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Jesse Sargent

Stephen Dopkins

John Philbeck

David Chichka

The George Washington University

Please address correspondence to:

Jesse Sargent
Psychology Department
George Washington University
2125 G Street, NW
Washington, DC 20052
jqs@gwmail.gwu.edu
phone: 202-281-6752
fax: 202-994-1602

Abstract

In order to gain insight into the nature of human spatial representations, the current study examined how those representations are affected by blind rotation. Evidence was sought that while certain environmental aspects may be updated independently of one another, other aspects may be grouped (or chunked) together and updated as a unit. Participants learned the locations of an array of objects around them in a room, then were blindfolded and underwent a succession of passive, whole-body rotations. After each rotation, participants pointed to remembered target locations. Targets were located more precisely relative to each other if they were 1) separated by smaller angular distances 2) contained within the same regularly configured arrangement, or 3) corresponded to parts of a common object. A hypothesis is presented describing the roles played by egocentric and allocentric information within the spatial updating system. Results are interpreted in terms of an existing neural systems model, elaborating the model's conceptualization of how parietal (egocentric) and medial temporal (allocentric) representations interact.

Keywords: spatial memory, spatial updating, egocentric, allocentric, chunking

Chunking in Spatial Memory

On the basis of perceptual experience with the immediate environment, humans and other animals construct internal representations of the landmarks, boundaries and objects that make up that environment. Evidence of these persisting internal representations is provided by the ability to locate objects and landmarks in the absence of ongoing perceptual support (e.g., Kosslyn, Ball & Reiser, 1978; McNamara, 1986) and by neurophysiological data (e.g., Burgess & O'Keefe, 1996; Cressant, Muller & Poucet, 1997; Ekstrom, et al., 2003). As an organism navigates through the environment, these internal representations are updated to reflect the changing relationship between the organism and its surroundings (e.g., Muller & Wehner, 1988; Philbeck, Loomis & Beall, 1997; Rieser, 1989; Waller, Montello, Richardson & Hegarty, 2002). The current study examines errors that accrue over this spatial updating process for evidence that a representation of a room-sized environment may be composed of "chunks", each of which contains location information for a different part of that environment.

Previous work provides a precedent for the possibility that this type of "chunking" might occur in spatial memory. Wang and Brockmole (2003a, 2003b) showed evidence that as we navigate through larger environments (e.g., college campuses) we only actively update spatial aspects of the sub-environment (e.g., room) currently inhabited. Thus, it appears that spatial memory for larger environments may be organized as groups of nested sub-environments, which may be thought of as chunks. It has also been suggested that object locations may be chunked together in memory for smaller, room sized environments as well. McNamara, Hardy, and Hirtle (1989) showed evidence that spatial memory for room sized object arrays is organized hierarchically, such that objects in a common branch are grouped, or “chunked” together. The current study builds on this work; participants immersed in room sized object arrays point to remembered object locations after varying degrees of blind rotation. This allows us to look for evidence of chunking in spatial memory for immediate, immersive environments. Furthermore, a “chunking hypothesis” is proposed describing the relevance that this type of chunking may have for how we update unseen locations within the environment over self motion. A description of this hypothesis begins with a discussion of some basic properties of spatial representation.

In considering what information needs to be encoded in order to specify (and update) the location of an external object or landmark, researchers have noted a relevant distinction between egocentric and allocentric coordinate systems. Egocentric position codes describe location relative to the body, while allocentric position codes describe location relative to an external referent, such as the south west corner of a room (see Gallistel, 1990, p. 108 for an illustration). Neurophysiological studies have identified neurons in the parietal cortex that encode locations egocentrically (e.g., Andersen, Essick & Siegel, 1985; Galletti, Battaglini & Fattori, 1995; Snyder, Grieve, Brotchie & Andersen, 1998) and are part of a system that controls motor behavior. Likewise, animal studies have identified various cell types in the medial temporal lobe (MTL) that appear to encode locations allocentrically (e.g., Feigenbaum & Rolls, 1991; O’Keefe & Nadel, 1978; Rolls & O’Mara, 1995; Taube, 1998), and homologous cells have been identified in humans (Ekstrom, et al., 2003). Neural models describing how, in humans, ego- and allocentric systems interact are still in relatively early stages of development (Burgess, 2008; Byrne, Becker & Burgess, 2007). To facilitate this development, the current study aims to further our understanding of this interaction *behaviorally*. Implications of our behavioral results for such neural models are discussed in the General Discussion.

The process of spatial updating over motion would, in principle, be different depending on whether the representation being updated was encoded ego- or allocentrically. If object locations are encoded egocentrically, then over self motion the reference point itself is moving and thus *all* of the object locations need to be updated. Consider a previous conceptualization of this process (Wang & Spelke, 2000). The location of an object may be represented in egocentric terms by a vector describing egocentric bearing (e.g., angle measured clockwise from straight ahead), and distance from the observer. Over self motion, a vector recording the change in the object's egocentric bearing and distance from the observer is added to the previous location vector for that object. Importantly, this conceptualization makes the assumption that there is at least some degree of independence in the displacement assessment and/or vector addition processes that occur for separate object locations. Accordingly, object locations should accrue updating error independently of one another. Alternatively, within an allocentric representation, only the relationship between the moving object (the self) and the external reference point needs to be updated because the relative locations of all the static environmental elements remain unchanged. In this case, error that accrues over self motion should accrue to the entire representation, i.e., all the object locations contained therein should be associated with the same updating error. Thus, in essence, egocentric environmental representations would be updated in piecemeal fashion while allocentric representations would be updated globally.

Sargent, Dopkins, Philbeck and Modarrez (2008) searched both for evidence that human subjects update spatial representations in piecemeal fashion, and for evidence that such updating occurs in global fashion. Participants learned the location of four target objects in a room sized environment from a fixed heading amid the array. Then, wearing blindfold and hearing protectors, participants underwent a succession of passive, whole body rotations. After each rotation, participants pointed to the objects without vision. Results showed that the errors in pointing to individual objects were not, across rotations, independent of one another, suggesting the influence of global (allocentric) representations. In accordance with the majority of previous studies (e.g., Burgess, Spiers & Paleologou, 2004; Holmes & Sholl, 2006; Mou, McNamara, Rump & Xiao, 2006; Mou, McNamara, Valiquette & Rump, 2004; Parslow, et al., 2004; Shelton & McNamara, 2001; Woodin & Allport, 1998), this cast doubt on the claim that object locations are encoded only in piecemeal (egocentric) fashion (Wang & Spelke, 2000). However, some evidence also showed that individual object representations *were* being updated independently of the larger object array, to some extent, in piecemeal fashion. Accordingly, a conceptualization was proposed (the chunking hypothesis), describing how spatial representations might simultaneously be updated partly in global fashion (allocentrically), and partly in piecemeal fashion (egocentrically).

According to the chunking hypothesis, certain object locations within a room sized environment are chunked together in spatial memory. The spatial relationships of objects within chunks are represented allocentrically while locations of the chunks themselves are represented egocentrically. This hypothesis may be elaborated in terms of the previously outlined conceptualization of how egocentrically encoded object representations are updated over self motion. A single vector representing the egocentric location code for a reference point within a chunk (e.g., the center) would be updated independently of other chunks. Over updating, all objects within a common chunk would be subjected to the same displacement assessment and vector addition processes, and so would be associated with the same updating error. Meanwhile, because separate chunks would be updated independently of one another, objects within separate chunks would be associated with different updating error. Consequently, within-chunk relationships would accrue less updating error than between-chunk relationships.

In order to test this prediction, it is necessary to first create a situation in which certain object locations are chunked together in spatial memory. So what might cause chunking in this domain? Gestalt principles have been shown to predict grouping in visual perception (e.g., Koffka, 1935; Palmer & Rock, 1994; Wertheimer, 1923) and thus are considered as factors that might cause grouping in spatial memory as well.

The current study sought evidence 1) for the chunking hypothesis, and 2) that chunking occurs for locations that are related on the basis of several Gestalt principles. The paradigm used here was similar to that used by Sargent et al. (2008). Participants learned the locations of an array of objects in an experimental room, were blindfolded, and then pointed to targets on the objects after each of a series of passive, whole body rotations. While specific pointing targets were generally defined as the centers of the objects, in Experiment 3 targets included other specific parts of objects as well. The precision with which participants pointed to pairs of targets relative to each other was compared for specific pairs that were, and were not, expected to be encoded within the same chunk (within- and between-chunk pairs, respectively) on the basis of Gestalt principles. Experiment 1 examined the principles of proximity and similarity. Experiment 2 examined collinearity, or the arrangement of objects into simple higher order patterns (i.e., rows). Finally, Experiment 3 examined what might be considered closure, or uniform connectedness (Palmer and Rock, 1994) - specifically, the tendency to group locations contained within a single object. It was hypothesized that within-chunk target pairs would be located more precisely relative to one another than between-chunk target pairs. For each experiment, the hypothesized result would 1) support the chunking hypothesis, and 2) support the viability of the chunking principle at issue.

Experiment 1

Experiment 1 sought evidence that object locations were chunked together in spatial memory on the basis of proximity, and similarity. Participants learned the locations of eight target objects: a tripod, a cone, a pipe, and purple, blue, yellow, green and orange balloons. (Henceforth, balloon targets will be referred to as "balloons" and non-balloon targets will be referred to as "objects".) Participants pointed to all the targets immediately after being blindfolded, again after being rotated 70°, and again after being disoriented. The disorientation condition was included primarily in order to increase the amount of updating error because the hypothesized difference between within- and between-chunk target pairs should emerge to the degree that there is updating error. Error in locating particular pairs of targets relative to each other was examined as a function of 1) Angular Proximity, or the size of the angle between target pairs, 2) Similarity (i.e., high similarity balloon-balloon pairs were compared to low similarity object-object pairs), and 3) Turn (no-turn, 70°, and disorientation). It was hypothesized that objects related on the basis of Angular Proximity and Similarity, as compared to objects not related on these factors, would tend to be chunked together, updated as a unit, and thus located more precisely relative to one another. Accordingly, it was also expected that the difference between within- and between-chunk relationships would increase with increases in the amount of updating error.

Method

Participants completed a single session lasting approximately one hour. The session consisted of a Pointer Training Phase, in which participants learned how to use the pointer, a Learning Phase, in which participants learned the target locations, and a Test Phase, in which the experimental manipulations occurred and data were gathered.

