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The effect of egocentric and environmental cues on macro-reference frame selection

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ABSTRACT

Knowledge of space is inherently relative. Therefore, in order to make use of spatial knowledge, it must be encoded with respect to a particular perspective so that values such distance and angle have meaning. This stored perspective is known as the reference frame, and many judgments about remembered space are calculated based on this perspective. Past work using a single layout of objects has identified egocentric, environmental, and intrinsic cues that affect which perspective will be selected as the reference frame and have demonstrated that the particular perspective chosen is not limited to those experienced. This project expands on preliminary work to determine whether these same cues used for individual layouts influence the macro-reference frame used when making judgments between two independent layouts. Macro-reference frames are not explicitly studied, and therefore may or may not be subject to the same cues observed previously in the literature. Throughout the course of this project, results mirror those from the single layout literature where egocentric experience, external environmental cues, and intrinsic features of the object set all contribute to macro-reference frame selection. Furthermore, the macro-reference frame is formed independent of the micro-reference frames selected for the multiple, independent groups. These results indicate that previous work regarding reference frames for a single layout can safely be extended to macro-reference frame selection.

CHAPTER 1: LITERATURE REVIEW

General Introduction

Knowledge of space is inherently relative. For example, saying that my book is “to the left” is meaningless unless I also specify what my book is to the left of. Relatively speaking, my book is on top of my desk, to the left of the coffee cup, but also to the right of my body. With this information, it is now possible to create a rough mental representation that my book is on the desk at my right hand while the coffee cup is further to the right and would require me to reach over the book in order to drink from it. Concepts like right and left are not only relative in that they require some frame of reference, but altering my own position will change how these terms are used. If I were to get up and walk 180 degrees around the desk, the book would instead appear to be to the right of my coffee cup and to the left of me.

Terms like “to the right” and “in front of” can be categorized by self-position, but it is also possible to for these concepts to be relative to a particular fixed point. For example, Ames will always be to the north of Des Moines no matter which direction I am facing as north and south exist relative to latitudinal position rather than the observer. Even more absolute and standardized coordinates like those used for GPS are relative to the intersection of the prime meridian and the equator where both values are set to zero.

The relative nature of spatial knowledge necessitates that all cognition or memory regarding physical space include some sort of reference system. Several distinct reference systems have been proposed and research has shown that the particular system utilized depends on the particular environmental features in play. This project seeks to identify and further understanding of the features that govern the selection of spatial reference systems.

Scales of Space

When discussing perception and memories of space, it is important to consider how different scales might affect the way this information is processed. Simplistic distinctions such as “large scale” and “small scale” are not particularly helpful as the difference is arbitrary and difficult to integrate with specific theories of spatial cognition. Montello (1993) describes extant definitions for scales of space and offers a new system that takes a functional approach, eliminating much of the ambiguity found in previous scales.

Montello (1993) describes four levels of space, *figural, vista, environmental*, and *geographical* space. These four distinctions are a refinement of Mandler’s (1983) small, medium, and large spaces which were themselves an expansion on Ittelson’s (1973) original work on the topic.

Figural space is that which is projected to be smaller than the body as it requires no body movement or head rotation to view in its entirety. An example of figural space would be a tabletop game where all of the pieces can be viewed and moved from the player’s chair; the entire space in question could be contained within a single viewpoint, similar to a photograph. Additional examples could include a cell phone or kitchen counter. Each of these objects exists within a space that can be fully viewed without any body manipulation required.

Vista space is projectively larger than the individual (requiring some sort of rotation to fully observe), but can still be observed without locomotion. Good examples of vista space include a rectangular room, a town square, and a forest clearing. In each of these cases, an individual could stand in the middle of the space and view the entirety by turning in a circle.

Environmental space is one step larger in that both rotation and locomotion would be required to view the entire space. For example, a classroom exists within vista space, but classrooms arranged along a hallway would require the individual to walk, turning to enter each room, in order to see the entire space. Similarly, a building with multiple hallways or a campus with multiple buildings would both also inhabit environmental space. Figural, vista, and environmental levels of spatial scale can all be learned through different types of movement. The fourth category, geographical space, is fundamentally different.

Geographical space is that which cannot be explored by waking or rotating. Instead, learning about geographical space requires semantic learning through symbolic structures such as maps. For example, a city center could be explored by walking in just a few hours, but exploring the contiguous United States by locomotion (even using a vehicle) is entirely impractical. Furthermore, learning about the globe through exploration alone is essentially impossible. Instead, learning for these spaces occurs through reading maps and determining how different locations are associated with one another through experiential means. It is important to note that while the map itself exists in figural space, the locations it represents exist in geographical space.

Research on spatial memory spans all four scales described by Montello. However, it is important to consider how the learning in different scales of space might affect the content of knowledge. For example, vista and environmental spaces necessitate learning through some sort of exploration while knowledge of geographical space must be learned through an aide such as a map. Thorndyke and Hayes-Roth (1982) examined differences in the type of knowledge acquired through direct experience compared to map learning. They did so by comparing employees in a complex building to students from the nearby university who had never explored the space and were confined to learning it through maps.

Thorndyke and Hayes-Roth (1982) found that participants who had learned the complex via a map were better at determining straight-line distances (ignoring all walls and rooms) between locations within the building than new hires who had only navigated the building for 1-2 months. However, as employment time increased, and the workers consequently had more time to build a solid knowledge of the building, their performance on straight-line distance estimations rose to match that of the participants who studied using maps. When comparing estimates of route length between rooms, the workers outperformed the map learners and did not show an effect of employment time. Straight-line estimates rely on survey knowledge of an environment and this explains the advantage for map-learning participants since maps primarily convey survey information. However, it is also clear that when route-learning is extensive, it is possible to develop solid survey knowledge of the environment independent of map study. The majority of research referenced here as well as the proposed experiments are designed with figural and vista spaces in mind. Extensions to geographical space should be considered with caution.

Systems of Reference

As mentioned earlier, all spatial knowledge must be relative to something, whether that is the viewer (egocentric) or some other aspect of the environment (allocentric) including nearby objects. Conceptually, egocentric coding of spatial locations is very straightforward; each object is at a particular location and distance relative to the viewer. For example, my computer screen is directly to my front and just over 2 feet away while the door to my office is 8 feet behind me and a little to the left. Although these egocentric terms are easy to understand, they do not specify what sort of coordinate system is being used by the brain to process these locations.

Huttenlocher, Hedges, and Duncan (1991) compared competing rectangular and polar coordinate models of spatial memory. A rectangular system of egocentric encoding (ignoring the vertical dimension for simplicity) would consist of a value for distance left/right and a value for distance forward/back, relative to the self. Similar to a Cartesian plane, these two values will converge at only one point, providing the object's location. By contrast, a polar system of encoding (again ignoring the vertical dimension) would consist of a rotation angle from straight ahead (azimuth) as well as a distance value relative to the self. Rotating the appropriate angle from zero and traveling the specified distance would allow one to reach the target location just as well as using a coordinate plane. Thankfully, Huttenlocher et al. (1991) describe a 2D scenario in which these two coordinate systems will yield contradictory results, negating the need for a more complex 3D experiment.

Huttenlocher et al. (1991) suggest a model of spatial knowledge where both categorical and fine-grain metric information is stored in memory. A similar model has been shown to exist for color perception (Reiger & Kay, 2009). In the color model, lots of different shades are all considered "red" but a particular shade might be more purple or more orange than others when considered in finer detail. In such a situation, judgments are biased away from category boundaries. In spatial memory, this bias comes in the form of truncation. Truncation occurs when a portion of the normal error cannot occur as it would cause the judgment to switch to an incorrect category. Consider a circle with a dot drawn in the top-left quadrant. If the average error in memory for that dot would instead yield a position outside the circle, the categorical memory would negate the response and thus the underlying error distribution would need to be adjusted accordingly. When this concept is applied to polar and rectangular coordinate systems, category boundaries should yield very different error patterns.

Figure 1 shows a circle with 2 dots, one near the center and one near the edge. The smaller, dashed circles around each dot represent normal error in memory for exact position. The left dot will not have errors in fine grain knowledge truncated because that error would not force the position to be remembered outside the circle. However, the right dot is close enough to the edge that error could conceivably yield a categorical result of "outside circle" and the right dot's error will have to be truncated in order to prevent this error. According to Huttenlocher et al. (1991), truncating the coordinate system will shrink both the x and y value of the error until it no longer causes a category violation. On the other hand, truncating the polar system only requires the distance error to be minimized, as errors in azimuth would not cause a category violation. Therefore, the shape of judgment error should vary near the category boundary dependent on which coordinate system is used. Huttenlocher et al. observed truncation only in distance from the edge of their circles, not in overall (x,y) position. These patterns in memory error match the expectations of a polar coordinate system for spatial location rather than a rectangular coordinate system.

Humans use polar coordinate system for spatial memory. However, the next logical question is whether spatial memory is limited to only azimuth and distance around the self, or whether these coordinates can also directly represent position around an object. The earlier example regarding my monitor and office door was given from a self-to-object perspective. While both items have an azimuth and distance in relation to myself, they also have object-to-object azimuth and distance values relating one to another. Examples of self-to-object and allocentric object-to-object codes can be seen in Figure 2. Easton and Sholl (1995) conducted a series of experiments to determine whether these object-to-object relationships could be processed allocentrically – without regard to the individual's location – or if these relationships only existed egocentrically in memory as a series of self-to-object values that are recalculated as necessary.

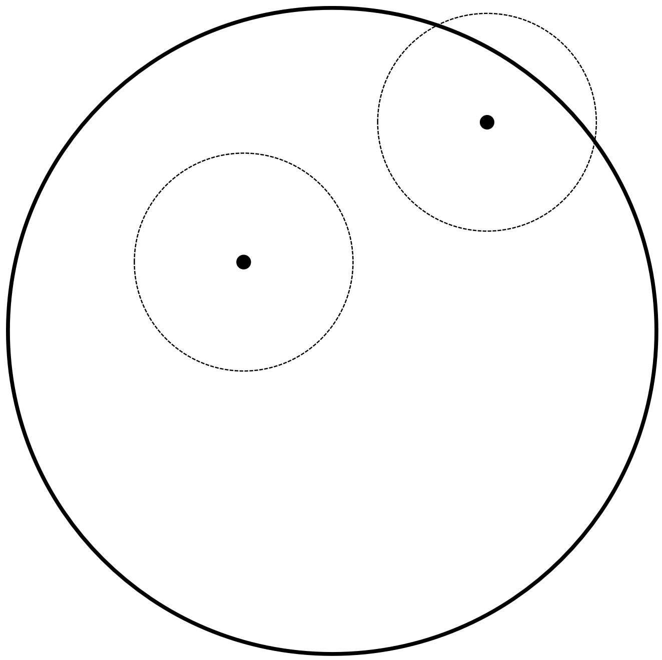

Figure 1. Illustration of errors that do (right dot) and do not (left dot) need truncation.

