coordinates is more stable, because it avoids feedback loops that compound error in updating. For present purposes, however, this issue is not critical, as the formalisms are interchangeable.

The key assumption made here is that different information is primitive in a navigator's allocentric and egocentric locational representations, as shown in Figure 2. An allocentric locational representation has an origin and reference direction. A point P in the allocentric representation has coordinates (d_o, β), where d_o is the distance from the origin and β is the bearing from the origin, defined with respect to the reference direction. A point in the egocentric locational representation has coordinates (d_e, μ) defined with respect to the ego, where d_e is the egocentric distance of the point and μ is its egocentric bearing. Note that the egocentric bearing is not defined relative to the navigator's heading (i.e., relative to an external reference direction); instead, egocentric bearing is defined with respect to an intrinsic axis of orientation that is imposed by the navigator's physical configuration.

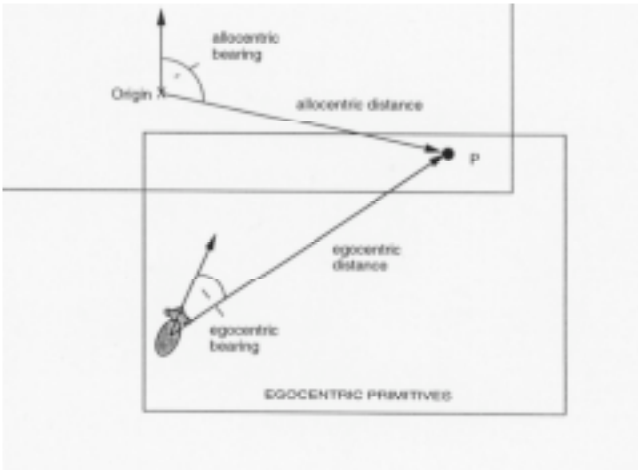

Figure 2. Egocentric and allocentric primitives

An important aspect of this formulation is that neither the egocentric nor allocentric locational representation directly conveys the headings of objects (including the navigator). Heading is not represented as a primitive in these systems, because they represent the locations of single points, which have no orientation. In contrast, object orientations -- which are needed in order to determine heading -- are defined with respect to the object's contours, comprising multiple points. An object has a heading in space only insofar as an axis of orientation can be defined, which requires that the object be represented as comprising at least two points, each with its own location. Although heading is not a primitive in the locational representation, it is a primitive in the allocentric heading representation, which conveys information solely about the heading of the navigator. The headings of other objects are derived properties rather than primitives.

5 Computation of Derived Properties from Allocentric and Egocentric Representations

In this section, I consider what derived properties could theoretically be derived from the various representations by a computational process. As was noted by Loomis et al. (1993), what can be computed in theory does not necessarily coincide with what actually is computable given the human architecture. It is unlikely, to say the least, that people have internalized computational algorithms equivalent to trigonometric axioms like the law of cosines or law of sines. Important spatial processes of humans reside in their ability to construct percept-like images of space that can be scanned, rotated, or otherwise transformed (see Finke, 1989, for review). The limitations on what can be computed are actually more interesting than the set of computable data, since the locational representations are rich enough to potentially convey all possible interpoint distances and angular relations.

5.1 Distance

Egocentric. The *egocentric distance* of a point is a primitive in the egocentric locational representation. The egocentric distance must be derived in the allocentric locational representation, since the navigator is without special status.

Point from Origin. The *distance of a point from an arbitrary origin* is a primitive in the allocentric representation. The distance of a point from an arbitrary origin must be derived in the egocentric representation.

Interpoint. In both representations, *distances between arbitrary pairs of points* (other than an origin or the ego) must be derived by computation.

5.2 Bearing

Egocentric. The *egocentric bearing* of a point is a primitive in the egocentric representation, but it requires computation within the allocentric representation. This computation can only be done if the ego is represented as an oriented object in the allocentric representation.