Participants

Twenty-nine George Washington University undergraduates participated in this study in exchange for course credit. Age information for one participant (near average undergraduate age) was lost. Experimental data for this participant were retained. Twenty participants were female, and nine were male. The mean age was 19 years (range: 18 – 21). Four participants reported being left-handed.

Apparatus

The experiment took place in a 5 x 7 m room. Participants were seated in a common wooden chair that was affixed to the top of a rotation platform that added approximately 7” to the height of the chair. The extent of rotation, peak velocity, and acceleration profile of the rotation platform were controlled by a desk top PC. The chair was situated in the center of a circular aperture in a square table (1.52 m square x .76 m tall). The aperture was marked with a 360° scale, according to which the chair was oriented at 0° when it faced the north wall of the experimental chamber. This heading, depicted in Figure 1, was the training heading.

A pointing device was mounted horizontally on the chair in participants' median sagittal plane, at approximately the level of the abdomen. The pointer itself was a thin rod extending 16 cm from its axis of rotation. The pointer's axis of rotation was offset 24.75 cm from that of the chair. While this offset may require slight transformations of self-to-target directional responses, use of such an offset is common in the literature (e.g., Easton & Sholl, 1995; Holmes & Sholl, 2005, Sargent, et al., 2008). Participants in the current study underwent pointer training so that they would become familiar with the offset. The pointer was oriented at 0° when it was perpendicular to the front of the chair (pointing directly away from the participant's abdomen). A wireless radio transmitter attached to the pointer allowed researchers to record, from a desktop PC, how far, measured clockwise from 0°, the pointer was set at any given time.

The eight targets were arranged around the participant (see Fig. 1). All targets were positioned in such a way that put them in approximately the same horizontal plane as the pointer. Targets were arranged so that the effects of angular separation (proximity) and target pair type (similarity) could be analyzed independently. Experimental target pairs comprised "close" and "far" pairs, separated by 18° and 153°, respectively, as measured from the axis of rotation of the chair. There was a close/similar balloon-balloon pair (orange-green) and a close/dissimilar object-object pair (cone-tripod). Likewise, there was a far/similar balloon-balloon pair (purple-yellow) and a far/dissimilar object-object pair (pipe-cone).

Insert Figure 1 about here

Procedure

Prior to testing, participants were alerted to the fact that the pointer's center of rotation was offset from that of the chair. Participants were instructed to use their preferred hand to set the pointer, and were given a Styrofoam ball to hold in the other hand in order to insure that the same hand was used for responding throughout.

Pointer Training Phase. On each trial, participants sat in the chair, viewed a small (5 cm tall) bottle of correction fluid, which was placed on the perimeter of the table at one of 4 positions (115°, 125°, 240°, and 260° measured in a clockwise direction from the training heading), and aimed the pointer at the bottle. Throughout this phase and the next (*Learning Phase*) the chair was oriented at 0° (training heading) but participants were allowed to turn their head and torso to look at a target when it was located behind them. Participants were instructed to set the pointer so that an imaginary line passing through the pointer would also pass through the bottle. Participants had full visual and auditory access during pointer training. A response was scored as correct if the pointer was aimed within +/- 3° of the bottle. After each incorrect response, the correct pointer direction was demonstrated to the participant. Once a position had elicited three correct responses without an intervening incorrect response, it was considered "passed" and tested no more. Positions were tested in random order until all were passed.

Learning Phase. In these trials, participants learned the locations of the eight targets and practiced pointing to them without vision. Participants first spent several minutes studying the locations of the targets and practicing pointing to each. They then donned a blindfold and attempted to point to each target as called out by an experimenter. A response was scored as correct if the pointer was within +/- 5° of the target. After each incorrect response, participants raised the blindfold to observe the location of the target and the correct direction of the pointer. Once a target had elicited three correct responses without an intervening incorrect response, it was considered “passed” and tested no more. Targets were tested in random order until all were passed. Similar pointer training and target learning procedures have been used previously (Sargent, et al., 2008).

Test Phase. Participants began facing 0° on the table scale (training heading). After donning the blindfold and a set of hearing protectors (overall noise reduction rating, 20dB) to minimize auditory orientation cues, participants pointed to the targets as they were called out by an experimenter. Three pointing responses were made to each target. The order in which the target objects were called out was randomly determined, i.e., repeated responses for a given target did not necessarily occur consecutively. Each pointing response was recorded (to the nearest degree) from the computer which received pointer readings. An experimenter returned the pointer to 0° (pointing directly away from the participant’s abdomen) after each response so that responses were always made from 0°. No error feedback was provided during this phase. After pointing to all targets three times each from the training heading, participants were rotated 70° clockwise. The rotation was computer controlled to have an acceleration/deceleration rate of 5°/sec./sec. and a maximum angular velocity of 60°/sec. All rotations were implemented according to an approximately triangular velocity profile. After again pointing to all the targets as before, participants underwent a sequence of five rotations meant to cause disorientation:

200° clockwise (c), 100° counterclockwise (cc), 40° cc, 100° c, and 90° cc. For the 2^{nd}, 3^{rd} and 4^{th} of these rotations, a slower maximum speed of 5°/sec. was used in order to increase the difficulty of remaining oriented. Such slow rates of rotation are difficult for the vestibular apparatus to detect because of its high pass characteristics (Mergner, Nasios, Maurer, & Becker, 2001). After the disorientation procedure pointing responses were again made for all targets, as described above.

Data Analysis

Raw data were processed as follows. First the pointer readings corresponding to all Test Phase responses were adjusted using trigonometry so that they represented the (indicated) target direction relative to the axis of rotation of the chair, instead of the pointer axis. This simplified the process of calculating error for responses made across a variety of perceived headings. Using circular statistics (Batschelet, 1981), mean pointing responses were then calculated across the three repeated pointings for each target at each heading. Thus, for each subject, at each heading, a single mean response value for each target was acquired. *Raw error* was then calculated as the difference between these mean response values and the actual (correct) target headings.

So that the circular *raw error* data might be analyzed as linear data, the *raw error* scores were adjusted as follows. First, for each participant and turn, heading error was calculated as the circular mean of the corresponding *raw errors* (across all targets). Heading errors were then adjusted, by adding or subtracting 360, to be within +/- 180° of the adjusted heading error for the previous turn, or to be within +/- 180° of zero (for 1^{st} and disorientation turns). Finally, *raw errors* were adjusted, again by adding or subtracting 360, to be within +/- 180° of the corresponding heading error. The result is referred to here as *linearized error*. In order to examine the errors that participants made in locating pairs of targets relative to each other, *angular separation error* (*ASE*) was calculated as the difference between the *linearized error* scores corresponding to the two targets of interest.[1]

Only experimental target pairs identified above ("close" and "far" similar balloon-balloon pairs, and "close" and "far" dissimilar object-object pairs) were included in the analyses. For each participant, at each level of Turn, each of the experimental target pairs provided one *ASE* score. Analyses were run separately for two dependent variables (absolute *ASE*, and variable *ASE*). Absolute *ASE* provides a measure of how far off (in either direction) was the indicated angle between a particular pair of targets. For a given participant and pair of targets, variable *ASE* was calculated as the standard deviation of the signed *ASE* scores across the different levels of Turn. Signed (or constant) *ASE* is not analyzed directly here because, as described above, the chunking hypothesis makes no specific predictions about signed error. Recall that what drives the current predictions is simply the proposition that, over updating, objects in separate chunks accrue error independently of one another while objects in common chunks accrue common error. No predictions are made regarding specific directions in which entire chunks, or objects within a common chunk, might "drift" relative to one another.[2]

In order to decrease the noise in the data, instances in which *ASE* was further than three standard deviations from the mean were excluded from the analyses. Standard deviation and mean were calculated across all *ASE* scores for the experimental target pairs, separately for absolute and signed *ASE* scores. This resulted in the elimination of the exact same 2.9% of *ASE* scores in both the absolute and the signed *ASE* data sets.

Subjects with missing data points (for any of the cells in the factorial), after the exclusion of outliers, were excluded from the analyses. One additional participant was missing data for one or more cells in the factorial because she did not finish the experiment within the allotted time. Thus analyses were conducted on data for the remaining 23 participants. All statistical tests were conducted against a significance criterion of .05. Reaction time was not measured in any of these experiments.

Absolute ASE. A repeated measures analysis of variance (2x2x3) included as factors: 1) Angular Proximity (close, and far), 2) Similarity (balloon-balloon, and object-object), and 3) Turn, (no-turn, 70°, and disorientation). Results showed significant main effects of Proximity ($F(1,22) = 48.84$, $MSE = 156.81$, $p < .0001$) and Turn ($F(2,44) = 10.8$, $MSE = 160.24$, $p = .0002$). Specifically, *ASE* for the "close" target pairs ($M = 8.1°$, $SE = 0.7°$) was lower than for the "far" target pairs ($M = 18.7°$, $SE = 1.5°$), and *ASE* for the no-turn condition ($M = 8.4°$, $SE = 0.9°$) was lower than for the 70° ($M = 16.0°$, $SE = 1.3°$) and disorientation ($M = 15.9°$, $SE = 1.8°$) conditions. However, a significant interaction between Proximity and Turn was also observed ($F(2,44) = 5.16$, $MSE = 128$, $p = .01$). Although Turn was not a factor of primary interest, visual inspection of the data reveal that the effect of Proximity is larger in the 70°, and disorientation conditions than in the no-turn condition (see Fig. 2). No effect of Similarity was observed (balloon-balloon: $M = 14.2°$, $SE = 1.2°$; object-object: $M = 12.6°$, $SE = 1.1°$), $F = 1.1$. Means for the full factorial are shown in table 1.

Variable ASE. Turn was not a factor in this analysis because the dependent variable was the within participant standard deviation of signed *ASE* across the three levels of Turn. A two-way repeated measures analysis of variance (2x2) including

Proximity and Similarity as factors showed a main effect of Proximity ($F(1,22) = 23.71$, $MSE = 99.26$, $p < .0001$). Specifically, variability of signed *ASE* across the levels of Turn was greater for "far" target pairs ($M = 17.8°$, $SE = 2.7°$) than for "close" target pairs ($M = 7.7°$, $SE = 1.1°$). No effect of Similarity was observed (balloon-balloon: $M = 13.3°$, $SE = 2.6°$; object-object: $M = 12.1°$, $SE = 2.1°$), $F = .34$.