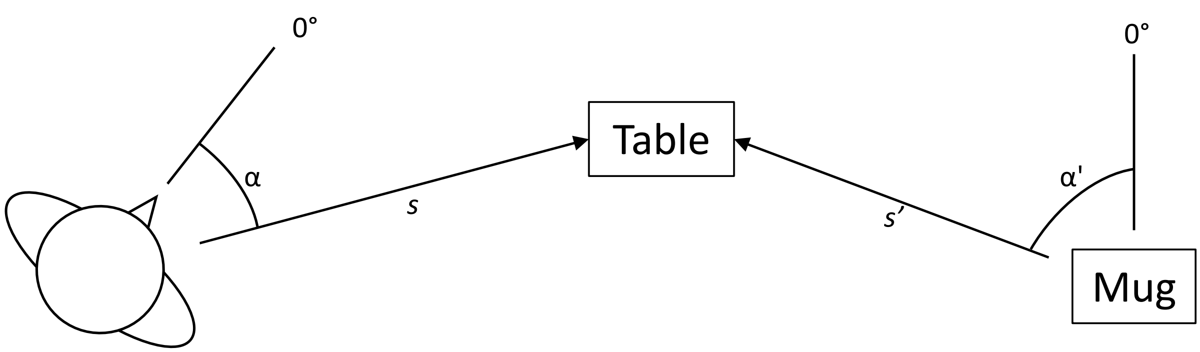

Figure 2. Examples of polar coordinates to the table reflected in egocentric (left) and allocentric (right) reference systems.

Participants pointed to a learned object either as if they were facing another object (imagined rotation) or as if they were located somewhere else (imagined translation). In theory, egocentric recall would be governed by a viewpoint-dependent representation of the environment in which the individual would imagine themselves rotating or translating to a new location, away from the stored memory, requiring recalculation of these self-to-object values and a processing cost should be seen in judgment latency and angular error (Shelton & McNamara, 1997). However, allocentric recall of object-to-object information should be immune to this effect as imagined rotation and translation would not be necessary (i.e. the object-to-object locations are directly stored in memory and just need to be retrieved).

Evidence was found for direct access for allocentric object-to-object information only when the object layout was distributed regularly. Complex and random environments showed a rotation and translation cost that suggests that the individual was imagining the new position and updating egocentric codes as necessary. Though direct recall of object-to-object relationships was only found under particular circumstances, this does suggest that both allocentric and egocentric representations can be utilized depending on certain features of the environment. This concept will be discussed more in the next section.

Reliance on Egocentric Codes

Easton and Sholl (1995) provided evidence that allocentric codes for object-to-object relationships could be accessed directly under a set of specific circumstances. However, an influential paper by Wang and Spelke (2000) cast doubt on that understanding and provided the alternate theory that all knowledge of spatial environments is transient, being mediated through egocentric codes that are continually updated to reflect self-motion.

Wang and Spelke (2000) compared two alternative models, one for allocentric representations of object-object relationships and another for purely egocentric representations. In the allocentric model, object-object relationships are maintained in memory similar to a physical map, they are enduring and stable no matter which direction the individual is facing. Imagine an individual standing in a forest clearing at noon with a map of nearby towns. If told what direction was north, it would be easy for the individual to turn the map to fit their current orientation and point to nearby cities. If the individual were then spun until disoriented, they could guess as to what direction was north before using the map again to point to the nearby cities with relative, if not absolute, accuracy. For example, cities A and B might be truly located 45 degrees apart due north and northeast of the clearing, but the individual might point south and south-west respectively after incorrectly guessing their orientation. In this case, the overall pointing error would be measured at 180 degrees (opposite the correct direction), but city B was still correctly identified as being 45 degrees clockwise of city A. The relative locations of the two cities were preserved despite overall error thanks to the map.

By contrast, the egocentric model proposes that object-to-object relationships are created by trigonometrically combining egocentric vectors to both targets in order to produce the third side of the triangle that represents the actual object-to-object vector. In this model, object-to-object relationships rely on accurate updating of all egocentric vectors and a breakdown of this system will make it difficult if not impossible to calculate the correct object-to-object vector. In the earlier forest clearing example, disorientation would cause a breakdown in all of the individual egocentric vectors so each must be guessed individually (without an allocentric map, guessing north wouldn’t be useful). Absolute accuracy will be lost just as it was for the allocentric model because the individual's orientation within the world must be guessed. However, while the allocentric model can look back to the stored map to restore relative accuracy, the egocentric model does not possess any object-to-object codes that could preserve that relative accuracy causing judgments to be more scattered. Wang and Spelke quantified this relative accuracy as *configuration error* or the standard deviation of pointing error. If an allocentric map were recalled perfectly, each location would be judged to the same distance away from actual (error in orientation estimation) and the resulting configuration error would be zero. However, if both direction and magnitude of error are allowed to vary as in the egocentric model, this configuration error will increase.

Several experiments conducted by Wang and Spelke (2000) were intended to demonstrate the correct model as well as rule out confounding variables. In Experiment 1, participants learned a series of objects scattered around the outer portion of a laboratory space before having the objects obscured by entering a small experimental chamber and pointing to objects as best they remembered. Participants were then disoriented by spinning in a circle while blindfolded before being asked to point to the target objects again. Results showed that both total pointing error and configuration error increased as a result of disorientation as predicted by the egocentric model.

Experiments 2 and 3 examined two potential confounds inherent to the pointing response method that may increase configuration error independent of reference model. Experiment 2 ruled out persistent vestibular confusion or perceived translation due to the act of standing and spinning by having the participant sit in a spinning chair during disorientation and test as well as allowing a 30 second break for the vestibular system to recover after the disorientation procedure. Again, both pointing error and configuration error increased as predicted by the egocentric model. Experiment 3 ensured that the disorientation task itself did not cause errors in pointing ability. Participants were asked to point, not to objects, but simply to various orientations from their own perspective (e.g. 90 degrees right or 135 degrees left) before and after disorientation. No differences were found between the tests, suggesting that observed errors were due to increasing error in the spatial representation rather than changes in the physical pointing response.

Experiment 5 expanded on the findings from the first three and examined how an orientation aid might change the outcome. A lamp was placed on the chamber wall and turned on before and after the disorientation procedure (the chamber was dark during disorientation). In this case, heading information and any associated egocentric vectors should be lost during disorientation, but individual heading should be recovered after the procedure when the light was turned on again. In this case, the allocentric model would predict no change in both pointing and configuration error just as it would be akin to using a compass to rediscover north in the earlier forest example. However, results showed that configuration error was significantly worse after disorientation even with the light allowing reorientation, suggesting that constant knowledge of one’s position is necessary to maintaining accurate object-to-object relationships further supporting the initial results.

While this series of experiments does provide evidence for a purely egocentric model of spatial knowledge, it does not propose a mechanism for the storage of long-term spatial knowledge or how it could be utilized later from a different location. For example, it would be incredibly difficult for an individual to maintain a series of egocentric vectors to every object in their office during the evening commute, yet they would still be able to describe a vector connecting the stapler and computer upon arriving home. In this example, some level of allocentric knowledge is being recalled and facilitating the judgment. In answer to this question, a two-system theory of spatial memory (Mou, McNamara, Valiquette & Rump, 2004) has been proposed that explains the findings from Wang and Spelke (2000) while still preserving the existence of long-term spatial memory.

The Two System Model

Everyday phenomena demand the existence of some long-term storage for allocentric spatial knowledge. For example, you can determine vectors between the couch, television, and door in a friend's living room even after not visiting for several weeks. However, this long-term storage of object-to-object relations is incompatible with the reference system supported by Wang and Spelke (2001) as updating these egocentric codes constantly for weeks at a time would be impossible. Additionally, you can determine vectors between object locations in an old home despite having moved away and relocated all of your items to a new building. Not even perfect egocentric updating can allow calculations between objects that have been moved. Mou, McNamara, Valiquette, and Rump (2004) proposed a new model that consists of a short-term, egocentric system similar to that of Wang and Spelke (2001) that exists parallel to a long-term, allocentric system that facilitates recall after disorientation or significant delay and from distant locations.

Mou et al. (2004) examined the discrepancy with Wang and Spelke (2001) by measuring pointing error on a judgment of relative direction task, also known as a JRD (e.g. imagine standing at A, facing B, point to C), for a layout learned from one particular perspective. After learning the layout, participants walked to the center of the layout (similar to Wang & Spelke, 2001) and performed JRDs with eyes closed. Participants showed less pointing error when making judgments where the imagined orientation (A facing B) was aligned with the learned view than when misaligned with the learned view. More importantly, this result persisted even when participants had turned their body prior to test so that their egocentric and imagined orientations were identical at time of test. These results contradict the egocentric model proposed by Wang and Spelke (2001) as pointing error should have been lowest when egocentric and imagined headings aligned with no regard for the learned view as egocentric codes would have been updated to reflect the new orientation.

Mou et al. (2004) proposed that egocentric codes are vital for easy and efficient navigation through an environment as they are updated in an online manner rather than being retrieved from long term memory and mentally adjusted to fit the scene. However, this egocentric representation is very short lived, existing only so long as it is rehearsed and updated any time the individual moves. When knowledge of object-to-object relations is required beyond those short-lived egocentric codes (as with many judgments of relative direction) an allocentric, viewpoint-dependent representation can be accessed. It is important to note that Mou et al. (2004) utilized a measure and procedure different from that used by Wang and Spelke (2001). However, Waller and Hodgson (2006) demonstrated further evidence for this two-system model of spatial memory using the same disorientation paradigm used by Wang and Spelke along with the JRD task used by Mou et al.

Waller and Hodgson (2006) included fidelity as an additional facet to differentiate the two systems proposed by Mou et al. (2004). According to Waller and Hodgson, the egocentric system is not only transient, but includes a much higher level of fidelity than the allocentric system. Based on this understanding, the increase in configuration error after disorientation observed by Wang and Spelke (2001) can be interpreted not as a loss of the ability to correctly calculate object-to-object codes, but as the point where the egocentric system failed and the allocentric system was recruited instead.

Waller and Hodgson (2006) predicted that the two-system model would show a double dissociation for egocentric pointing tasks and JRDs while oriented and after disorientation. Although disorientation should disrupt egocentric codes (and therefore increase egocentric pointing error) it should also remove any interference with mentally rotating the allocentric representation caused by processing actual body orientation (thus reducing JRD pointing error). In a near replication of Wang and Spelke (2001), Waller and Hodgson found the predicted dissociation where egocentric pointing was impaired and JRD pointing was facilitated by disorientation. Consistent with the view that the transient egocentric system possesses higher fidelity, pointing errors in the JRD task were higher both before and after the disorientation than the egocentric pointing measure. Further evidence for the two-system model was demonstrated by examining egocentric pointing for the local, experimental environment as well as a remote environment (the participant's bedroom) before and after disorientation. Unlike the local environment, egocentric pointing error for objects in the remote environment did not increase after disorientation suggesting that the allocentric was being used in both cases. Additionally, pointing error for non-local objects was not significantly different from pointing error to local objects after disorientation, suggesting that the allocentric system utilized for the non-local objects was recruited for local objects after the egocentric codes were confused.