Point from Origin. The *bearing of a point from an origin* is a primitive in the allocentric locational representation. See the next section for the bearing of a point from the origin within an egocentric representation.

Interpoint. *Bearings between arbitrary points* can be computed from either an egocentric or allocentric representation. However, there is no external reference direction in the egocentric representation. A bearing between two arbitrary points could still be defined with respect to the navigator's axis of orientation; this would be the ego-oriented bearing. It could be computed from the distance and angle coordinates that are primitives of the egocentric representation, but since the reference direction (i.e., the navigator's axis of orientation) changes with the navigator's rotations, the ego-oriented bearing within an egocentric representation is intrinsically unstable.

5.3 Heading

Object Heading. The *heading of an arbitrary object* in space is the angle between its axis of orientation and some reference direction. Heading is the sole primitive in the allocentric heading representation. As was noted above, an object's heading can be computed as a derived parameter from primitives in the allocentric locational representation, if the object is represented as two (or more) points with an axis of orientation. The object's heading is then the bearing along the axis of orientation, with respect to the reference axis.

In the egocentric representation, it might be possible to use the navigator's axis of orientation as a reference axis, in order to define the heading of other objects. In this case, the object's heading would be equivalent to the ego-oriented bearing. However, like other ego-oriented bearings, this is intrinsically unstable, because the object's heading, so defined, would change as the navigator turned.

Navigator Heading. The *heading of the navigator* cannot be represented within egocentric space, since heading is defined in allocentric terms, and the reference axis within the egocentric representation always remains aligned with the navigator. That is, the navigator's heading is always zero in egocentric space. If, in the allocentric space, the navigator is represented as an object with an axis of orientation, then the navigator's allocentric heading can be computed.

6 Allocentric and Egocentric Representation in Rodents: A Systems Organization

Gallistel (1990) suggested that allocentric (in his terms, geocentric) maps of a spatial environment are constructed from two lower-level processes. One is the construction of an egocentric representation, which is assumed to result from early perceptual processes. The second is path integration, the process by which velocity or acceleration signals are integrated to keep track of a navigator's position in allocentric coordinates. Knowing their allocentric position in the space, and having the egocentric coordinates to other objects, navigators can build a map that allows the object-to-object relations to be represented allocentrically.

A functional system that connects egocentric and allocentric representations in rodents has been developed in more detail, with assumptions about neural localization, by Touretzky and Redish (Redish, 1997; Redish and Touretzky, 1997; Touretzky & Redish, 1996). As described by Touretzky and Redish (1996), the system has five interconnected components that convey information about spatial layout. Inputs to these components come from sensory (visual and vestibular) signals and motor efference copy. The components are as follows.

i) A *visual-perception component* provides egocentric coordinates of objects in the environment; this component is also assumed to determine the object type through pattern-recognition processing. The neural localization of this component is not considered in depth by the authors, but the relevant perceptual outputs presumably result from processing by both "what" and "where" streams in early vision. The spatial (cf. object type) information conveyed by this component corresponds to the primitives of an egocentric locational representation, as described here (i.e., egocentric bearing and distance).

ii) A *head-direction component* conveys the animal's heading in allocentric coordinates. This component is neurally instantiated by head-direction cells, which fire when the rat adopts a particular heading, regardless of its location. Head-direction cells that could serve this function have been found in several areas of the rat brain. The reference direction for heading is established by remote landmarks and/or vestibular signals.

(iii) A *path-integration component* provides an allocentric representation of the animal's position. In the rat, efference copy, vestibular signals, and optic flow could all contribute to path integration. The process has been studied in a wide variety of lower animals (reviewed in Gallistel, 1990; Maurer & Séguinot, 1995; Etienne, Maurer & Séguinot, 1996) and to some extent in humans (reviewed in Loomis, Klatzky and Golledge, in press). Redish (1997) suggested that the path integration component in the rodent involved a loop among several cortical areas.