Insert Figure 2 about here

Insert Table 1 about here

Discussion

Over blind rotation, pointing responses more consistently reflected the inter object relationships for target pairs that were "close" to each other (separated by a 18° angle) than for target pairs that were "far" from each other (separated by a 153° angle). In addition, the difference between "close" and "far" target pairs was greater in the updating than in the non-updating conditions. These results are consistent with neither a wholly global nor a wholly piecemeal updating system. If a single updating process is applied, globally, to all elements of an environmental representation, then the error that accrues over that updating process should apply to all elements of the representation equally. Alternatively, if each target location in an environment is updated independently of the others, then the error that accrues to each target should be independent of the error that accrues to all other targets. In both cases, the consistency of *ASE* for any given target pair should not differ systematically from the consistency of *ASE* for any other target pair. Current results *are* consistent with a conceptualization in which target locations that are “close” to each other are chunked together and updated in global fashion, preserving within-chunk relationships. Meanwhile, target locations that are “far” from each other are not chunked together, and their respective chunks are updated independently of one another. Accordingly, responses are less consistent for “far”, or between-chunk location relationships.

However, it is also possible that observed results were caused by a non-uniform pointing bias. Philbeck, Sargent, Arthur, and Dopkins (2008) showed that stationary participants, using a pointer very similar to that used in the current experiment, exhibited considerable bias when pointing to targets in the rear hemispace. Specifically, participants did not set the pointer far enough in the rearward direction. If such a bias exists in the current paradigm, and persists over updating, then “close” targets would always be subjected to bias of similar extent and direction, while “far” targets would be subjected to dissimilar bias. This might cause lower *ASE* for “close” than for “far” target pairs.

In order to determine whether current results were caused by the pointing bias identified by Philbeck et al. (2008), absolute *ASE* scores for target pairs in the front hemispace, which *should not* be affected by such a bias, were compared with absolute *ASE* scores for target pairs in the rear, which *should* be affected by such a bias. This analysis was conducted on data from the no-turn condition wherein a) the perceived location of particular targets as being in the front or rear hemispace was unambiguous, and b) conditions most closely matched those tested by Philbeck et al. Absolute *ASE* for rear target pairs most likely to be affected by pointing bias (pipe-blue balloon [M = 9.2°, SE = 1.6°], pipe-cone [M = 10.7°, SE = 1.2°], yellow-blue balloons [M = 11.0°, SE =

3.1°], yellow balloon-cone [*M* = 13.2°, *SE* = 2.3°]) was compared to that for comparable frontal target pairs (purple-green balloons [*M* = 12.2°, *SE* = 4.1°], tripod-green balloon, [*M* = 10.7°, *SE* = 1.7°], purple-orange balloons [*M* = 13.5°, *SE* = 3.2°], tripod-orange balloon [*M* = 10.5°, *SE* = 1.4°], respectively).[3] In only the last of these comparisons was *ASE* for the rear target pair (13.2°) larger than for the comparable frontal target pair (10.5°), and this difference was not significant ($t(27) = 1.01$, $SE = 2.71$, $p = .32$). This ancillary analysis suggests that the higher *ASE* scores observed for "far" than for "close" target pairs may not be explained by a pointing bias. The possibility that current evidence of chunking reflects a pointing bias will be addressed further in the General Discussion in light of results from Experiments 2 and 3.

It should be noted that although the difference between "close" and "far" target pairs was greater after updating occurred, a difference was observed even in the no-turn condition. One possible explanation of this result is that "close" pairs of objects are "chunked" together in spatial memory, as suggested above, and that error accrues independently to egocentrically represented "chunks" over the process of simply *maintaining* an environmental representation in the absence of perceptual support. This is in keeping with the association of within-chunk relationships with allocentric coding, and allocentric coding with longer term spatial memory (e.g., Burgess, 2008; Milner, Dijkerman & Carey, 1999; O'Keefe & Nadel, 1978). Another factor that might be contributing to this result is the hierarchical structure of spatial memory discussed in the Introduction (e.g., McNamara, Hardy & Hirtle, 1989). Even before any updating occurs, uncertainty regarding the relationship between different branches (or chunks) at a given hierarchical level may lead to greater *ASE* for between chunk target pairs, compared to within chunk target pairs. This possibility, also, will be addressed in the General Discussion in light of results from Experiments 2 and 3.

As noted, evidence of chunking was greater in the updating than in the no-turn conditions. However, it is possible that this difference was driven not by the higher levels of updating error observed in the updating conditions, but by other factors that distinguish no-turn from updating conditions. For example, memory for specific pointing responses acquired during the *Learning Phase* may be masking the effects of chunking in the no-turn condition. Therefore, further support for the chunking hypothesis is sought in the form of increasing evidence of chunking with increasing amounts of updating error. In Experiment 1, the amount of updating error was no greater in the disorientation than in the 70° turn condition (see Fig. 2). Accordingly, Experiments 2 and 3 include additional updating conditions in order to produce increased amounts of updating error, without relying on the no-turn condition. Finally, results provided no support for the possibility that similar targets (balloons) tend to group together in spatial memory. The color differences between the balloons may have been salient enough to prevent chunking on the basis of similarity. Experiments 2 and 3 examine additional factors that may facilitate the “chunking” together of certain locations in spatial memory.

Experiment 2

Experiment 2 sought evidence that object locations are chunked together in spatial memory on the basis of collinearity. All methods and analyses were the same as in Experiment 1 except for the changes described below. The critical comparison was between pairs of objects that were part of the same configural arrangement, and pairs of objects that were not arranged in any obvious, orderly fashion. Such pairs are referred to as “collinear” pairs and “random” pairs respectively. In order to control for the effect of Proximity observed in Experiment 1, “collinear” and “random” experimental pairs were matched for angular separation. So here, absolute and variable angular separation error (*ASE*) was examined as a function of 1) Collinearity, and 2) Turn.

Method

Participants

Thirty George Washington University undergraduates participated in this study in exchange for course credit. Handedness information for one participant was lost. Experimental data for this participant were retained. Twenty-six participants were female, and four were male. The mean age was 19 years (range: 16 – 31). One participant reported being left-handed.

Apparatus

The chair and rotation platform described in Experiment 1 were used here, but the square table, with the circular aperture, that surrounded the chair was removed. Also, a new pointing apparatus was used. The new pointer, like that previously described, rested on, and was secured to, the arms of the chair and rotated with the participant. This apparatus consisted of a spokeless bicycle rim (57cm in diameter) resting on a round piece of medium density fiberboard (MDF) with a hole cut in the middle, through both of which the participant protruded. The pointer itself was a thin 18cm rod attached to the top of the bicycle rim extending 13cm out over the edge, and 3cm into the middle, of the circle delineated by the rim. A line extended from the rod would have bisected the circle delineated by the rim. Where this line would intersect the other side of the rim, a smaller 9cm rod (the 'back' of the pointer) was also attached to the top of the rim so that it was aligned with the forward pointer (see Fig. 3). The rim was held in place on the MDF by guides that allowed the rim to be rotated easily around a fixed axis. Thus participants could put one hand on the front and one hand on the back of the pointer and rotate it around them. A pointer scale graduated to the nearest 5° (zero aligned with participants' straight ahead) was inscribed on the MDF just under the pointer rod allowing an experimenter to record pointing responses (to the nearest degree) by noting the scale value under the rod. This pointing apparatus allowed the chair and the pointer to share a common axis of rotation that was located within the participant's body, so that pointing responses might reflect, to the extent possible, self to object relationships. Examination of the pointing bias described above suggests the bias is specific to judgments of exocentric direction, made by aligning a pointer that has an axis of rotation outside the body (Philbeck, Sargent, Arthur, & Dopkins, 2007). Thus, adoption of the new pointer served to minimize possible pointing bias.

Twelve objects – a remote control device, a stack of large washers, a tape measure, a small can of spray paint, a small level, a soda can, a pair of goggles, a spool of fishing line, a battery, a Styrofoam ball, a roll of masking tape, and a flashlight were arranged on the floor to the right and left of the participants' initial (training) heading (see Fig. 3). The objects were all roughly the same size and no pattern of grouping by semantic relationship was obvious. The first six objects in the above list ("collinear" objects) were arranged in two rows of three, as shown in Fig. 3. The last six comprised the "randomly" arranged objects. Two pairs of objects (washers – level, and remote –

soda can), composed the "collinear" experimental object pairs. They were separated by 46° and 63°, respectively, as were the two "random" experimental object pairs (battery – tape, and goggles – battery).

Insert Figure 3 about here

Procedure

Because the axes of rotation of the pointer and the chair were aligned with each other, and situated within participants' bodies, pointer use was assumed to be more intuitive, and so the Pointer Training Phase was eliminated. However, participants had considerable practice (and feedback) with the pointer during the Learning Phase. Given the large number of objects, in order to save time the criteria for scoring a pointing response in the Learning Phase as "correct" was relaxed (from within +/- 5° of the target, to +/- 10°), but only for the objects which were *not* part of experimental pairs. Also to save time, after each turn in the Test Phase, the number of responses that was required for objects which were *not* part of experimental pairs was reduced from three to one.

Finally, the sequence of turns used in Experiment 1 was altered as follows. Because of the issues, mentioned previously, involved in using data from the no-turn condition this condition was eliminated. Thus, blindfolded participants were rotated 70° clockwise before making any Test Phase pointing responses. Also, after participants underwent the disorientation procedure (as in Experiment 1) and pointed to all the objects as required, they remained blindfolded and underwent three more 70° (clockwise) rotations, pointing to the objects after each. This change was made because it was believed that including additional updating conditions would provide the best chances of showing 1) evidence of chunking, and 2) increasing evidence of chunking with increasing amounts of updating error.

Data Analysis

Raw data were processed exactly as in Experiment 1, except that pointer readings did not need to be initially adjusted because they already represented the (indicated) target direction relative to the axis of rotation of the chair. As in Experiment 1, outlying data points (*ASE* scores further than three standard deviations from the mean) were excluded. This resulted in the elimination of 2.3% and 1.5% of the absolute and signed *ASE* scores, respectively. Because visual inspection of the data revealed no clear pattern in results for the different post disorientation turns, and in order to include participants who did not complete all the turns, for analyses of absolute and signed *ASE*, scores were collapsed across post disorientation turns (within participants). Thus, these analyses included only two levels of Turn, pre- and post-disorientation. After collapsing data in this way, no subjects were missing data points for any cells in the factorial.