The evidence presented by Mou et al. (2004) as well as Waller and Hodgson (2006) demonstrates an alternative theory to Wang and Spelke (2001) that explains the increase in error after disorientation as a transition from the fine-grain and transient egocentric system over to a coarse and enduring allocentric system. Furthermore, the two-system model is more consistent with the neurological base of spatial cognition as described by Burgess (2006). The next section will discuss what factors determine the frame of reference selected for storing these coarse, allocentric representations.

Reference Frame Selection

With the need for an enduring allocentric representation of space established, the next step is to discuss how a particular reference direction is selected for storing the long-term representation. As discussed previously, reference frames are usually identified experimentally by looking for a processing cost (increased error or latency) associated with mentally rotating the recalled representation to match the to-be-imagined perspective. The imagined perspectives that demonstrate the lowest error and latency are assumed be aligned with the reference frames used to store the memory as they require the least effort to retrieve.

The perspective from which an environment is initially viewed is a ubiquitous cue, present in every situation. Shelton and McNamara (1997) as well as Mou and McNamara (2004) demonstrated that JRDs (i.e., tests of imagined perspective taking) aligned with the learned view were faster and more accurate than those that were misaligned. Additionally orthogonal perspectives (rotated 90 or 180 degrees from the given perspective) have been shown to have a special status within memory. For example, if the reference frame is aligned with 0 degrees, the 90, 180 and 270 degree perspectives would show increased error, but not as much as 45, 135, 225, and 315 degree perspectives even though 45 and 315 require fewer degrees of rotation from the stored reference frame than 90 and 270. Learned view is assumed to be a default cue to reference frame selection that is used whenever no other cues are available or none are salient enough to override learned view. For example, Shelton and

McNamara (1997b, 2001) demonstrated that the environment surrounding the items to be remembered can play a role in selecting the reference frame.

Shelton and McNamara (1997b) observed facilitation for perspectives orthogonal to the learned view only when the walls of the surrounding rectangular room were also parallel/orthogonal to the learned view. However, learning from views 45 and 135 degrees which were misaligned with the room walls only resulted in facilitation for the initial learned view. Shelton and McNamara (2001) expanded on these findings by examining how environment interacted with initially learned view. Participants learned a layout from either 0 or 135 degrees relative to room walls, and subsequent JRDs showed that each group performed best from their learned orientation. In a follow up experiment, participants learned from either 0 then 135 or 135 then 0 before being tested. When participants were given the opportunity to study from both perspectives, both groups performed best along the 0 degree imagined heading irrespective of learning order. Neither group showed any indication that the 135 degree orientation was stored in memory, only the 0 degree perspective showed an advantage in memory. Considering the two experiments together, learned view was adopted as the reference frame until a more salient cue such as room wall orientation was presented, at which point participants made use of the more salient cue without regard for previous or subsequent experience (135 – 0 and 0 – 135 respectively). A final experiment placed a local environment cue (rectangular rug) in conflict with a more global environment cue (room walls) and demonstrated participant’s ability to store spatial information with regard to two reference frames. In this case, both 0 and 135 degree views were facilitated after learning unlike the previous experiment where there was no conflict and 135 was dropped from memory entirely. While most experiments demonstrate that only one reference frame is stored in memory, Shelton and McNamara have provided some evidence that multiple reference frames may be stored given the proper circumstances.

Mou and McNamara (2002) carried on from the previous results and demonstrated that learned views and environmental features are not the only important cues for reference frame selection. Reference frames selection can be guided by other properties inherent to the layout such as symmetry or through verbal instruction. When viewing a layout from 315 degrees relative to the walls, participants were instructed to learn objects in an order that either corresponded to 0 or 315 degrees depending on which axis lined up with the object learning order. Additionally, the layout in question had a symmetry axis parallel to 0 degrees, in line with the environmental cues. Participants performed more accurately for perspectives aligned with their instructed direction irrespective of the other available cues. These results persisted even when the environmental cues were removed by placing a curtain around the layout to obscure the room walls.

In addition to learning instruction, layout structure can define which reference frame will be selected. In a series of experiments, Mou, Zhao and McNamara (2007) demonstrated that participants would utilize a layout symmetry axis to define a reference frame even when other perspectives were viewed first. In a pattern similar to Mou and McNamara (2002), the order in which learning views were experienced did not matter so long as a cue (symmetry in this case) was available to make a particular learned view more salient than the rest.

These studies not only demonstrate a range of cues that can be used to determine reference frame selection, but also that the selected reference frame does not have to be directly experienced in order to be effective. The saliency of particular cues will influence whether the cue is noticed and whether it is subsequently used to facilitate the storage of long-term spatial information. It is important to note that the studies up until now have primarily dealt with memory for objects in a room-sized laboratory environment (i.e., a vista space).

Marchette, Yerramsetti, Burns, and Shelton (2011) examined JRD performance for memory of campus buildings that participants had learned naturally during their time at Johns Hopkins University. This spatial scale is consistent with Montello's definition of an environmental space. Participants demonstrated highest performance from the 0 degree (North) perspective with facilitation along orthogonal axes (east, west, and south). North may have been selected as the reference due to the fact that most maps place north at the top and this could serve as a suitable anchor for understanding the object-to-object relationships. It is also possible that this axis was selected because many of the campus buildings are rectangular and are parallel to the north/south axis. Finally, a major road runs parallel to campus from north to south and may have served as an environmental cue for reference frame selection. Performance along the non-orthogonal axes (northeast, northwest, southwest, southeast) showed the greatest error. These results align with findings from the previously mentioned laboratory studies and provide evidence for external validity thus far. The next section discusses another way in which natural learning environments might affect the way spatial memories are stored.

Contrary to previous findings regarding intrinsic reference frame cues (Mou & McNamara, 2002; Mou, Zhou, & McNamara 2007), Richard and Waller (2013) demonstrated minimal evidence of intrinsic cues when utilizing irregular, non-symmetrical layouts. Consequently, the authors suggested that the effect of intrinsic cues might be overstated given the regular use of layouts similar to those presented by Mou and

McNamara. These results do not necessarily preclude the existence of intrinsic reference frames, but rather question the relative weight of intrinsic reference frames as compared to a more body-based, egocentric system for location encoding. Instead of intrinsic axes allowing for allocentric encoding misaligned with the body, symmetry and orthogonality might make it easier to create an abstract representation of space. If the layout lacks a strong intrinsic axis, the only option may be to encode the layout from a more egocentric approach. This finding should be taken into consideration when considering the effect of egocentric and intrinsic cues, and further research may continue to shed light on how these findings play into the greater understanding of spatial memory.

Hierarchies of Spatial Memory

Natural environments are not learned as a single piece in their entirety during one session as with laboratory studies. Instead, locations are learned separately, perhaps over several different excursions. For example, one might learn locations downtown when going to work but learn about locations in the suburbs when running weekend errands. Hirtle and Jonides (1985) examined whether natural learning would produce unique groups of landmarks and what sort of effects these groups would have on spatial judgments. Participants freely recalled landmarks within the city of Ann Arbor. The authors subsequently used those data to create a unique, ordered tree for city landmarks based on response order whereby items frequently mentioned together were considered part of the same group. Because learning was natural and necessarily individualized for each participant, a unique tree was created for each participant. Results demonstrated that individuals had some similar groupings based on either physical landmark location or functionality with natural barriers such as rivers or major roads helping to define groups. Additionally, several different measures of remembered distance showed a group bias where locations in the same group were judged as being too close while locations in different groups were judged as being too far away from one another. Despite all landmarks being within the same downtown area, mental grouping caused a hierarchy to develop where the relative nature of the two groups influenced the judgments between individual items within or across the groups.

Similar effects were found in pointing error by Istomin and Dwyer (2009). Interviews with nomadic reindeer herders in northern Russia and Siberia demonstrated very precise pointing judgments to landmarks of the current grazing region and very high errors in pointing judgments to landmarks of a neighboring region. However, when the herders had crossed a river into the neighboring region, error patterns flipped such that judgments that were error-prone in the previous region became highly precise and vice versa. Biases in spatial judgments due to hierarchies are not only limited to distance, but also extend to directional information.

The two studies above demonstrate hierarchical groupings in the presence of physical boundaries such as rivers and roads, but McNamara, Hardy and Hirtle (1989) demonstrated that groups can be formed even without the presence of these natural divides. By using the same ordered tree paradigm as Hirtle and Jonides (1985), McNamara et al. were able to find spatial groupings for random objects scattered around a laboratory floor.

Both perceptions of distance and angle can be affected by spatial groupings that are developed naturally, even without obvious cues. This raises the question as to how reference frame selection would be affected by crossing a group boundary. It is possible that two different spatial groups might be encoded using different reference frames based on the available cues (e.g. group A along 0 degrees, but group B along 45 degrees), but then which reference frame would be selected when making spatial judgments across two different groups?

Micro- and Macro-Reference Frames

Complex spatial judgments may require integrating information from more than one category, and each category may have its own reference frame (herein known as the micro-reference frame). This raises the question as to what reference frame, if any, is utilized to facilitate these cross-category judgments. Greenauer and Waller (2010) discuss several models of cross-category spatial knowledge, and how each would affect a JRD trial. The authors also offer experimental evidence for one particular model.

The first spatial memory model proposes that no metric values are stored for cross-group locations. This could explain why the reindeer herders interviewed by Istomin and Dwyer (2009) were incredibly accurate at making spatial judgments at any distance so long as the judgment did not cross any environmental boundaries. In this case, JRDs should not show facilitation for a particular orientation as no cross-group information is stored in memory. A second model proposes that a reference frame established for one group will be extended to encompass any referenced items outside the group. In this case, judgments between groups would show facilitation for one of the perspectives also facilitated by the one of the individual groups. Finally, a third model suggests that individual groups might have a micro-reference frame that is utilized to store representations within each group individually. Then, a separate macro-reference frame would be utilized to store representations for how each group relates to another. JRDs under this model should show the ability for a between group judgment to be facilitated at a perspective different from either of the two individual groups (Greenauer & Waller, 2010).

In a series of experiments, Greenauer and Waller (2010) created two separate groups of objects (office supplies and toys) and arranged them such that the two were non-overlapping and possessed different intrinsic reference frame cues. The toy layout possessed a symmetry axis along the 0 degree perspective while office supply layout were placed diagonal to the toys and were symmetrical along the 90 degree axis. The two groups were aligned along the 315 degree axis which also served as the learning view. Within group judgments showed lowest pointing error when aligned with the respective symmetry axis (intrinsic reference frame) while judgments between groups showed lowest error when aligned with the learned view, suggesting that two different reference frames were utilized depending on the judgment type. The within group judgments were governed by the individual micro-reference frames parallel to the appropriate group's symmetry axis while the between group judgments were facilitated by the macro-reference frame parallel to the learned view. Coincidentally, the learned view was aligned with the geometric relationship between the two groups.

In another experiment, the two layouts were placed in alignment along the 0 degree axis instead of the learned view at 315 degrees. Facilitation for between group judgments was shown along the 0 degree axis instead of the learned 315 degree axis from the earlier experiments demonstrating that the macro-reference frame could be affected by geometric cues in line with previous research.