(iv) A *local-view component* receives inputs from the visual-perception and head-direction components. It represents objects in space using the same coordinates as the egocentric representation -- that is, the distance and bearing of objects from the navigator -- but now the bearing is relative to an allocentric reference direction rather than to an axis oriented with the navigator. In order to determine the allocentric bearing, the navigator's heading, obtained from the head direction component, has been taken into account.

(v) The local view and path integrator components feed into a *place-code component*, which serves to associate them. The neural instantiation of the place code is a set of place cells, which fire when the animal is in a specific location (the cell's place field) without regard to its orientation. Place cells in the hippocampus of rodents have been widely studied since their discovery more than two decades ago (e.g., O'Keefe & Dostrovsky, 1971; O'Keefe, 1976; O'Keefe & Nadel, 1978). The response to place is not driven entirely by visual cues, since vestibular contributions have been demonstrated by the finding that place cells fire even in the dark (McNaughton, Leonard, & Chen, 1989).

For present purposes, the first three of these components are most relevant, since they clearly differentiate between egocentric and allocentric forms of locational representation in the rodent, and they specify an additional component, concerned with allocentric heading direction, that is necessary to compute one representation from another. The allocentric representation is instantiated in the dead-reckoning component within the system, and the egocentric representation is instantiated by the product of perception (visual, in this model, although contributions from other modalities are clearly possible).

The analysis of the rodent system supports the general proposal that an egocentric locational representation, allocentric locational representation, and allocentric heading component constitute distinct, interconnected functional modules that interact to produce higher-level representations and support functioning in space. The local view is a higher-level representation of a hybrid nature, in that its distance coordinate is egocentric (referred to the rat's viewing position), but its bearing coordinate is allocentric.

While the rodent's spatial system offers general support for distinctions among representations, one must be careful in extending the parallels to humans. One point worth noting is that the egocentric and allocentric representations proposed for the rodent reside at fairly low levels in the perceptual-cognitive stream. Humans, however, are capable of forming spatial representations through top-down, cognitive processes such as generative imagery and memory retrieval. The extent to which they do this appears to be constrained, however, as will be described below.

7 How Well do Navigators Form Representations of Spatial Parameters? Empirical Studies

There is a large body of research literature evaluating the ability of humans to represent various spatial parameters. Studies of particular interest are those in which subjects must maintain and even update a representation after it has been formed perceptually, rather than the more typical psychophysical task in which a response is made in the presence of an ongoing stimulus. On the whole, the literature is suggestive of a more accurate representation of egocentric parameters than allocentric parameters.

Consider first egocentric parameters. There has been considerable work on representing visually perceived *egocentric distance* over the course of open-loop travel without vision. This research indicates highly accurate perception and maintenance of the perceived representation for distances out to more than 20 m (see Loomis, Da Silva, Fujita, & Fukisima, 1992, for review). Recently, this work has been extended to auditorially perceived targets (Loomis, Klatzky, Philbeck and Golledge, in press). With respect to *egocentric bearing,* studies addressing this issue have used various perceptual modalities, including vision, audition, and touch. On the whole, they suggest that there is excellent ability to represent egocentric bearing after perceptual exposure and even to update it over the course of travel, without further perceptual input (e.g., Amorim, Glasauer, Corpinot, and Berthoz, 1997; Fukisima, Loomis, & DaSilva, 1997; Loomis et al., 1992; Rieser, 1989).

Allocentric parameters have not always been studied without ambiguity. Consider, for example, *allocentric heading*. Ideally, a study of allocentric heading perception should have some means of establishing a reference direction independent of the subject's orientation, relative to which the subject's heading in the space could be indicated. The reference direction could be defined by the geometry of a room, by a direction of travel, or by alignment of salient landmarks, and heading could be determined while the subject was stationary or moving . Typically, however, studies of heading first establish a reference direction aligning a target object with the subject's axis of orientation (or in some cases, direction of gaze). The subject then changes his or her position in the space and the ability to update heading is assessed from his or her ability to keep track of the target's azimuth (Berthoz, 1991; Bloomberg, Jones, Segal, McFarlane, & Soul, 1988). But heading is confounded with egocentric bearing in this situation.