Absolute ASE. A repeated measures analysis of variance (2x2) included as factors: 1) Collinearity ("collinear", and "random"), and 2) Turn, (70°, and post-disorientation). Results showed a significant main effect of Collinearity ($F(1,29) = 6.48$, $MSE = 210.77$, $p = .016$). Specifically, *ASE* for the "collinear" target pairs ($M = 19.9°$, $SE = 1.8°$) was lower than for the "random" target pairs ($M = 20.5°$, $SE = 1.9°$) (see Fig. 4). No other significant effects were observed. Means for each turn are shown in Table 2.

Variable ASE. Within subject variability of signed *ASE* across turns for the "collinear" target pairs (M = 21.4°, SE = 1.9°) was lower than for the "random" target pairs (M = 25.5°, SE = 1.9°). A one-tailed, paired t-test showed that this difference is marginally significant ($t(29) = 1.68$, $SE = 2.46$, $p = .053$).

Insert Figure 4 about here

Insert Table 2 about here

Discussion

As measured by absolute *ASE*, pointing responses more consistently reflected the inter object relationships for pairs of objects that were part of an orderly configural pattern (collinear), than for pairs of objects that were not arranged in an orderly configural pattern. This result is consistent with a conceptualization in which the spatial memory system makes use of the structural regularity embodied by collinearly arranged objects. Such objects might be grouped, or chunked together more readily than "haphazardly" arranged objects. The salience of configural regularity in spatial memory for object arrays has been suggested in previous studies (e.g., Easton & Sholl, 1995; Mou & McNamara, 2002).

An alternative explanation of these results arises, however, if we consider the fact that after the first 70° (oriented) turn, the "collinear" objects were all in front of participants, while most of the "random" objects were behind participants. As discussed previously, participants are more accurate and precise when pointing to remembered locations in the front compared to the rear hemispace (Franklin, Henkel & Zangas, 1994;

Philbeck, et al., 2008). Thus, the higher absolute *ASE* observed for “random” objects in the 70° turn condition may have occurred simply because these objects fell in the rear hemispace. In order to address this issue, absolute *ASE* for “collinear” and “random” object pairs was repeated on data from turns wherein perceived headings, across participants, were randomly distributed around the circle.[4] In these “disoriented” conditions (Turn 5), across participants neither “collinear” nor “random” objects would disproportionately fall in the rear hemispace. Results again showed significantly lower absolute *ASE* for target pairs related on the basis of Collinearity (M = 20.5°, SE = 3.1°) than for target pairs not so related (M = 37.2°, SE = 5.7°), ($t(20)$ = 2.52, SE = 6.16, p = .02). This issue is addressed procedurally in Experiment 3, and discussed again in the General Discussion.

It should be noted that the collinearity factor was confounded with angular target density. More work is needed to distinguish whether current results reflect chunking on the basis of collinearity, target density, or both. It is not suggested that the factors examined in the current study are the only factors that might cause chunking. While the target density issue per se is not damning to the primary arguments of this paper, a related alternative explanation of current results should be addressed. Consider the possibility that object locations were represented as egocentric vectors throughout, but that a non-spatial record of target order (Wang & Spelke, 2000) was used to limit pointing error, specifically by “correcting” instances wherein two target vectors crossed one another. Error accruing to targets with proximal neighbors would have a greater chance of being corrected. If this is the case, however, then *signed* error for targets with a proximal neighbor on one side would, on average, tend to be in the direction opposite to that neighbor. This prediction was tested by looking at the remote-washers and the level-soda can target pairs (see Figure 3). Mean error should be counterclockwise for the remote relative to the washers, and clockwise for the washers relative to the remote. Likewise, for the level and soda can respectively. For both pairs then, signed *ASE*, calculated by subtracting the *linearized error* score for the counterclockwise most object from that for the clockwise most object, should be positive. However, the observed *ASE* across both pairs (M = .80°, SE = 1.6°) did not differ from zero ($t(29)$ = .49, SE = 1.62, p = .63). Thus, it seems unlikely, at least in this case, that high target density was limiting the error for these proximal targets through corrections made on the basis of target order. In Experiment 3, the chunking factor of interest is not confounded with target density.

As in Experiment 1, neither the amount of updating error nor the amount of evidence for chunking was greater in the disoriented than in the oriented turn conditions. Experiment 3 extends the degree of updating even slightly further in hopes of producing a greater amount of updating error and a correspondingly greater amount of evidence for chunking.

Experiment 3

Experiment 3 sought evidence that locations corresponding to constituent parts of a common object (or related by “Connectedness”) were chunked together in spatial memory. All methods and analyses were the same as in Experiment 2 except for the changes described below. The critical comparison here was between pairs of targets that were contained within the same object (within-object pairs), and pairs of targets that were contained within distinct objects (between-object pairs). Absolute and variable angular separation error (*ASE*) was examined as a function of 1) Connectedness, whether targets were contained within the same object or not, and 2) Turn.

Method

Participants

Thirty-eight George Washington University undergraduates participated in this study in exchange for course credit. Thirty-one participants were female, and seven were male. The mean age was 19 years (range: 18 – 21). Two participants reported being left-handed. One female, right handed participant was run according to the wrong set of instructions and so was excluded from all analyses. Several participants completed relatively few experimental trials. One participant became nauseated after the disorientation procedure, another broke the pointing apparatus early in the experiment, another became re-oriented (or differently oriented) in the midst of responding due to a loud noise in the lab, and four participants were unable to complete all experimental trials due to time constraints.

Apparatus

The chair and pointing apparatus used in Experiment 2 were used here. However, this experiment took place inside a circular chamber (3.75m in diameter) that was created within the larger experimental room by an opaque, black, ceiling-to-floor curtain. This change was made in order to reduce any influence, on spatial memory for the object locations, of the reference directions, or axes, created by the walls of the room (Shelton & McNamara, 2001). This represents a general methodological improvement; that is, there is no clear alternative explanation of previous results that arises in view of potential reference directions created by the walls of the room. Five objects – a wide board, a two by four (2x4), an upright vacuum, a chair, and a narrow board were arranged around the participant (see Fig. 5). The narrow board was piece of plywood, and the wide board was fiberboard painted a cream color. The wide board (2cm x 77cm x 125cm) was propped up on one of its long (125cm) edges, so that, from the perspective of the participant, it was wider than it was tall. The narrow board (2cm x 61cm x 122cm) was propped up on one of its short (61cm) edges, so that it was taller than in it was wide. The 2x4 (2in x 4in x 36in) was attached to a small base that allowed it to stand vertically (1m tall), and was arranged so that the narrow (2in) side faced the participant. (Although technically a board, the 2x4 is here referred to as a non-board object to distinguish it from the wide and narrow boards.) Seven pointing targets were identified to participants: the centers of the three non-board objects, and the right and left edges of each of the two boards (from the perspective of the seated participant, facing the board in question). These targets were indicated by red paper dots (5cm in diameter) taped to the objects in approximately the same horizontal plane as the pointer. The two "within-object" experimental pairs comprised the left and right edges of the wide and narrow boards, separated by 45° and 23°, respectively. The right edge of the wide board and the 2x4 composed one of the two "between-object" experimental pairs, while the chair and the left edge of the narrow board composed the other. These also were separated by 45° and 23°, respectively (see Fig. 5). The targets on the edges of the two boards were referred to as "plywood, left edge", "wide board, right edge", etc.

<u>Insert Figure 5 about here</u>

Procedure

In Experiment 3, participants were randomly assigned one of two Training headings. Half the participants underwent the Learning Phase at (and began the Test Phase from) the first Training heading, while the other half of the participants were assigned the second, opposite Training heading (see Fig. 5). Thus, in each turn condition, half the participants were facing in one direction and the other half were facing in the opposite direction. The two opposite Training headings were used to control for any previously discussed effects that might apply to portions of the representation as a result of where those portions fell relative to egocentric "front". As in Experiment 1, pointing responses for all targets in the Learning Phase were scored as "correct" if they were within +/- 5° of the target. In the Test Phase, two responses were required for each target after each turn. Finally, because there were fewer targets in Experiment 3, and thus reduced time constraints, we were able to add an additional 70°, clockwise turn to the end of the sequence of turns used in Experiment 2.

Data Analysis

Exclusion of outlying data points (*ASE* scores further than three standard deviations from the mean) resulted in the elimination of 3.3% and 3.4% of the absolute and signed *ASE* scores, respectively. As in Experiment 2, for analyses of absolute and signed *ASE*, scores were collapsed across post disorientation turns (within participants). After collapsing data in this way, four participants were still missing data points (for one or more cells in the factorial) due to the elimination of outliers, inability to complete an adequate number of experimental trials, or a combination of the two. Thus analyses were conducted on data for the remaining 33 participants.

Absolute ASE. A repeated measures analysis of variance (2x2) included as factors: 1) Connectedness (“within-object” and “between-object”), and 2) Turn (70°, and post-disorientation). Results showed a significant main effect of Connectedness ($F(1,32) = 8.93$, $MSE = 160.33$, $p = .005$). Specifically, absolute *ASE* for the “within-object” target pairs ($M = 18.8°$, $SE = 2.1°$) was lower than for the “between-object” target pairs ($M = 25.1°$, $SE = 2.0°$) (see Fig. 6). No other significant effects were observed. Means for each turn are shown in Table 3.

Variable ASE. A one-tailed, paired *t*-test showed within subject variability of signed *ASE* across turns for the “within-object” target pairs ($M = 20°$, $SE = 2°$) was lower than for the “between-object” target pairs ($M = 24.4°$, $SE = 2.5°$), ($t(32) = 2.64$, $SE = 1.67$, $p = .008$).

<u>Insert Figure 6 about here</u>

<u>Insert Table 3 about here</u>

Discussion

Pointing responses more consistently reflected the inter target relationships for “within-object” target pairs (opposite edges of a board) than for “between-object” target pairs. This result is consistent with a conceptualization in which locations in the environment which correspond to parts of a common object are updated as a group over blind rotation. Previous work on object based attention illustrates the salience of the object as an organizational unit in early visual processing and in visual working memory for figural scale stimuli (e.g., Baylis & Driver, 1993; Gajewski & Brockmole, 2006; Luck & Vogel, 1997; O'Craven, Downing & Kanwisher, 1999; Vogel, Woodman, & Luck, 2001). This salience may be reflected in the environmental scale spatial memory assessed by the current paradigm. As in the previous two experiments, we did not observe a greater amount of updating error, and consequently, did not observe greater evidence for chunking, in the disoriented compared to the oriented turn conditions. This issue will be addressed in the General Discussion.