These results demonstrate that the macro-reference frames are independent of the two micro-reference frames and may potentially be determined based on the same rules that govern reference frame selection with individual layouts (e.g. Shelton & McNamara, 2001). However, Greenauer and Waller (2010) only examined layouts that were physically distinct (i.e. non-overlapping) and did not examine whether the macro-reference frame could be independent of micro-reference frames in situations where the two micro-reference frames were aligned with one another. This issue will be examined in the next section.

Preliminary Work

Expanding on work by Greenauer and Waller (2010), Siegel, Sjolund, Kelly, and Avraamides (2013) created a pair of overlapping layouts (black and white) that each possessed pronounced symmetry axes (Figure 3). Similar to Greenauer and Waller, the overarching structure of the two layouts was in line with the 315 degree axis. In these cases, the overarching structure would be considered as either the relative position of the two group means or the long axis of the overall shape created by combining the two groups (the resulting axis is the same using both definitions). However, participants in this experiment viewed the layout from the 0 degree perspective (in Greenauer and Waller, learning was from 315 degrees). The black circles represent locations of toys and the white circles represent locations of office supplies. Objects were placed on black and white paper disks respectively to further aid in group differentiation. Participants always viewed the objects from the 0 degree perspective during learning, but three different conditions demonstrated the nature of macro-reference frames when object groups overlap.

In the first condition, participants were instructed to learn all objects together along the 0 degree axis. As expected based on results from Mou and McNamara (2002), JRDs showed facilitation for the 0 degree axis as well as orthogonal perspectives. This condition serves as a control for conditions 2 and 3 where instruction was used to differentiate the two groups.

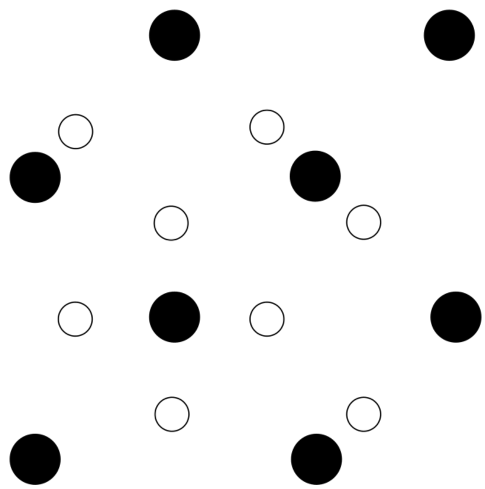

Figure 3. *Layout used by Siegel, Sjolund, Kelly, & Avraamides (2013). Black and white circles indicate the two object groupings (toys vs office supplies).*

The second condition instructed participants to learn both groups of objects (toys and office supplies) along the 0 degree axis. The only difference from the first condition is that the two groups were learned sequentially rather than as a single layout. As with the first condition, within-layout JRDs showed lowest error for the 0 degree perspective and facilitation for the orthogonal axes indicating micro-reference frames for both groups along the 0 degree axis. However, between-layout judgments showed lowest error along the 315 degree axis that is both symmetrical for the entire set of objects as well as the prevailing geometric shape of the combined layouts. Importantly, this condition demonstrates that macro-reference frames can be independent of micro-reference frames even when the two groups overlap and both micro-reference frames are aligned with each other.

In the third condition, participants again viewed all objects from the 0 degree perspective but were instructed to learn the toy layout along the 315 degree axis and the office supplies layout along the 0 degree axis. As expected, the two micro-reference frames were aligned with their respective instructed axes and the macro-reference frame was again aligned with the 315 degree axis. This condition is redundant given the results of Experiment 2 except in that it most closely relates to the design used by Greenauer and Waller (2010).

The experiments discussed so far demonstrate that the independence of macro-reference and micro-reference frames is not limited to scenarios where the layouts are physically separate. It also demonstrates that the macro-reference frame is independent, even when two layouts utilize the same micro-reference frame. The experiments proposed for this project will expand on these results and determine whether macro-reference frame selection is affected the same cues that determine micro-reference frame selection.

CHAPTER 2: INTRODUCTION

Experiments

Spatial memory for a given layout of objects/landmarks is stored from a particular reference frame utilizing a coarse, allocentric coding scheme (Waller & Hodgson, 2006). Two different groups of objects may be remembered using separate micro-reference frames while judgments between these two groups are facilitated by a macro-reference frame that is independent of the two individual micro-reference frames. It is currently unknown if macro-reference frame selection is influenced by the same egocentric, environmental and intrinsic cues as micro-reference frames (Shelton & McNamara 2001; Mou & McNamara, 2002) or if a different set of cues determine macro-reference frame selection instead. These two potential scenarios have significant implications for spatial memory research because the former will allow existing research on single layout reference frames to be applied to macro-reference frames as well. However, the latter would create a sharp distinction between macro- and micro-reference frames and demand further experimentation to determine what other cues are relevant for macro-reference frame selection.

It is unknown what cues may affect macro-reference frames if not egocentric, environmental, and intrinsic. It is possible that the geometric relationship between two layouts or the principle axis for the combined set of objects may play a role. Additionally, it is possible that macro-reference frame selection is unique to each individual and no pattern will be discernable in aggregate. As discussed earlier, hierarchical spatial categories can significantly alter performance on spatial tasks when crossing categorical boundaries (Hirtle & Jonides, 1985; McNamara, Hardy & Hirtle, 1989). It is possible that both individual layout groups would be stored normally, but that the physical relationship between the two groups would determine the macro-reference frame instead of egocentric, environmental, or intrinsic cues. Each individual layout would have a geometric center (mean location of all objects), and a line connecting the two layout centers could serve as a macro-reference frame cue similar to the Reno, NV, and SanDiego, CA, example given earlier. The geometric center of Nevada is east of the geometric center for California, so the relationship between the two states influences judgements of locations within the two states, even causing some judgments to be incorrect.

It is also possible that the overall structure of the layout would affect macro-reference frame selection. Instead of drawing a line between two geometric centers, the combined structure of the two layouts might determine the macro-reference frame. The layout used by Siegel et al. (2013) possessed an overall symmetry axis along the 315-135 degree axis (intrinsic cue), but that same axis was also the principal axis for the layout (line of best fit for the set of objects). The principal axis could provide a long reference line for remembering object locations even if the symmetry were removed. In the case that any of these possible alternatives are true, the existing literature on reference frame selection should be limited to only those situations where all objects or landmarks are encoded as a single group.

In order to determine whether egocentric and environmental cues affect macro-reference frame selection, three new experiments were conducted based on the method used by Shelton and McNamara (2001). Siegel et al. (2013) provided evidence for intrinsic cues in the form of a symmetry axis, and those results should be considered in context with the novel experiments described here.

Power Analysis

A sample size weighted effect size was calculated from studies included in the introduction that provide suitable effects. The effect chosen for the power analysis is difference between pointing error when imagining the reference perspective compared to the set of all others. This test has been used in the past literature and examines whether the assumed reference frame significantly deviates from the others. Table 1 contains all samples used along with subject count and effect size converted to Cohen's d. Experiments in Shelton and McNamara (2001) provided a separate effect for each condition and have been included in the power analysis accordingly. Each listed effect is derived from separate individuals as condition manipulations were between subjects.

The sample size weighted effect size used for the power analysis was 1.39. Using g*power (Faul, Erdfelder, Lang & Buchner, 2007) it was determined that 5 participants would be required per condition for the experiments to detect a macro-reference frame effect with power set at .8. Recruiting only 5 participants per condition would raise concern given that previous work has regularly included 12-15 participants per condition. Additionally, examining macro-reference frames requires participants to remember more than double the number of objects used for single layout studies and response variability should increase as participants attempt to make judgments based on the larger object set. It was determined that 15 participants would be recruited for each condition to align with previous work and ensure sufficient power should the added complexity of this project make the results less distinct. All three experiments included here examine the same effect and therefore make use of the same power analysis.

Table 1

Effect size for pointing error

Sample	N	Cohen's d
Marchette et al. (2011)	58	1.20
Shelton & McNamara (2001) – Exp. 2a	12	1.64
Shelton & McNamara (2001) – Exp. 2b	12	1.28
Shelton & McNamara (2001) – Exp. 4a	12	1.20
Shelton & McNamara (2001) – Exp. 4b	12	1.31
Shelton & McNamara (2001) – Exp. 6a	12	1.41
Shelton & McNamara (2001) – Exp. 6b	12	1.29
Shelton & McNamara (2001) – Exp. 7a	12	0.96
Shelton & McNamara (2001) – Exp. 7b	12	1.09
Siegel et al. (2013) – Exp. 1	15	2.05
Siegel et al. (2013) – Exp. 2	13	2.30

Testing for Reference Frames

Historically, the reference frame for a particular layout has been determined through a few steps. First, the reference frame perspective is assumed to be the imagined heading with the lowest absolute pointing error or reaction time. If the reference frame serves as the perspective from which memory is remembered, imagined rotation should increase both error and response time. In these experiments, the perspective that replicates the findings of Shelton and McNamara (2001) will be examined as well as the perspective with the lowest nominal error in the case that the results fail to replicate.

Second, the reference frame perspective should be significantly more accurate than the set of all other imagined perspectives. Taking an imagined perspective other than the reference frame should cause error to increase. The exact amount that error will increase is unknown, so these experiments will test a planned contrast where the suspected reference frame perspective is weighted 7 against the set of other perspectives all weighted at -1.

Finally, some reference frame experiments have shown facilitation for perspectives orthogonal (rotated 90 or 180 degrees) to the reference frame (Mou & McNamara, 2002).

These experiments will test for a sawtooth with a planned contrast comparing perspectives geometrically orthogonal to 0 degrees (0, 90, 180, 270) each weighted 1 against perspectives orthogonal to 45 degrees (45, 135, 225, 315) each weighted -1. The amount of variance explained by a sawtooth pattern is not particularly important, rather, the simple existence of a significant sawtooth pattern with lower error for perspectives orthogonal to the suspected reference frame strengthens evidence that the suspected reference frame is correct. This third result is not always present in all layouts, but is generally more common in grid-like layouts. The absence of a sawtooth pattern should not necessarily be considered evidence against a reference frame if the rest of the data fits. The object layout used in this project was constrained to a strong grid-like pattern to improve the chances of finding a sawtooth pattern should macro-reference frames be processed in a similar fashion to micro-reference frames.

In principle, all three of these criteria can coexist in a single set of JRD data. If a reference frame is present (for example, 0 degrees), that perspective should show the lowest pointing error. Simultaneously, the other imagined perspectives (i.e. 45, 90, 135, 180, 225, 270, 315) should yield significantly higher error than the reference frame perspective. Within the pattern of increased error as imagined perspective deviates from the reference frame, a sawtooth pattern may reveal better performance for perspectives orthogonal to the reference frame (0, 90, 180, 270) as compared to the non-orthogonal perspectives (45, 135, 225, 315). Experiment 2 of Mou and McNamara (2002) provides a visual representation of these three features present in a single set of JRD responses. In that experiment, one group has a reference frame along the 0 degree axis and the other along the 315. Both groups have higher error away from the reference perspective and the two groups additionally show opposite sawtooth patterns as 0 and 315 are orthogonal to different perspectives.