An important study of people's ability to represent nonegocentric *interpoint distance* was conducted by Loomis and associates (1992). It asked subjects to match an interpoint interval in depth (saggital plane) so that it appeared to match an interpoint interval in the frontoparallel plane. Considerable distortion was evidenced by inequalities in the adjustments: Depending on the distance of the configuration from the subject, the sagittal interval was made greater than the frontal interval by up to 90%. The literature on cognitive mapping also indicates considerable error in distance perception, being subject, for example, to a filled-space illusion (Thorndyke, 1981) and to distortions resulting from higher-order units in a spatial hierarchy such as state boundaries (Allen, 1981; Kosslyn, Pick, & Fariello, 1974; Maki, 1981).

In order to assess representation of allocentric *interpoint bearings,* a study is needed in which people indicate the angle formed by a line from one object to another, relative to a reference axis. Lederman et al. (1985) assessed interpoint bearings within the haptic domain by having subjects reproduce the angle between a raised line that was traced on the table top, without vision, and a reference axis aligned with the table edge. The responses erred by being drawn toward the perpendicular by about 20%. The cognitive mapping literature also assesses people's ability to determine interpoint bearings, in this case from perceived and remembered visual displays. There is substantial tendency for error (e.g., Stevens & Coupe, 1978; Tversky, 1981).

8 Processes for Computing Egocentric and Allocentric Parameters

How are egocentric and allocentric parameters computed? Up to this point, I have focused on the nature of the parameters, rather than the underlying representations and processes that produce them.

Suppose, for example, a person is asked to estimate the distance between two objects in front of her. This is, by definition, a nonegocentric distance. But by what process is the response computed? There are at least four general types of processing that one can envision, depending on the type of representation that is accessed (allocentric or egocentric) and the type of process that is applied (abstract and symbolic, or imaginally, by a perceptual analogue). Of these processes, it seems more likely that people have access to computational machinery that will allow them to create and retrieve information from images than that they have an internal equivalent of the law of cosines. The imaginal process is itself certainly nontrivial. It subsumes two components: forming the appropriate image, and retrieving the information from it. If an allocentric image is to be used in computing the distance between two objects, the subject must somehow externalize the two objects; if an egocentric image is required, the subject must somehow have a representation of himself in the image at the same location as one of the objects.

If the content of an image is congruent with a person's current field of view (e.g., the perspective to be taken in the image matches the current visual perspective), perceptual processes will support formation of the requisite representation. But if there is a mismatch between the demands of the image and the subject's current perceptual field, some imaginal process must be performed that transforms the relative positions of person and/or objects. This has been called imaginal updating.

The demands of imaginal updating differ for images that constitute allocentric and egocentric representations. To update ego's position in an allocentric representation means to create new coordinates for ego only. To update ego's position in an egocentric representation means to compute primitive locational parameters for all the objects in the space, since these are defined relative to ego. If ego rotates, bearing parameters must be changed. If ego translates, both bearing and distance coordinates change.

9 Imagined Rotation Vs. Translation: Implications for Relation Between Representations

Seminal studies demonstrating the difference between imagined translations and rotations were performed by Rieser (1989). The subject first learned about a circular array of equally spaced objects while standing at the center of the circle. In the translation condition, the subject was then asked to imagine being at one of the objects, facing in the same direction as his or her current heading, and to point to each of the others from that new position. In essence, the subject was asked to indicate the bearing of each object from a new position, but relative to his or her current heading -- this is what we have called the ego-oriented bearing. Subjects were able to do this as accurately as if they were pointing from their current position (averaging 16° of error in both the translation and no-change conditions). Thus they showed ability to compute the ego-oriented bearing without physical movement. Moreover, their response times did not differ, depending on whether they were to remain stationary or mentally translate.