General Discussion

Over passive rotation, pointing responses made without vision more consistently reflected angular distance relationships for targets that were related (compared to those that were not) on the basis of Proximity, Collinearity, and Connectedness (being located within a common object). We also observed an effect of Proximity in the absence of rotation in Experiment 1. As a whole, these results are consistent with the view that human spatial representations of room sized environments are maintained and updated neither in wholly global fashion, as unified entities, nor in wholly piecemeal fashion, as groups of independent object representations. These findings may be interpreted in light of current two-system theories of human spatial memory. First, however, we address the fact that evidence of chunking did not increase from oriented to disoriented updating conditions in any of the experiments.

Increasing evidence of chunking with increasing updating error. If, as suggested by the chunking hypothesis, separate chunks are updated independently of one another, then as the degree of updating error increases, so too should the difference between within and between chunk *ASE*. However, in all three experiments, the disorientation procedure failed to produce greater degrees of updating error, as measured by *ASE*.[5] Thus, we searched, post hoc, for means of examining the effect of chunking at lower and higher levels of updating error.

We first considered the possibility that our disorientation procedure may not have been entirely effective, and that if we could more confidently identify pre- and post-disorientation conditions, the desired result might emerge in comparisons made across these conditions. The Rayleigh test, described in the Discussion of Experiment 2, was used to identify levels of Turn at which, across participants, the distribution of perceived headings did not significantly differ from uniform.[4] In Experiment 1 none of the levels of Turn met criteria for disorientation. In Experiment 3, turns 4-6 met disorientation criteria, but the amount of updating error observed for these turns was no greater than for turns 1-3. However, in Experiment 2, the data for turn 5 met disorientation criteria *and* showed higher levels of updating error. The absolute *ASE* analysis described in the *Data Analysis* section of Experiment 2 was re-run using turns 1-4 and turn 5 as the oriented and disoriented levels of Turn, respectively.[6] A significant effect of Collinearity was again observed ($F(1,29) = 11.07$, $MSE = 234.32$, $p = .002$). However, in this analysis, the effect of Turn and the interaction (Collinearity x Turn) were significant as well ($F(1,29) = 5.63$, $MSE = 232.57$, $p = .025$; $F(1,29) = 9.69$, $MSE = 120.20$, $p = .004$, respectively). See Figure 7a. Thus, we have stronger evidence for chunking in disoriented than in oriented conditions when these conditions, identified statistically rather than procedurally, are associated with higher and lower updating error, respectively.

Because the manipulations we used to induce higher levels of updating error were ineffective in Experiments 1 and 3, as an alternative strategy we divided cases (a given participant, on a given turn) into categories corresponding to high and low updating error. *Configuration error* (Wang & Spelke, 2000) was calculated for each case as the standard deviation of the corresponding *linearized error* scores across all targets. Within each level of turn (the no-turn condition was excluded) the cases were split into those above and below the median *configuration error*. Cases above the corresponding median were considered the "high updating error" sample, and those below were considered the "low updating error" sample. Within- and between-chunk absolute *ASE* for critical target pairs was examined across the high and low updating error samples. Repeated measures analyses of variance again showed significant main effects of Proximity ($F(1,22) = 90.67$, $MSE = 57.34$, $p < .0001$) and Connectedness ($F(1,32) = 12.36$, $MSE = 89.20$, $p = .001$) for Experiments 1 and 3, respectively. There were also significant effects of high vs. low updating error ($F(1,22) = 30.19$, $MSE = 44.97$, $p < .0001$; $F(1,32) = 42.15$, $MSE = 195.34$, $p < .0001$, respectively), and significant interactions as well ($F(1,22) = 22.24$, $MSE = 24.30$, $p = .0001$; $F(1,32) = 4.4$, $MSE = 95.95$, $p = .044$, respectively). See Figures 7b and 7c. Thus, we also have stronger evidence for chunking in high than in low updating error conditions when these conditions are created by grouping cases as a function of *configuration error*.

<u>Insert Figure 7 about here</u>

Although these analyses are post-hoc, they provide additional support for the chunking hypothesis. First, they provide evidence that as the degree of updating error increases, the difference in *ASE* for within- and between-chunk target pairs increases as well. This is in keeping with the idea that this difference is caused, at least partly, by the fact that within-chunk targets are updated jointly, while between-chunk targets are updated independently of one another. These results also touch base with several previous studies wherein memory for the relative locations of targets was disturbed by disorientation (Waller & Hodgson, 2006; Wang & Spelke, 2000). Greater *configuration error* post- as compared to pre-disorientation has been offered as evidence of a switch from an egocentric to an allocentric system (e.g., Mou, McNamara, Rump & Xiao, 2006). Interpreting current results within this context, when greater inter-target error was observed post- as compared to pre-disorientation, a greater reliance on chunked representations was also observed. That is, reliance on allocentric encoding of inter-object locations increased with disorientation.

Current results and two-system theories of human spatial memory. Current results may be interpreted within the model of Wang et al. (Wang et al. 2006, Wang & Spelke, 2000) which posits that object locations are updated independently of one another. This model has trouble accommodating results of Experiments 1 and 2 showing that some inter-object relationships are remembered more consistently than others because this implies that some pairs of objects are more independent than others. However, if the definition of “object” is relaxed to include groups of locations that may be chunked together, current results fit well within this model. For example, Wang and Spelke (2000) showed that memory for the relative locations of objects in a room was disturbed by disorientation, while memory for the relative locations of the corners of the room was not. Based on these results, they suggested that object locations are updated in a dynamic, egocentric system, while environmental geometry is updated in a more enduring allocentric system. This conceptualization fits well with the chunking hypothesis if we consider that there are a number of factors that might cause the corners of a room to chunk together. More generally, in both conceptualizations, egocentric and allocentric systems are used concurrently in updating room sized environmental representations.

Mou, McNamara, Rump and Xiao (2006) showed the same pattern observed by Wang and Spelke (2000): increased *configuration error* after disorientation compared to before. However, this pattern was observed only when participants learned object locations from amid an irregular array (no more than two objects were collinear). When participants were allowed external integrative views of an array with salient intrinsic axes (as defined by object collinearity), no increase in *configuration error* was observed. It was suggested that the latter conditions facilitated the formation of reliable allocentric representations which were then used both before and after disorientation. Here, there is nice conceptual overlap with the chunking hypothesis in that collinearly arranged objects are more likely than irregularly arranged objects to be encoded allocentrically.

Alternative interpretations of current results. Alternative interpretations (to that provided by the chunking hypothesis) are possible. Perhaps updating occurred within wholly egocentric or wholly allocentric systems and the evidence of chunking arose not from the independent updating of allocentric chunks, but from some other source. For example, as suggested previously, results may reflect the hierarchical nature of allocentric spatial memory. Also addressed previously, pointing responses may exhibit different degrees of error depending on the direction in which they are made, relative to egocentric “front”. It is possible that some of the current results, particularly those corresponding to the no-turn and oriented turn conditions, are partly driven by such factors. The difficulty for most of these interpretations is in explaining why evidence of chunking *increased* with the degree of overall updating error. It is unclear why the influence of the hierarchical structure of spatial memory, or the bias associated with pointing to rearward targets, for example, should have a greater effect after disorientation than before. One remaining alternative interpretation is that “chunks” actually comprise visual snap-shot type representations, which are usually considered egocentric (e.g. Burgess, Spiers & Paleologou, 2004; Wang & Simons, 1999). However, snap-shot representations are viewpoint dependent and thus are of no use unless they correspond to the viewpoint needed at testing. While it may be argued that participants in the current paradigm had a common viewpoint at study and test, it seems unlikely that the spatial memory system would rely on chunks that are rendered useless over any degree of translation. Future research might search for evidence of chunking over translation to assess this possible alternative.

Integrating current behavioral results and cognitive neuroscience. Given that the observed differences in absolute and variable *ASE* were consistently in the direction predicted by the “chunking hypothesis”, this hypothesis merits further consideration.

Here, we consider how the chunking hypothesis might be elaborated within the framework of a neural model of spatial memory. Byrne, Becker and Burgess (2007) propose a model in which dynamic egocentric representations in the precuneus support direct interaction with the environment. Motor activities such as pointing to remembered targets would presumably be directly supported by these parietal representations. Allocentric spatial information is stored in longer term memory in the medial temporal lobe (MTL). According to the model, spatial information may be translated readily from one brain region and frame of reference to the other via recurrent connections, including Papez's circuit. The model suggests that in the absence of visual input attention may be directed to, and thus boost the activation of, a particular region of the currently maintained, egocentric, parietal representation. Via the recurrent connections, this activation then feeds back into associated allocentric MTL representations, and through pattern completion activates stored visual and allocentric spatial features of the attended region (for details see Byrne, Becker & Burgess, 2007).

This conceptualization may be applied to the current paradigm. Consider a group of locations contained within a single object, thus related by Connectedness and stored as an allocentric chunk in the MTL. Over blind rotation, the continually maintained and updated parietal representation of this object may be thought of as a place marker for the object. Specifically, for example, a vector describing egocentric bearing and distance from the observer to the center of the object may be maintained, as suggested in the introduction. When a pointing response is required to a specific part of the object (the target part), attention is directed to the parietal representation of that object. As mentioned above, activation then feeds back into the MTL which acts as an attractor network, activating the information describing the relative locations of the object's constituent parts in allocentric terms. Based on this allocentric information and the egocentric vector describing the location of the object's center, the egocentric vector describing the location of the target part may be derived, and maintained in the precuneus. Support for the possibility that information describing the relative locations of an object's constituent parts is stored in the MTL comes from studies showing that the perirhinal cortex is important for object recognition (Davachi & Goldman-Rakic, 2001; Murray & Bussey, 1999; Norman & Eacott, 2004). The above outline of how single-object chunks might be updated within the model of Byrne et al. (2007) may be applied to multiple-object chunks as well. While speculative, we believe that such efforts to bring behavioral/theoretical findings into alignment with neural models will generate fruitful questions for future research.

References

Andersen, R., Essick, G., & Siegel, R. (1985). The encoding of spatial location by posterior parietal neurons. *Science, 230*, 456-458.