CHAPTER 3: EXPERIMENT 1

Experiment 1 was designed to examine the effects reported in Mou and McNamara (2002) Experiment 6 to test the hypothesis that learned view defines macro-reference frame selection. Participants learned the layout from one of two perspectives (0 or 45 degrees) in a virtual environment with all other potential cues removed. If learned view is a cue for macro-reference frame selection, participants should select the axis that matches their viewing condition. If both groups select the same reference frame (or none at all), it would suggest that learned view does not play a role and lend support to the hypothesis that macro-reference frames are decided by some other factor if they can even be detected.

Method

Participants

Thirty-four participants (13 female) were recruited from the Iowa State SONA system in exchange for course credit. Participants were randomly assigned to condition with gender approximately balanced. Four participants were replaced during the course of the experiment due to their error on the final test. Because an average error of 90 degrees represents chance performance, 80 degrees of error was selected as the cutoff for replacing a participant. Near-random error is indicative of either poor learning during the training phase or a poor understanding of the test instructions. In either case, these high errors are not representative of an accurate memory and should not be considered in the evaluation of reference frames.

Stimuli and Design

The layout in Figure 4 was used for all three experiments. The two object categories (toys and office supplies) were assigned to sub-layouts indicated by black and blue circles respectively. If viewing the images in greyscale, the black circles appear as a darker grey while the blue circles appear as a lighter grey. These black and blue circles were included in the virtual environment underneath the objects to aid in category discrimination (see Figure 5). Blue was selected for this project instead of white as used by Siegel et al. (2013) because white circles made it difficult to identify some virtual objects. Blue circles provided higher contrast and better identification while still serving as a category cue.

The overall layout was designed to not have a symmetry axis or a strong principal axis. However, it should be noted that the office supply sub-layout does possess a symmetry axis aligned with 0 degrees. The symmetry axis for the office supplies is not a concern as the method will also attempt to constrain the micro-reference frame to the 0 degree axis. This project examines macro-reference frame selection and therefore preference during stimulus design was given to controlling cues in the overall layout.

Figure 5 also shows the virtual environment for Experiment 1; an infinite grassy field with no walls or other objects aside from those included in the layout. The computer screenshot in Figure 5 gives the illusion of converging lines, but the objects were laid out in parallel rows to form a grid-like structure. Participants viewed the virtual environment through an HTC Vive head-mounted display (HMD) and the scene was rendered using the Vizard software (WorldViz, Santa Barbara, CA).

JRDs were administered in a neighboring lab room using Vizard software with pointing direction and response time recorded as participants manipulated a Logitech Joystick. The JRD trial set included six pointing responses for each possible imagined perspective (0, 45, 90, 135, 180, 225, 270, and 315). A full set of items was included for each of the layouts (toys, office supplies, and joint) for a total of 144 trials selected at random from the list.

Participants were assigned to one of two conditions defined by the learning view; half of the participants learned from the 0 degree position while the other half learned from the 45 degree perspective. These experiments were designed to test macro-reference frame selection, so efforts were made to ensure participants consistently picked the same micro-reference frames for the office supply and toy sub-layouts. Based on results from Shelton and McNamara (2001) as well as Siegel et al. (2013), participants learned the sub-groups separately along the 0 degree axis from front to back and left to right irrespective of viewing perspective. Therefore, participants learned the toys in the order: bear, train, ball, duck, boat, car, block, and robot while the office supplies were learned in the order: disk, mouse, stapler, book, tape, keys, scissors, and mug.

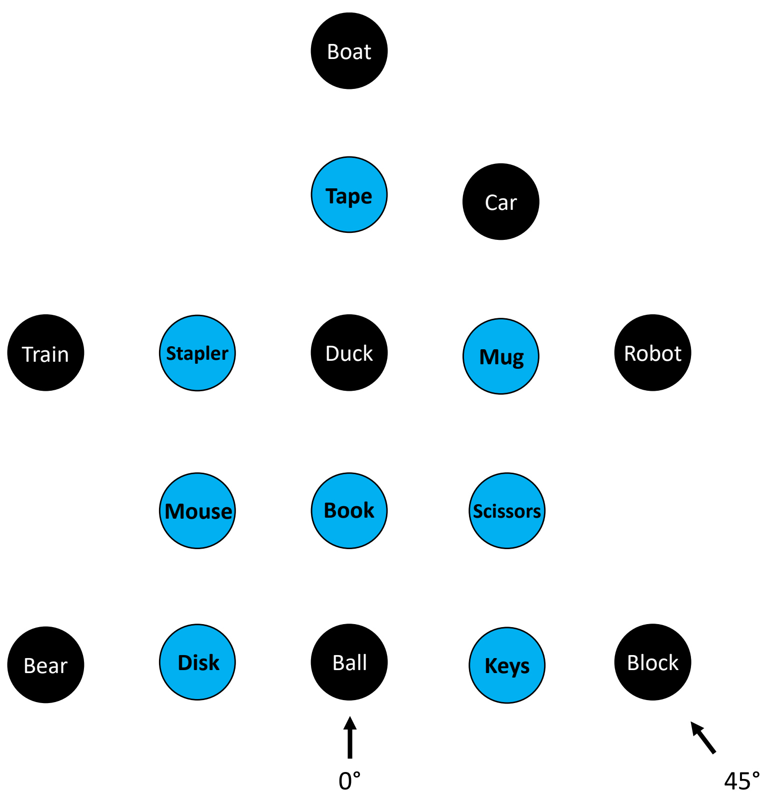

Figure 4. *Object layout for Experiments 1 – 3. Color indicates sub-layout (black = toys, blue = office supplies)*

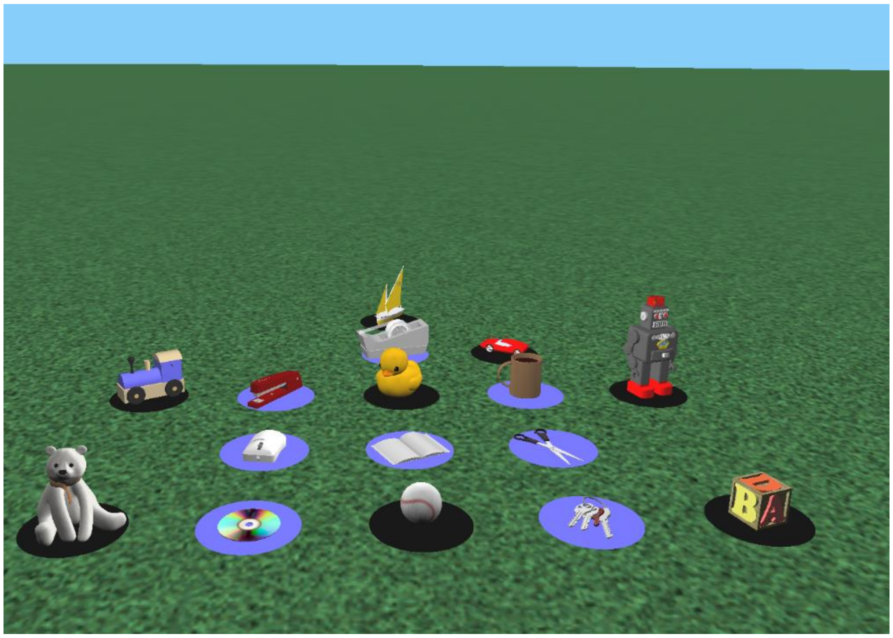

Figure 5. *Virtual environment used in Experiment 1.*

Procedure

After providing informed consent, participants donned the HMD in one corner of the lab and before the experimenter guided participants along an irregular path to the viewing location. The objects were not visible prior to arrival at the viewing location. The irregular path was intended to decouple the real and virtual environments, preventing participants from using the real-world walls to influence reference frame selection for the virtual objects.

All toys and office supplies were visible to the participants simultaneously, but participants learned the two sub-layouts separately with the toy sub-layout being learned first. To begin, the experimenter named each of the objects in order and asked the participants to locate and then point to the object. This continued until all the objects were located and the experimenter was satisfied that all objects were readily identifiable. Next, the experimenter named the objects in order while the participant pointed to and repeated the object names to practice the learning order. Finally, the participant named and pointed to each object in order on their own to verify that they understood which objects were part of the sub-layout and that they knew the correct order. Once the participant had pointed to and named all objects successfully, the experimenter explained the second phase of learning.

In the second phase, the experimenter used a controller key press to reveal the virtual environment for 20 seconds and participants were instructed to study only the toys, leaving the others for later. After 20 seconds, the screen went blank and participants attempted to point to and name all of the toys from memory. After an initial practice trial, the cycle of 20 second study and test continued until the participant successfully pointed to and named all objects in order 3 times (correct responses did not need to be consecutive). After successfully completing the second stage of learning, the experimenter revealed the environment and began the process again with the office supplies. During this portion, participants only studied the office supplies and were asked to ignore the toys.

After both groups were successfully learned, participants were tested again on the toys to ensure that they had not forgotten the objects during the office supply training. Participants performed the same study/test pattern until they successfully named and pointed to the toys in order 2 more times. After the toys, participants performed the same final check on the office supplies. After both groups were successfully tested again, the experimenter guided the participant back to the starting point along an irregular route and asked the participant to take off the HMD.

Once participants were out of the HMD, they were taken to an adjoining room and asked to sit in front of a computer. The experimenter used objects in the room to illustrate the format of a JRD task (i.e. imagine sitting in my chair, facing the whiteboard, point to the door). Participants pointed using their hand and feedback was provided. Participants were then told they could give their responses by moving a Logitech joystick in the direction of their response. Participants were told to think about their response before pushing the joystick because once the joystick reached 80% of maximum deflection, the computer would record the stick position and calculate the pointing angle. After the explanation, participants then entered the names of 3 familiar buildings from campus into the computer to serve as locations for practice trials. Participants completed 3 practice trails with the joystick and campus buildings before beginning the 144 study-relevant JRDs. No feedback was provided on the practice trials with campus buildings nor on experimental trials. The experimenter remained in the room to answer any questions and monitor for completion.

Results & Discussion

Each participant performed 144 JRD trials by responding to a prompt with the format: “Imagine standing at the Block, facing the Robot, point to the Ball”. Participants thought about their response and then moved the joystick in the correct pointing direction. Degrees of error from the correct response as well as response time were recorded. The 144 trails were broken into 3 groups of 48 trials each representing between-layout judgments, office supply within layout, and toy within layout judgments respectively. Each set of 48 layout specific judgments consisted of 6 responses for each potential imagined perspective (i.e. 0°, 45°… 315°). These 6 repeated judgments were collapsed to provide one average value for each perspective. The final data set consisted of 24 data points per participant (3 groups * 8 perspectives).