In the rotation condition, the subject was to imagine rotating from the current orientation, without translating. He or she was then to point to each object as if from the rotated orientation. This corresponds to computing a new egocentric bearing. Subjects found this difficult, producing relatively high error (18° to 37°) and manifesting response latencies that increased with the angular difference between their physical heading and the imagined reference direction.

Presson and Montello (1994) verified Rieser's results with simpler displays that equated rotations and translations with respect to the mean and variance of directional change. Easton and Sholl (1995) demonstrated that to some extent, the results of Reiser reflected the use of regular object arrays. They found that when subjects stood within regular arrays (e.g., circle, square), even if not at the center, then the errors and response latency for pointing responses after imagined translation (without rotation) did not depend on the translation distance. If the arrays were irregular, however, there was a tendency for errors and latency to increase with the distance from the actual location to the imagined response point. Even with the irregular arrays, however, imagined rotations produced substantially longer response latency and higher error than imagined translations (see also May, 1996).

Why do people have so much difficulty in reporting a new egocentric bearing after imagined rotation, when they can do quite well in reporting an ego-oriented bearing after imagined translation? It is important first to understand that there is a fundamental difference between the effects of translation and rotation:

(i) Translation (without rotation) changes the egocentric distances and egocentric bearings of objects, but does *not* change distances between objects or allocentric bearings, including ego-oriented bearings.

(ii) Rotation (without translation) changes the egocentric bearings of objects and ego-oriented bearings between objects, but does not change egocentric distances of objects, allocentric distances between objects, or allocentric bearings that are not defined by an ego-oriented axis.

A critical difference, then, is that under translation, ego-oriented bearings remain constant, whereas under rotation, they change. Egocentric bearings, on the other hand, must be updated whether rotation or translation occurs.

There are two general ways to account for the difficulty of rotation, relative to translation, depending on the type of representation that is assumed to be used, allocentric or egocentric. One might propose that an allocentric representation is used, and that the difficulty of updating under rotation reflects difficulties in using the imagined sensory cues to change ego-oriented, allocentric bearings. However, an egocentric representation could also be used. In this case the data indicate it is easier to update egocentric bearings under translation than rotation. Regardless of which source of difficulty is assumed, imagined updating with physical rotation is clearly problematic.

Klatzky, Loomis, Beall, Chance, and Golledge (in press) conducted a study that directly indicates a failure to update egocentric bearings in the absence of physical cues to rotation. The task was as follows: Subjects were asked to imagine walking two legs of a triangle and then to physically make the turn that would be required to face the origin. For a hypothetical example, illustrated in Figure 3, suppose subjects were asked to imagine moving forward 1 m, make a turn of 90° (call this the stimulus turn), and then move forward another 1m. At that point, they were to immediately make the turn that a person who physically walked the path would make, in order to face the origin. We will call their final heading, which would result from that turn, the response heading. (We dealt with response heading rather than turn, because what is important is the direction the subject finally pointed in, rather than how he or she got there.) The subject was to make the response while still standing at the origin, since he or she did not actually walk along the described path.

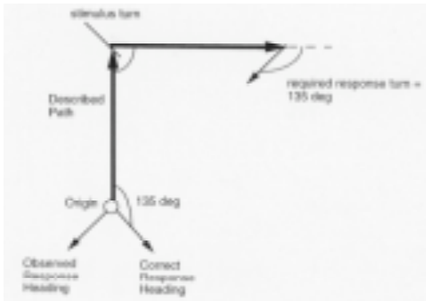

Figure 3. Task used by Klatzky et al. (in press). The subject learns about the first two legs of a triangular pathway while at the origin and then attempts to make the turn required to complete the triangle

Subjects made a highly consistent error: They overturned by an amount equal to the stimulus turn. In terms of our example, where the stimulus turn was 90˚, the correct response turn would be 135˚ -- but the subjects would assume a heading corresponding to a turn of 225˚, a +90˚ error. When a set of paths was used varying in stimulus-turn angle, the function relating the signed error in response heading to the value of the stimulus turn had a slope close to 1.0.