Batschelet, E. (1981). *Circular statistics in biology*. London: Academic Press.

Baylis, C. G., & Driver, J. (1993). Visual attention and objects: evidence for hierarchical coding of location. *Journal of Experimental Psychology: Human Perception and Performance, 19(3)*, 451-470.

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, *1124*, 77-97.

Burgess, N., & O'Keefe, J. (1996). Neuronal computations underlying the firing of place cells and their role in navigation. *Hippocampus, 6*, 749-762.

Burgess, N., Spiers, H. J., & Paleologou, E. (2004). Orientational manoeuvres in the dark: Dissociating allocentric and egocentric influences on spatial memory. *Cognition, 94(2)*, 149-166.

Byrne, P., Becker, S., & Burgess, N. (2007). Remembering the past and imagining the future: A neural model of spatial memory and imagery. *Psychological Review, 114(2)*, 340-375.

Cressant, A., Muller, R., & Poucet, B. (1997). Failure of centrally placed objects to control the firing fields of hippocampal place cells. *Journal of Neuroscience, 17*, 2531-2542.

Davachi, L., & Goldman-Rakic, P. (2001). Primate rhinal cortex participates in both visual recognition and working memory tasks: Functional mapping with 2-dg. *Journal of Neurophysiology, 85*, 2590-2601.

Easton, R. D., Sholl, M. J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*, 483-500.

Ekstrom, A.D., Kahana, M.J., Caplan, J.B., Fields, T.A., Isham, E.A., Newman, E.L., & Fried, I. (2003). Cellular networks underlying human spatial navigation. *Nature*, *425*, 184-187.

Feigenbaum, J. D., & Rolls, E. T. (1991). Allocentric and egocentric information processing in the hippocampal formation of the behaving primate. *Psychobiology*, *19*, 21-40.

Franklin, N., Henkel, L. A., & Zangas, T. (1995). Parsing surrounding space into regions. *Memory and Cognition*, *23(4)*, 397-407.

Gajewski, D. A., & Brockmole, J. R. (2006). Feature bindings endure without attention: Evidence from an explicit recall task. *Psychonomic Bulletin & Review*, *13(4),* 581-587.

Galletti, C., Battaglini, P. P., & Fattori, P. (1995). Eye position influence on the parieto-occipital area PO (V6) of the macaque monkey. *European journal of neuroscience*, *7*, 2486-2501.

Gallistel, C.R. (1990). *The organization of learning.* Cambridge, MA: MIT Press.

Holmes, M. C., & Sholl, M. J. (2005). Allocentric coding of object-to-object relations in over-learned and novel environments. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. *31(5)*, 1069-1087.

Koffka, K. (1935). *Principles of Gestalt Psychology*. London: Lund Humphries.

Kosslyn, S. M., Ball, T. M., & Reiser, B. J. (1978). Visual images preserve metric spatial information: Evidence form studies of image scanning. *Journal of Experimental Psychology: Human Perception and Performance*, *4*, 47-60.

Luck, S. J, & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*, 279-281.

McNamara, T. P. (1986). Mental representations of spatial relations. *Cognitive Psychology*, *18*, 87-121.

McNamara, T. P, Hardy, J. K., & Hirtle, S. C. (1989). Subjective hierarchies in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15(2)*, 211-227.

Mergner, T., Nasios, G., Maurer, C., & Becker, W. (2001). Visual object localisation in space: Interaction of retinal, eye position, vestibular and neck proprioceptive information. *Experimental Brain Research*, *141*, 33-51.

Milner, A. D., Dijkerman, H. C., & Carey, D. P. (1999). Visuospatial processing in a case of visual form agnosia. In N. Burgess, K. J. Jeffry, & J. O'Keefe (Eds.), *The hippocamal and parietal foundations of spatial cognition* (pp. 443-466). Oxford, UK: Oxford University Press.

Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28(1),* 162-170.

Mou, W., McNamara, T. P., Rump, B., Xiao, C. (2006). Roles of Egocentric and Allocentric Spatial Representations in Locomotion and Reorientation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32(6),* 1274-1290.

Mou, W., McNamara, T. P., Valiquette, C. M., & Rump, B. (2004). Allocentric and egocentric updating of spatial memories. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 30(1)*, 142-157.

Müller, M., & Wehner, R. (1988). Path integration in desert ants, *Cataglyphis fortis. Proceedings of the National Academy of Sciences*, *85*, 5287-5290.

Murray, E., & Bussey, T. (1999). Perceptual mnemonic functions of the perirhinal cortex. *Trends in Cognitive Sciences, 3*, 142-151.

Norman, G., & Eacott, M. (2004). Impaired object recognition with increasing levels of ambiguity in rats with perirhinal cortex lesions. *Behavioral Brain Research*, *148*, 79-91.

O'Craven, K. M., Downing, P. E., & Kanwisher, N. (1999). fMRI evidence for objects as the units of attentional selection. *Nature*, *401*, 584-587.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map.* Oxford: Calrendon Press.

Palmer, S., & Rock, I. (1994). Rethinking perceptual organization: The role of uniform connectedness. *Psychonomic Bulletin & Review, 1*, 29-55.

Parslow, D. M., Rose, D., Brooks, B., Fleminger, S., Gray, J. A., Giampietro, V, Et al. (2004). Allocentric spatial memory activation of the hippocampal formation measured with fMRI. *Neuropsychology*, *18*, 450-461.

Philbeck, J. W., Loomis, J. M., & Beall, A. C. (1997). Visually perceived location is an invariant in the control of action. *Perception & Psychophysics, 59*, 601-612.

Philbeck, J, Sargent, J., Arthur, J., & Dopkins, S. (2008). Large manual pointing errors, but accurate verbal reports, for indications of target azimuth. *Perception, 37*, 511-

538.

Rieser, J.J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 15(6),* 1157-1165.

Rolls, E., & O'Mara, S. (1995). View-responsive neurons in the primate hippocampal complex. *Hippocampus*, *5*, 409-424.

Sargent, J., Dopkins, S., Philbeck, J., & Modarres, R. (2008). Spatial memory during progressive disorientation. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *34(3)*, 602-615.

Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive Psychology*, *43*, 247-310.

Taube, J. (1998). Head direction cells and the neurophysiological basis for a sense of direction. *Progress in Neurobiology*, *55*, 225-256.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception & Performance*, *27*, 92-114.

Waller, D., & Hodgson, E. (2006). Transient and enduring spatial representations under disorientation and self-rotation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32(4)*, 867-882.

Waller, D., Montello, D. R., Richardson, A. E., & Hegarty, M. (2002). Orientation specificity and spatial updating of memories for layouts. *Journal of Experimental Psychology: Learning Memory, & Cognition*, *28*, 1051-1063.

Wang, R. F., & Brockmole, J. R. (2003a). Human navigation in nested environments. *Journal of Experimental Psychology: Learning Memory, & Cognition*, *29(3)*, 398-404.

Wang, R. F., & Brockmole, J. R. (2003b). Simultaneous spatial updating in nested environments. *Psychonomic Bulletin & Review*, *10*, 981-986.

Wang, R. F., Crowell, J. A., Simons, D. J., Irwin, D. E., Kramer, A. F., Ambinder, M. S., Thomas, L. E., Gosney, J. L., Levinthal, B. R., & Hsieh, B. B. (2006). Spatial updating relies on an egocentric representation of space: Effects of the number of objects. *Psychonomic Bulletin and Review*, *13 (2)*, 281-286.

Wang, R. F., & Simons, D. J. (1999). Active and passive scene recognition across views. *Cognition*, *70*, 191-210.

Wang, R. F., & Spelke, E. S. (2000). Updating egocentric representations in human navigation. *Cognition*, 77,215-250.

Wertheimer, M. (1923). Untersuchungen zur Lehre von der Gestalt, II. *Psychologische Forschung*, *4*, 301-350.

Author note

Jesse Sargent, Stephen Dopkins, and John Philbeck, Department of Psychology, David Chichka, Department of Mechanical and Aerospace Engineering, George Washington University, Washington, DC. This research was partially supported by NIH grant R01 MH067674-01 to John Philbeck. Correspondence should be addressed to Jesse Sargent, George Washington University, Department of Psychology, 2125 G St. N.W., Washington, DC 20052. Email: jqs@gwmail.gwu.edu

Footnotes

[1] Previous studies have used *configuration error* (standard deviation of individual object errors) to assess the degree of inter-target error for multi-object arrays (Wang & Spelke, 2000). The advantage of using *ASE*, which assesses the same thing for two-target "arrays", is that it makes possible the *Variable ASE* analysis, which, as described shortly, actually uses *signed* error. Analyses run using *configuration error* produced results identical to those reported (using absolute *ASE*, our primary dependent variable) and mean levels of configuration error observed in this study were comparable to those observed in previous studies.

[2] McNamara, Hardy, and Hirtle (1989) found that object pairs from common hierarchical branches in spatial memory were remembered as being closer than pairs from different branches. However, these results were acquired using a very different paradigm than that used in the current study, e.g., names of object pairs were presented on a computer screen and the remembered distance between them was reported in feet. In light of the important differences between current and prior studies, no predictions about signed error are made on the basis of these prior results.

[3] Because this analysis was post-hoc, front and rear pairs were not exactly matched on angular proximity. However, *ASE* did not differ even in comparisons wherein the angular separation was greater for rear than for front target pairs. Thus, the observed lack of significantly greater *ASE* values for rear pairs is probably not explained by differences in angular proximity between the front and rear pairs that were compared.

[4] Perceived heading for a given participant on a given turn was calculated as the mean of the corresponding *linearized error* scores across all targets. The Rayleigh test (*z*

= nr^2) showed the distribution of perceived headings did not significantly differ from uniform (i.e., was random) for turn 5, approximately 20% of the data.

[5] Previous studies have failed to show greater degrees of updating error, as measured by *configuration error*, after a disorientation procedure (Holmes & Sholl, 2006) and thus this result is not that surprising.

[6] No data excluded from the main analyses were included here. However, because of the relatively high level of subject attrition associated with the fifth and final turn (disoriented condition), for this, and all subsequent analyses, missing data were replaced with the group means so that no additional participants would be excluded.

Table 1.

Experiment 1: Mean Absolute ASE (with standard error in parentheses).