Of the 30 retained participants, 1 failed to finish the entire set of JRDs in the allowed time. The pattern of missing data for this participant is completely at random because the JRD trials were presented in a random order by the computer. Due to time constraints, this participant could not be replaced. However, no imputation or further consideration is required for the unfinished participant as data is present for all cells (imagined heading * layout type). Average value and maximum likelihood imputation would be possible methods for dealing with missing data, but both would yield exactly the same result because the six responses for each cell were collapsed to create an average error for each imagined heading. Choosing not to impute or account for the missing data does affect the error within a cell, but collapsing eliminates the problematic error term all together.

Response time was collected for all experiments, and used to determine whether participants sacrificed accuracy in order to complete the JRD trials faster. A negative correlation between speed and accuracy would indicate such a tradeoff. No individuals showed a significant negative correlation and the mean correlation (although small) across all participants in the experiment was significantly positive, $\rho=.05$, $t(29)=2.90$, $p=.007$, and there is no evidence of a speed-accuracy tradeoff. The strength of the significant positive correlation is not relevant as the intent was to determine whether a negative correlation (indicating a speed-accuracy tradeoff) was present. Response time does not contribute further to understanding macro-reference frame selection, so only the pointing error results are reported and discussed in the body of this paper. Response time data can be found Appendix A (Figures 20-22).

Distribution of responses

Overall, performance on the JRD trials was very high. Figure 6 shows the proportion of responses equal to or below the designated amount of error, increasing in 5 degree increments. The figure includes all 4320 JRD responses collected from both the between- and within-layout judgments. Error was measured in absolute distance from the correct answer, therefore, 4.8 degrees of error clockwise and 4.8 degrees counterclockwise would both be binned at less than 5 degrees of error. The 5 degree increments in Figure 6 represent 5 additional degrees of error in both the clockwise and counterclockwise directions.

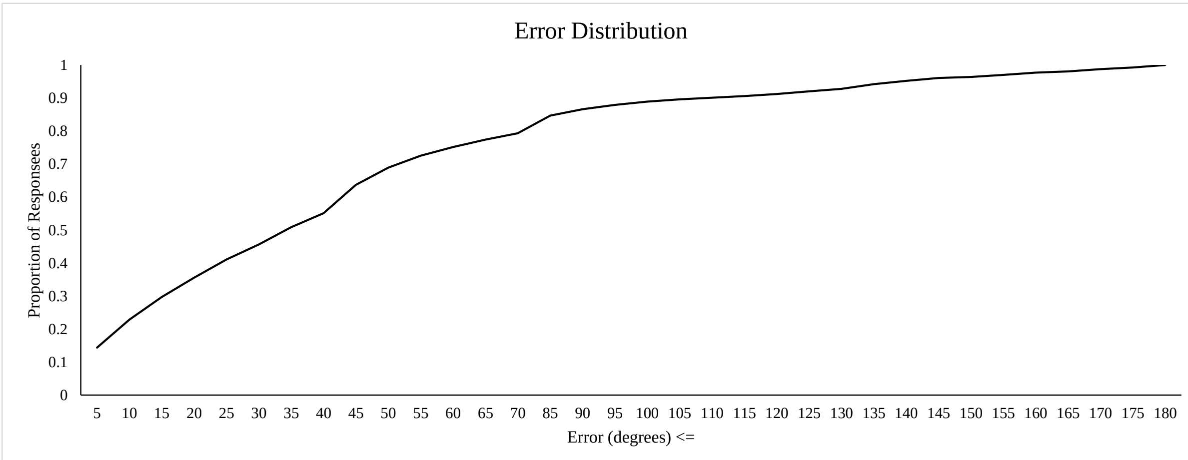

Figure 6. Experiment 1 - Proportion of total responses less than or equal to the specified degree of error.

Of the 4320 total responses collected across the entire experiment, 14% were within 5 degrees of the correct answer (either clockwise or counterclockwise). Furthermore, over 50% of responses are accounted for when including errors up to 35 degrees in either direction. These results suggest that participants learned the layout well and were able to respond accurately using the joystick.

Macro-reference frame selection (between-layout judgments)

The response graphs for between-layout JRDs (split by condition) can be seen in Figure 7. One-tail tests were used for a priori planned contrasts consistent with the results of Shelton and McNamara (2001). For the 0 degree viewing condition, it was hypothesized that the 0 degree axis would serve as the macro-reference frame because it is consistent with the participant’s view and no other cues should be present. Participants who viewed from 0 degrees performed best at the 0 degree perspective (M=40.29, SD=13.48). Performance from this heading was significantly better than the average performance of all other imagined perspectives. MeanDiff = 9.91, *t*(14)=2.62, *p*=.020. There is a significant sawtooth pattern supporting the 0 degree macro-reference frame, where participants performed better when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining the non-orthogonal perspectives (45, 135, 225, 315), MeanDiff = 8.35, *t*(14)=3.02, *p*=.009.

For the 45 degree viewing condition, it was hypothesized that the 45 degree axis would serve as the macro-reference frame because it is aligned with the participant's view and no other cues were present. However, participants who viewed from 45 degrees did not perform best at the 45 degree perspective (M=45.39, SD=14.52). Rather, performance from the 90 degree perspective was numerically lowest. Performance from the 45 degree heading was significantly better than the set of all other perspectives, MeanDiff = 8.96, *t*(14)=2.56, *p*=.022, but it should be noted that the difference between the 45 and 90 degree imagined perspectives was not significant, MeanDiff = 6.89, *t*(14)=1.38, *p*=.188. There is significant evidence of a sawtooth pattern, where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 6.36, *t*(14)=3.09, *p*=.008.

These results do not support the hypothesis that egocentric experience defines the macro-reference frame because those who viewed from 45 degrees did not perform best from the 45 degree heading and the sawtooth pattern was opposite of the hypothesized result. Considering the graph, it appears that a 90 degree reference frame for the 45 degree view fits the data better. Participants performed best along the 90 perspective (M=38.35, SD=18.14) and a two-tailed test for this perspective shows significantly better performance compared to the set of all other perspectives, MeanDiff = 16.84, $t(14)=3.77$, $p=.002$. This conclusion is also supported by the significant sawtooth pattern.

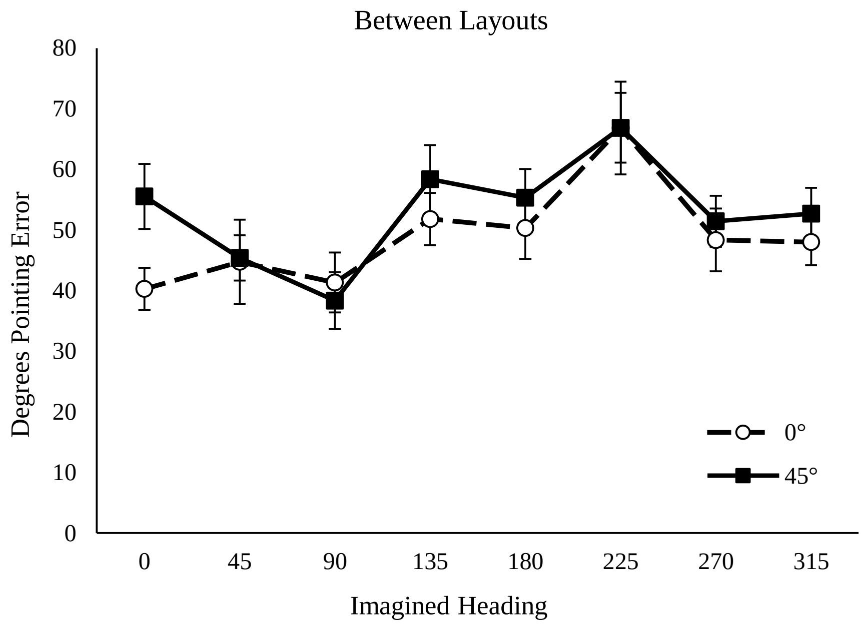

Figure 7. Experiment 1 – Average absolute pointing error for between layout JRDs. Standard error bars represent between subjects error.

Shelton and McNamara (2001) found that reference frame selection was determined by the learned view when no other cues were available. While the experiment did not replicate these exact results, Experiment 1 does show that macro-reference frame selection is influenced by egocentric experience. Rather than define the reference frame, the learned view appears to makes certain aspects of the layout more or less salient, and the variation in this salience influences which axis is selected as the reference frame.

Specific to this experiment, it is possible that when participants viewed from 0 degrees, the line connecting ball, book, duck, tape, and boat was highly salient and the 0 degree axis was consequently selected as the macro-reference frame. In the other condition, viewing from 45 degrees may have made the two parallel lines that connect block to bear, and robot to train, more salient than the single line connecting ball and boat. Those viewing from 45 may have selected 90 degrees as their reference frame to align their memory with these two parallel lines instead. If true, these results would contradict the findings of Richard and Waller (2013) as a non-obvious intrinsic axis (90 degrees) influences reference frame selection. Richard and Waller suggested that only obvious intrinsic axes in highly orthogonal and symmetric layouts are able to elicit a reference frame misaligned with the learned view. However, the layout used for this experiment is not symmetrical along the 90 degree axis, yet that axis is used for those with egocentric experience from 45 degrees. Richard and Waller suggested that the effect of intrinsic axis is overemphasized, and that may be true, but their findings may go too far and underestimate the effect. Admittedly, the current project was not intended to question the findings reported by Richard and Waller, but the discrepancy opens the door to an interesting line of research worth investigating.

The finding that egocentric cues influence, but do not define, macro-reference frame selection is not entirely surprising as intrinsic features of a layout have been shown to be highly influential in reference frame selection (Mou & McNamara, 2002; Mou, Zhao, & McNamara, 2007). The theory that egocentric experience affects feature salience can account for both the results of Experiment 1 as well as Shelton and McNamara. However, it is also possible that this finding is specific to macro-reference frame selection as the full set of objects were never studied together from any learning position and all association between the groups was incidental. It is possible that, if the entire set of 16 objects here were learned together, results would be similar to Shelton and McNamara (2001). Further experimentation with this particular layout would determine whether the influence of egocentric experience needs to be redefined for all types of reference frames.

Micro-reference frame selection (office supply and toy layout judgments)

The results for office supply and toy within-layout judgments are listed separately because the two groups should exist as separate memories with potentially unique reference frames. In order to demonstrate that the macro-reference frame is independent of the two micro-reference frames, in is necessary to understand how each sub-layout was remembered.

The response graphs for office supply and toy layout JRDs (split by condition) can be seen in Figures 8 and 9. One-tail tests were used for a priori planned contrasts consistent with the results of Mou and McNamara (2002) as well as Siegel et al. (2013). For the 0 degree viewing condition, it was hypothesized that the 0 degree axis would serve as the micro-reference frame for office supplies due to the explicit learning instructions. Participants who viewed from 0 degrees performed best when remembering office supplies along the 0 degree perspective (M=27.83, SD=20.83). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 13.12, $t(14)=2.11$, $p=.053$. There is a significant sawtooth pattern supporting the 0 degree reference frame, where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 9.53, $t(14)=4.14$, $p=.001$.