By consistently over-responding by the amount of the stimulus turn, subjects appeared to ignore the change of heading that occurred at the stimulus turn. That is, where a physically walking subject would make a response turn that took into account having already turned 90˚ between the first and second leg, the imaginally walking subjects did not take the stimulus turn into account. The same outcome was found in a version of the task where subjects were disoriented (by being randomly rotated) before beginning the experiment. This suggests that their failure to take the described turn into account was not due to their representing themselves as at a fixed heading in terms of the external room, since knowledge of their heading within the room should have been eliminated by the initial disorienting movement. It is likely that they represented their heading relative to features of the path itself, for example, using the first leg of the triangle, along which they faced, to define a reference direction.

We proposed that subjects did not register the change of heading that occurred at the stimulus turn, because they did not receive proprioceptive cues. Similar results were obtained in other conditions where proprioceptive signals were absent -- when subjects watched someone else walk, and when they viewed optic flow corresponding to the walked path, by means of a VR display. In contrast, subjects turned correctly when they made a physical turn corresponding to the stimulus turn. Two such cases were tested. In one condition, the subjects physically walked, which would produce efference, kinesthetic, and vestibular cues. In the other condition with a physical turn, they saw the VR display while seated on a rotating stool, and were turned by the experimenter at the point of the stimulus turn. In this latter condition, kinesthetic cues and efference would be absent, but vestibular signals (along with optic flow) would still be present. The contrasting results from the two VR conditions -- with and without a physical turn -- indicate that optic flow alone was not sufficient to change the representation of heading, and that vestibular signals were critical.

At the same time that the subjects did not respond correctly, the regular pattern in their responses indicated that they could represent the spatial layout of the pathway. And, the pattern of responses indicates that they must have represented something more -- their axis of orientation aligned with the first leg. Although they did not make the turn that a physically walking subject would make, their response was equivalent to turning the value of the ego-oriented bearing. The ego-oriented bearing would not be known if the subject's axis of orientation relative to the pathway was unknown.

The operative representation remains ambiguous. In using an egocentric representation, for example, the subject might (a) imagine standing at the end of the second leg, then (b) respond by turning the value of the egocentric bearing to the origin. In using an allocentric representation of pathway layout, the subject could (a) determine the ego-oriented bearing from the end of the second leg to the origin, and then (b) respond by turning the value of that bearing. While the operative representation is ambiguous, it clearly failed to incorporate the change of heading commensurate with the description of an imagined turn.

These results are consistent with the idea that proprioceptive signals accompanying physical rotation are input to an allocentric heading representation, which in turn provides information to locational representations that allow updating of bearings. This process fails, however, when the rotation is purely imaginary. In contrast, the translational movement of traveling the pathway -- either by imagination or by physical movement -- can be used to update a representation that permits the computation of the bearing from the end of the traveled pathway back to the origin.

10 Summary

In this chapter, I have attempted to clarify fundamental concepts related to allocentric and egocentric representations -- and also to indicate where ambiguity is inevitable. By starting with straightforward assumptions about three types of representation and their primitives, I have indicated what derived parameters can be computed, and with what degree of stability. A brief review of the literature cites studies indicating that egocentric parameters can be encoded accurately, along with studies indicating that allocentric parameters may be encoded with substantial error. The well-documented contrast between updating after imagined translation, as compared to rotation, appears to place constraints on the connectivity between different representational systems. Updating under translation requires reporting ego-oriented bearings from a new station point; updating under rotation requires reporting new egocentric bearings from the same station point. Imagination allows us to do the former but not the latter, because, it is argued, proprioceptive signals are essential to incorporating changes of heading into the operative representation, be it egocentric or allocentric.

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