Proximity	Similarity*	Turn		
		no-turn	70°	disorientation
close	high	7.2° (1.5°)	10.6° (1.9°)	9.1° (1.5°)
	low	5.2° (0.9°)	7.3° (1.4°)	9.3° (2.4°)
far	high	11.3° (3.1°)	25.8° (3.9°)	21.3° (3.4°)
	low	9.8° (1.2°)	20.1° (2.9°)	23.7° (4.0°)

* High and low similarity refers to balloon-balloon and object-object target pairs, respectively.

Table 2.

Experiment 2: Mean Absolute ASE (with standard error in parentheses).

Collinearity	Turn*				
	1	disorientation	3	4	5
collinear	16.7° (2.5°)	20.0° (3.2°)	16.5° (2.3°)	29.2° (4.6°)	20.5° (3.1°)
random	26.1° (3.5°)	24.5° (3.2°)	20.4° (2.5°)	20.6° (3.0°)	37.2° (5.7°)

* All turns except disorientation were 70°, clockwise.

Table 3.

Experiment 3: Mean Absolute ASE (with standard error in parentheses).

Connectedness	Turn*					
	1	disorientation	3	4	5	6
within-object	21.2° (4.2°)	14.0° (1.9°)	17.7° (3.3°)	21.0° (2.2°)	15.3° (2.0°)	16.8° (1.9°)
between-object	28.2° (4.0°)	21.2° (2.4°)	18.9° (2.8°)	26.7° (4.0°)	24.9° (3.9°)	24.7° (3.1°)

* All turns except disorientation were 70°, clockwise.

Figure Captions

Figure 1. Schematic overhead view of the experimental chamber (not to scale), pointing device, and approximate locations of objects used in Experiment 1. Angle, measured clockwise from the training heading (shown), and distance from the axis of rotation of the chair are shown for each object.

Figure 2. Experiment 1: Mean Angular Separation Error (*ASE*) for “close” and “far” target pairs by Turn condition. Because there was no significant effect of Similarity, data are collapsed across Similarity conditions. Error bars are the standard errors of the mean.

Figure 3. Schematic overhead view of the experimental chamber (not to scale), pointing device, and approximate locations of objects used in Experiment 2. Regularly configured (“collinear”) portion of the array is indicated by dotted lines. Angle, measured clockwise from the training heading (shown), and distance from the axis of rotation of the chair are shown only for objects belonging to experimental pairs. Relative positions of other objects were approximately as shown.

Figure 4. Experiment 2: Mean Angular Separation Error (*ASE*) for “collinear” and “random” target pairs by Turn condition. Error bars are the standard errors of the mean.

Figure 5. Schematic overhead view of the experimental chamber (not to scale), pointing device, and approximate locations of objects used in Experiment 3. All targets were approximately 1.5m from the axis of rotation of the chair.

Figure 6. Experiment 3: Mean Angular Separation Error (*ASE*) for “within-object” and “between-object” target pairs by Turn condition. Error bars are the standard errors of the mean.

Figure 7. a. Experiment 2: Mean Angular Separation Error (*ASE*) for “collinear” and “random” target pairs by oriented/disoriented levels of Turn (disorientation defined statistically). b. and c. Experiments 1 and 3, respectively: Mean Angular Separation Error (*ASE*) for (b) “close” and “far” and (c) “within-object” and “between-object” target pairs by high/low configuration error cases. Error bars are the standard errors of the mean.

Figure 1.

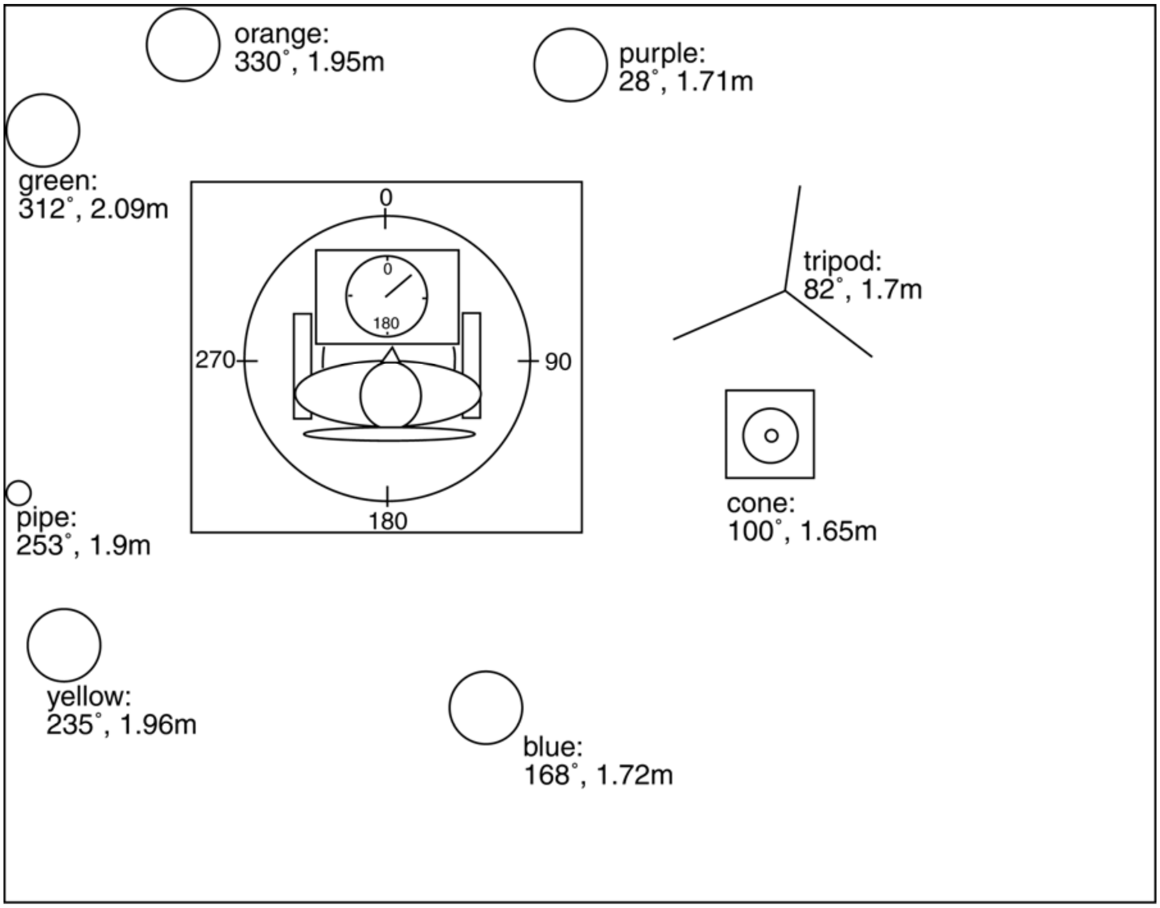

orange:
330˚, 1.95m
purple:
28˚, 1.71m
green:
312˚, 2.09m
0
0
180
270
90
180
tripod:
82˚, 1.7m
cone:
100˚, 1.65m
pipe:
253˚, 1.9m
yellow:
235˚, 1.96m
blue:
168˚, 1.72m

Figure 2.

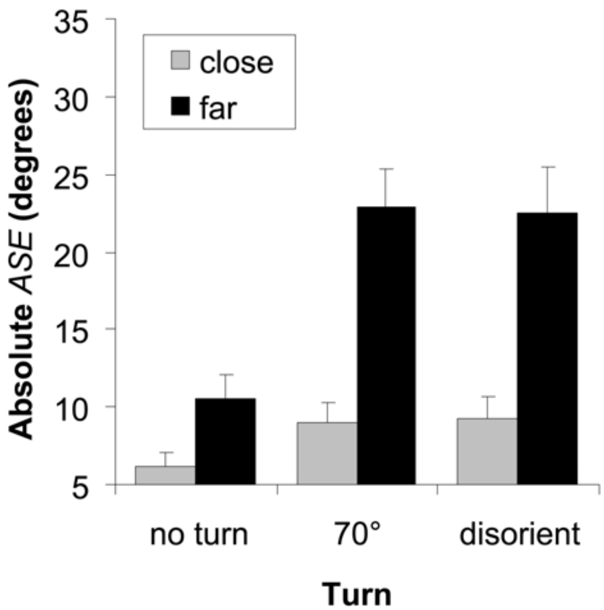

35
30
25
20
15
10
5
Absolute ASE (degrees)
close
far
no turn
70°
disorient
Turn

Figure 3.