Additionally, it was hypothesized that those who viewed from 0 degrees would use the 0 degree axis as the reference frame for toys due to explicit instruction. Participants who viewed from 0 degrees performed best when remembering toys along the 0 degree perspective (M=23.72, SD=12.45). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 18.72, $t(14) = 5.61$, $p<.001$. There is a significant sawtooth pattern supporting the 0 degree reference frame, where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 6.17, *t*(14)=3.03, *p*=.009.

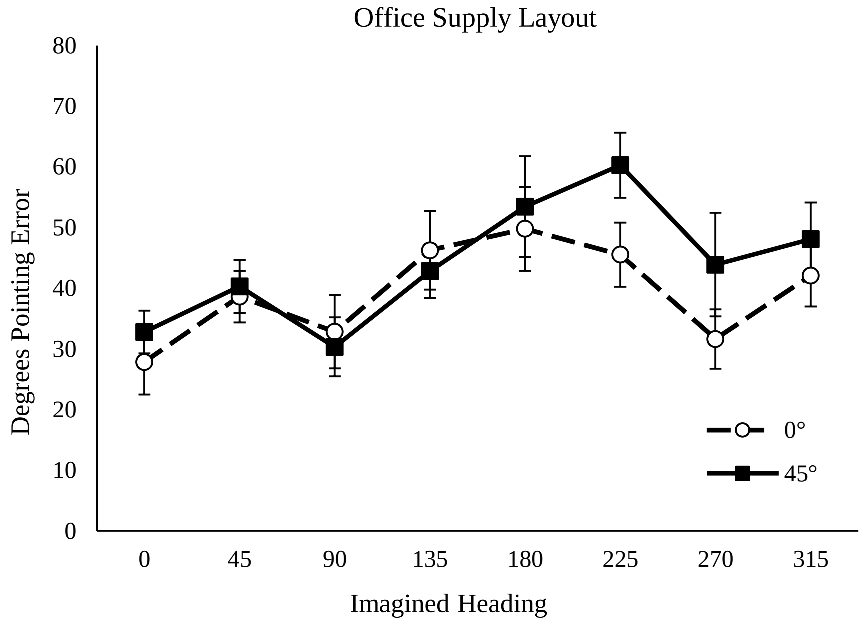

Figure 8. Experiment 1 – Average absolute pointing error for office supply only JRDs. Standard error bars represent between subjects error.

Participants who learned from 0 degrees utilized micro- and macro-reference frames aligned with the 0 and degree perspectives. Participants selecting 0 degree macro- and micro-reference frames is not surprising and was not intended to examine macro-reference frame independence because both the participant's view and training were aligned with one another. Rather, the results of the 45 degree viewing condition are vital for determining whether the macro-reference frame is independent.

For the 45 degree viewing condition, it was hypothesized that the 0 degree axis would serve as the micro-reference frame for the office supplies due to the explicit learning order. However, participants who viewed from 45 degrees did <u>not</u> perform best when remembering office supplies along the 0 degree perspective (M=32.78, SD=13.65). Rather, performance was numerically lowest when imagining the 90 degree perspective. Performance from the 0 degree heading was significantly better than the set of all other perspectives, MeanDiff = 13.91, $t(14)=4.23$, $p=.001$, but it should be noted that the difference between the 0 and 90 degree imagined perspectives was not significant, MeanDiff = 1.56, $t(14)=.34$, $p=.737$. There is significant evidence of a sawtooth pattern supporting either a 0 or 90 degree reference frame, where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 7.93, $t(14)=3.35$, $p=.005$.

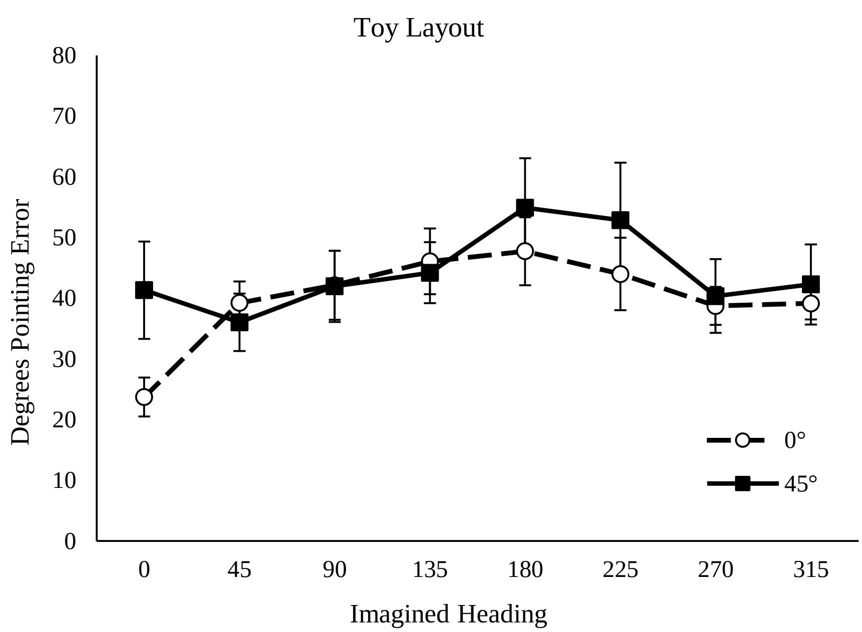

Figure 9. Experiment 1 – Average pointing error for toy only JRDs. Standard error bars represent between subjects error.

These results do not support the hypothesis that training would cause 0 to be selected as the reference frame for the toys in the 45 degree view condition. Instead, performance was best along the 90 degree axis (M=30.31, SD=18.83). A two-tailed test for the 90 degree perspective shows that participants performed best along that axis compared to the average error at all other imagined perspectives, MeanDiff = 15.67, $t(14)=5.05$, $p<.001$. The sawtooth pattern supports either a 90 or 0 degree reference frame equally well as the two perspectives are on the same side of the test.

It was also hypothesized that the 0 degree axis would serve as the micro-reference frame for the toys in the 45 degree viewing condition due to the learning order. However, participants who viewed from 45 degrees did not perform best when remembering toys along the 0 degree perspective (M=41.33, SD=31.04). Rather, performance was numerically lowest when imagining the 45 degree perspective. Performance from the 0 degree heading was not significantly better than the set of all other perspectives, MeanDiff = 1.56, $t(14)=.26$, $p=.802$. Additionally, there is no significant evidence of a sawtooth pattern supporting any particular reference frame MeanDiff = 2.84, $t(14)=1.37$, $p=.193$.

These results do not support the hypothesis that training would constrain the micro-reference frame for toys to the 0 degree axis because those who learned from 45 degrees did not perform best from the 0 degree heading implied in the training. Instead, performance was best along the 45 degree axis (M=36.00, SD=18.32) and two-tailed test for the 45 degree perspective shows that participants performed better along that axis compared the set of all other perspectives, MeanDiff = 9.16, $t(14)=2.62$, $p=.020$.

Unlike Siegel et al. (2013), participants who viewed from 45 degrees did not select micro-reference frames aligned with the training, instead they selected micro-reference frames aligned with 90 and 45 degrees for office supplies and toys respectively. This experiment cannot exclusively support the hypothesis that macro-reference frames are independent of the micro-reference frames because the alternate hypothesis that the macro-reference frame is selected from one of the two micro-reference frames is equally supported by these results (participants who viewed from 45 degrees selected a 90 degree reference frame for both the overall layout and office supply sub-layout). It should be noted that these results do not discredit the possibility that macro-reference frames are independent of the micro-reference frames, they only fail to reject an alternative possibility.

CHAPTER 4: EXPERIMENT 2

Experiment 2 was modeled after Shelton and McNamara (2001) Experiment 2 to test the hypothesis that environmental cues serve as a cue for macro-reference frame selection if the participant has had a chance to view the layout from a perspective aligned with the environment. Similar to the first experiment, participants viewed the layout from either 0 or 45 degrees, but this time the virtual environment included environmental cues in the form of walls and a square carpet aligned with the 45 degree perspective.

This experiment serves as a first step in determining the effect of environmental cues on macro-reference frames. If macro-reference frames are selected in the same way as micro-reference frames, participants in the 0 degree condition should select the reference frame made salient by their learned view despite the existence of the environmental cues. However, those in the 45 degree condition should select a 45 degree macro-reference frame because they were allowed to view a perspective aligned with the environmental cues. Egocentric experience appears to serve as a baseline cue, but an appropriate presentation of environmental cues should cause that perspective to supersede any reference frame selected based on egocentric experience (Shelton & McNamara, 2001).

Method

Participants

Thirty-three participants (21 female) were recruited from the Iowa State SONA system in exchange for course credit. Participants were randomly assigned to condition with gender approximately balanced. One participant was dropped for having average error greater than 80 degrees on the JRD test. Three participants did not finish the entire test, but only two could be replaced due to time constraints. Of the three that did not finish the JRD test, the participant with the lowest overall error of the three was kept as that participant likely had the most accurate representation. In total, the data from 30 of the 33 recruited participants was kept for this study.

Stimuli and Design

The stimuli for this experiment were identical to that of Experiment 2, but the surrounding virtual environment was altered. The virtual environment for this experiment consisted of a 5m square room with a 4m square carpet in the middle rather than an endless grassy field. The walls of the room and edges of the carpet were both aligned to be parallel to the 45 degree axis (see Figures 10 and 11). The layout of office supplies and toys was identical to Experiment 1 and the same JRD trials were collected. Participants were again instructed to learn the two layouts separately along the 0 degree axis irrespective of learned view.

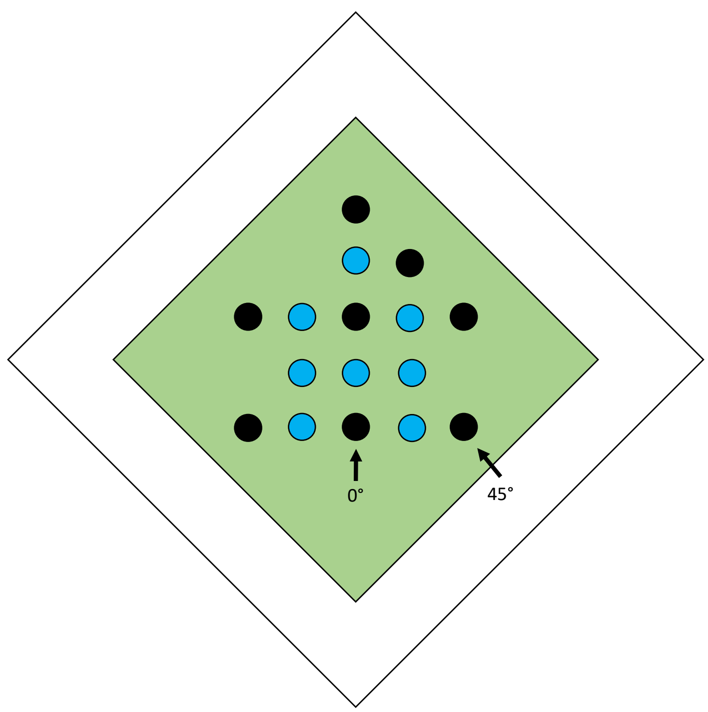

Figure 10. *Representation of walls (outer diamond) and floor mat (shaded area) used as environmental cues for Experiments 2 and 3.*