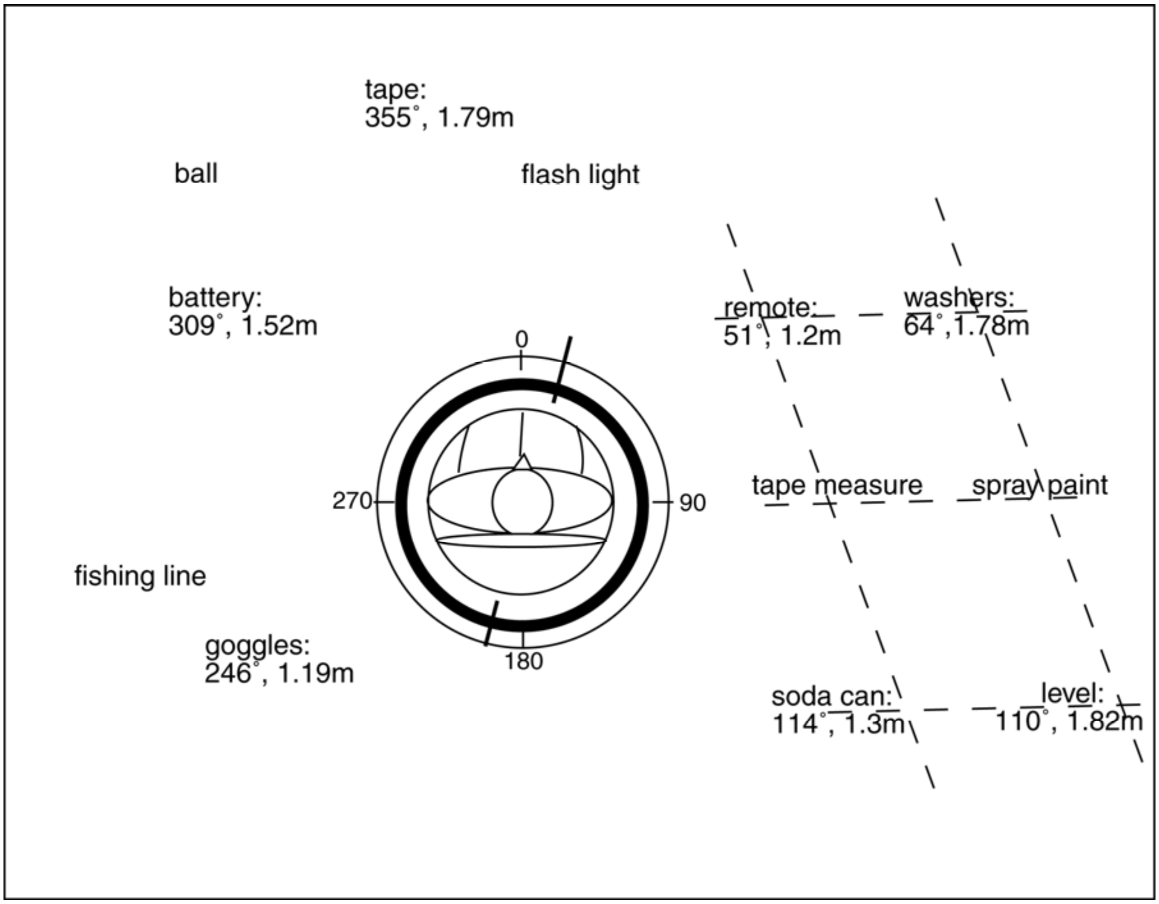

tape:
355°, 1.79m
ball
flash light
battery:
309°, 1.52m
remote:
51°, 1.2m
washers:
64°, 1.78m
0
270
90
180
tape measure
spray paint
fishing line
goggles:
246°, 1.19m
soda can:
114°, 1.3m
level:
110°, 1.82m

Figure 4.

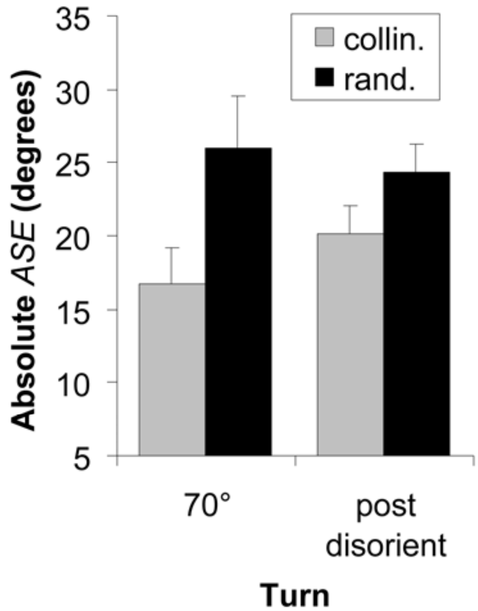

35
30
25
20
15
10
5
collin.
rand.
Absolute ASE (degrees)
70°
post
disorient
Turn

Figure 5.

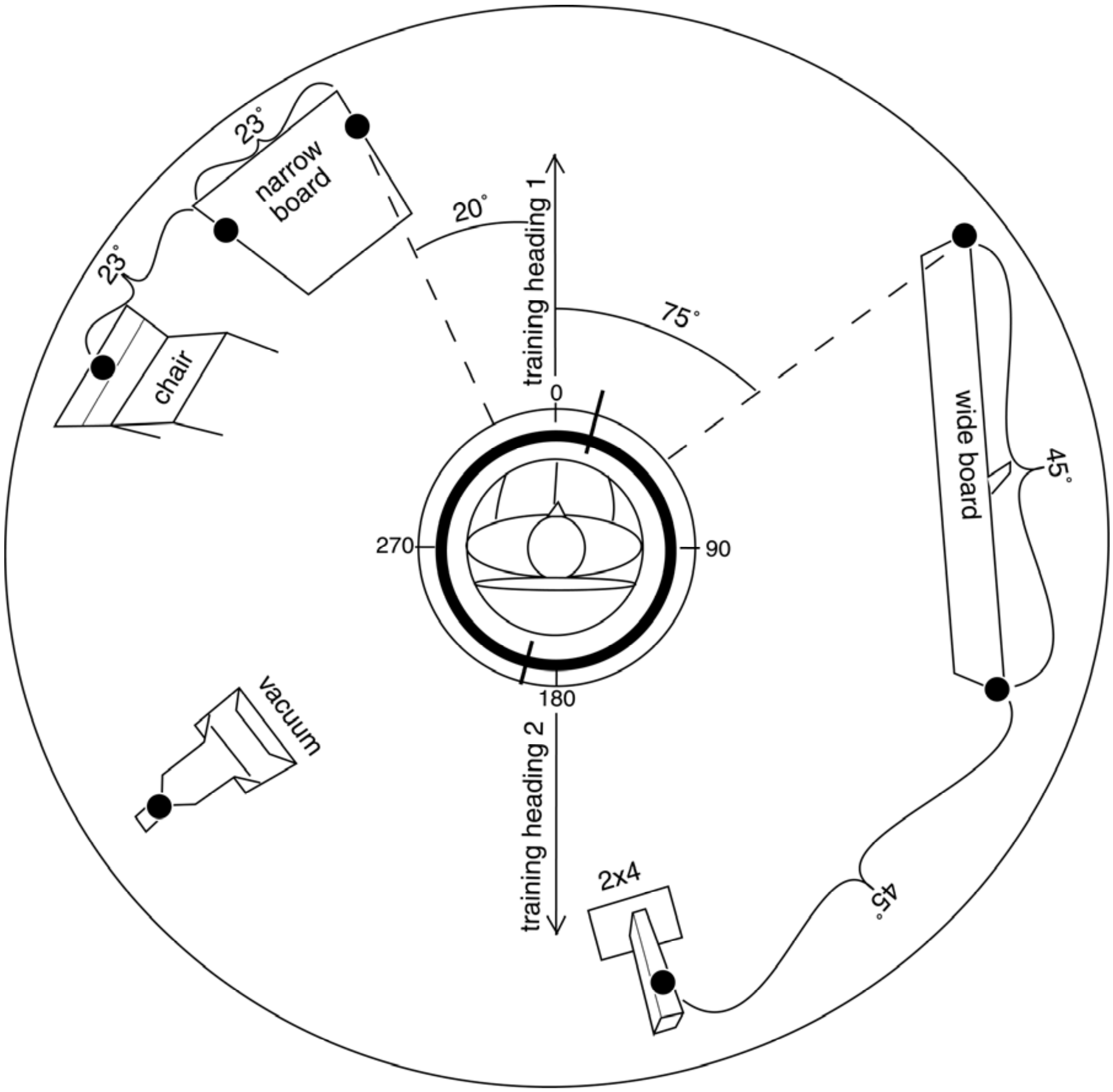

23°
23°
narrow board
20°
training heading 1
75°
chair
wide board
45°
0
270
90
180
vacuum
training heading 2
2x4
45°

Figure 6.

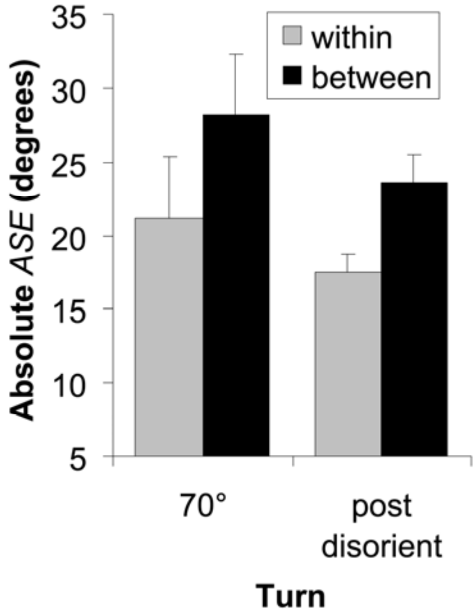
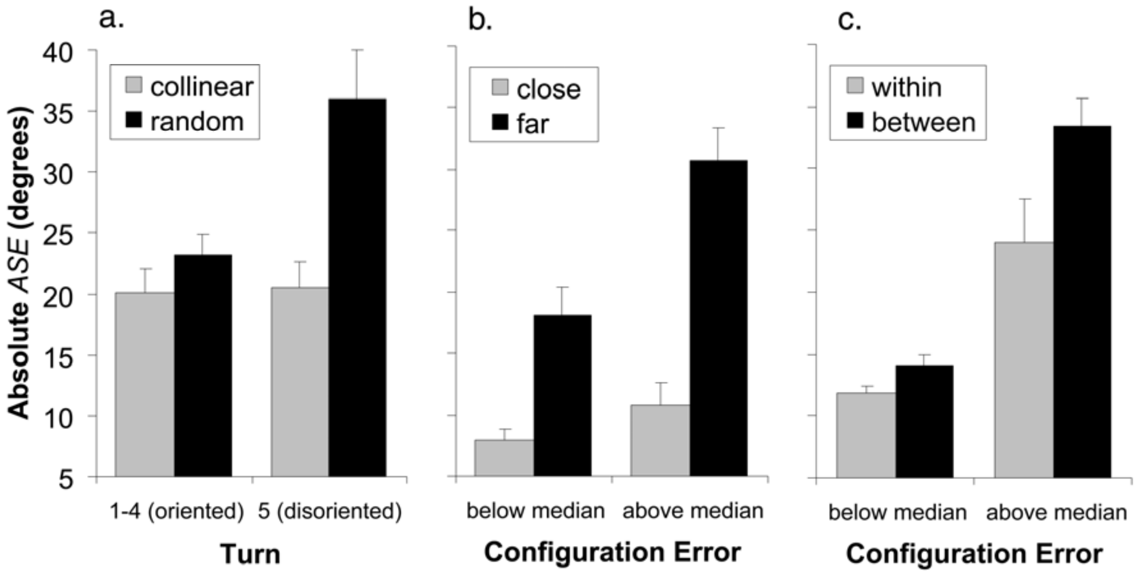

35
30
25
20
15
10
5
within
between
Absolute *ASE* (degrees)
70°
post
disorient
Turn

Figure 7.


a.
b.
c.
Absolute ASE (degrees)
40
35
30
25
20
15
10
5
collinear
random
close
far
within
between
1-4 (oriented)
5 (disoriented)
Turn
below median
above median
Configuration Error
below median
above median
Configuration Error