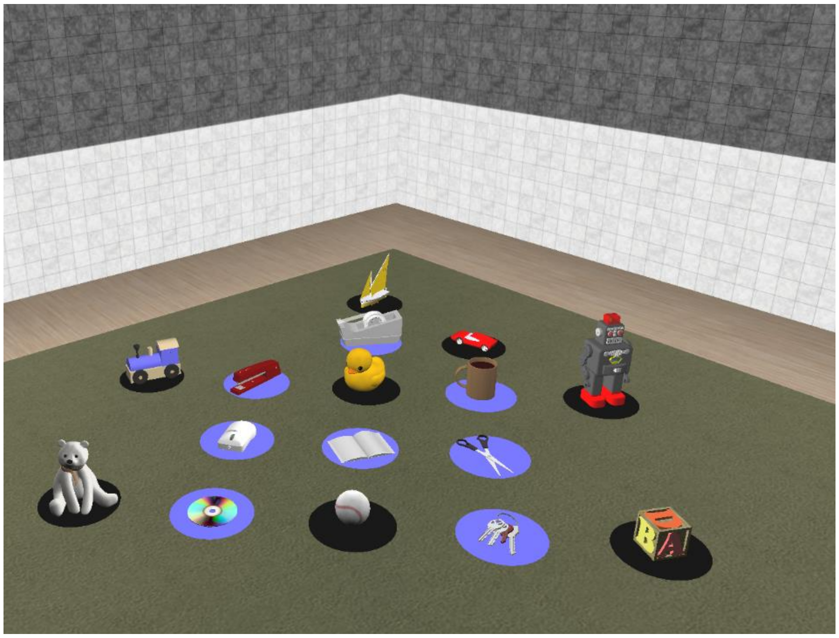

Figure 10. Virtual environment used for Experiments 2 & 3.

Procedure

The procedure was identical to that of Experiment 1, only the virtual environment was altered. Participants donned the HMD and were then walked to the learning position via an irregular path. Participants learned both the toys and office supplies along the 0 degree axis and had to successfully name and point to each object, in order, from memory 3 times before moving on to the next stage. A final check was conducted where participants had to correctly name and point to each object from memory twice per layout before being guided back to the starting point. Participants took off the HMD and walked to the test room where they learned about JRDs and then performed the 144 trials presented at random.

Results & Discussion

Responses were processed in the same manner as Experiment 1. Participants imagined standing at one object and facing another before using the joystick to point to the target. Participants performed 6 JRDs at each imagined perspective (0, 45 … 315) for each layout type (between, office supply, toys) which were then collapsed to provide 24 total data points for each participant (3 layout * 8 imagined perspectives).

Response time was collected for all experiments, and used to determine whether participants sacrificed accuracy in order to complete the JRD trials faster. A negative correlation between speed and accuracy would indicate such a tradeoff. No individuals showed a significant negative correlation and the mean correlation across all participants in the experiment was significantly positive, $\rho=.08$, $t(29)=3.82$, $p=.001$, and there is no evidence of a speed-accuracy tradeoff. As in Experiment 1, the strength of the positive correlation is not relevant as this test was designed to determine if a significant negative correlation (indicative of a speed-accuracy tradeoff) exists. Response time does not contribute further to understanding macro-reference frame selection, so only the pointing error results are reported and discussed in the body of this paper. Response time data can be found in Appendix B (Figures 23-25).

Distribution of responses

Overall, performance on the JRD trials was very high. Figure 12 shows the proportion of responses equal to or below the designated amount of error, increasing in 5 degree increments. The figure includes all 4320 JRD responses collected from both the between- and within-layout judgments. Error was measured in absolute distance from the correct answer, therefore, 4.8 degrees of error clockwise and 4.8 degrees counterclockwise would both be counted as less than 5 degrees of error. The 5 degree increments in Figure 12 represent 5 additional degrees of error both clockwise and counterclockwise.

Of the 4255 total responses collected across the entire experiment, 11% were within 5 degrees of the correct answer (either clockwise or counterclockwise). Furthermore, over 50%

of responses are accounted for when considering errors up to 40 degrees in either direction. These results differ only slightly from Experiment 1 and suggest that participants learned the layout well and were able to respond accurately using the joystick.

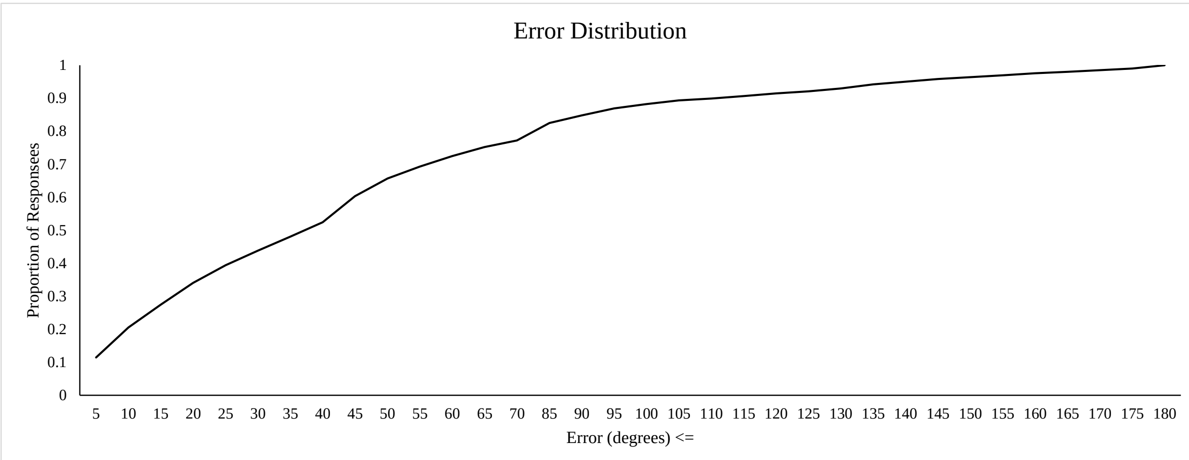

Figure 12. Experiment - 2 Proportion of total responses less than or equal to the specified degree of error.

Macro-reference frame selection (between-layout judgments)

The response graphs for between-layout JRDs (split by condition) can be seen in Figure 13. One-tail tests were used for a priori planned contrasts consistent with the results of Shelton and McNamara (2001). For the 0 degree viewing condition, it was hypothesized that the 0 degree axis would serve as the macro-reference frame due to egocentric experience. Participants who viewed from 0 degrees performed best at the 0 degree perspective (M=40.00, SD=16.66). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 16.29, $t(14)=2.92$, $p=.011$. A one-tailed test shows a significant sawtooth pattern supporting the 0 degree reference frame, where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 6.50, $t(14)=1.78$, $p=.097$.

For the 45 degree viewing condition, it was hypothesized that the 45 degree axis would serve as the macro-reference frame due to the presence of environmental cues. Participants who viewed from 45 degrees performed best at the 45 degree perspective (M=43.91, SD=15.38). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 9.59, $t(14)=1.78$, $p=.096$. No significant sawtooth pattern exists for this condition, MeanDiff = 2.46, $t(14)=1.01$, $p=.331$.

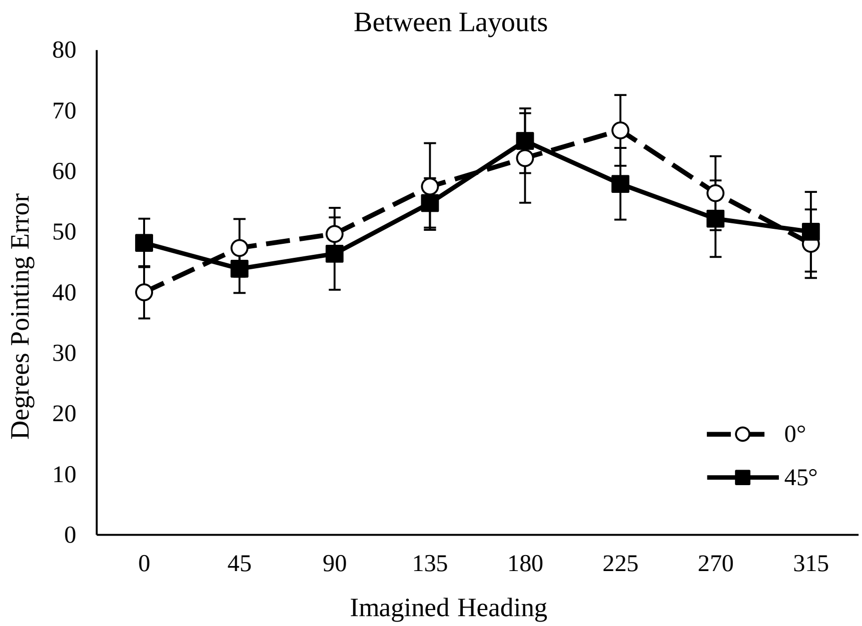

Figure 13. Experiment 2 – Average pointing error for between layout JRDs. Standard error bars represent between subjects error.

The results provide evidence that macro-reference frame selection is affected by environmental cues, so long as the participant has had the opportunity to view an aligned perspective. Participants who learned the layout from the 45 degree perspective aligned their macro-reference frame with the 45 degree perspective, replicating the findings of Shelton and McNamara (2001). This finding serves as particularly strong evidence because those who learned from 45 degrees utilized a 90 degree macro-reference frame in Experiment 1, but instead aligned with the environmental cues in this experiment. The only difference between Experiments 1 and 2 was the change in virtual environmental, therefore the environment shift elicited the change in response for those who learned from 45 degrees.

Furthermore, the 0 degree learning condition was not aligned with the carpet or walls and those participants do not seem to utilize the environmental cues for reference frame selection, instead relying on their egocentric experience. Participants who learned from 0 degrees in both Experiments 1 and 2 selected the 0 degree reference frame and the shift in environment appears to have had no effect.

Micro-reference frame selection (office supply and toy layout judgments)

The response graphs for office supply and toy layout JRDs (split by condition) can be seen in Figures 14 & 15. One-tail tests were used for a priori planned contrasts consistent with the results of Mou and McNamara (2002) as well as Siegel et al. (2013). For the 0 degree viewing condition, it was hypothesized that the 0 degree axis would serve as the micro-reference frame for office supplies due to the explicit training instructions. Participants who viewed from 0 degrees performed best at the 0 degree perspective (M=20.42, SD=8.91). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 27.20, $t(14)=7.22$, $p<.001$. There is a significant sawtooth pattern where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 12.47, $t(14)=7.44$, $p<.001$.

Additionally, it was hypothesized that those in the 0 degree viewing condition would utilize a 0 degree micro-reference frame due to the training instructions. Participants who viewed from 0 degrees performed best from the 0 degree perspective (M=22.80, SD=11.45).

Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 24.48, $t(14) = 7.90$, $p<.001$. There is a significant sawtooth pattern, where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 9.01, $t(14)=4.22$, $p<.001$.

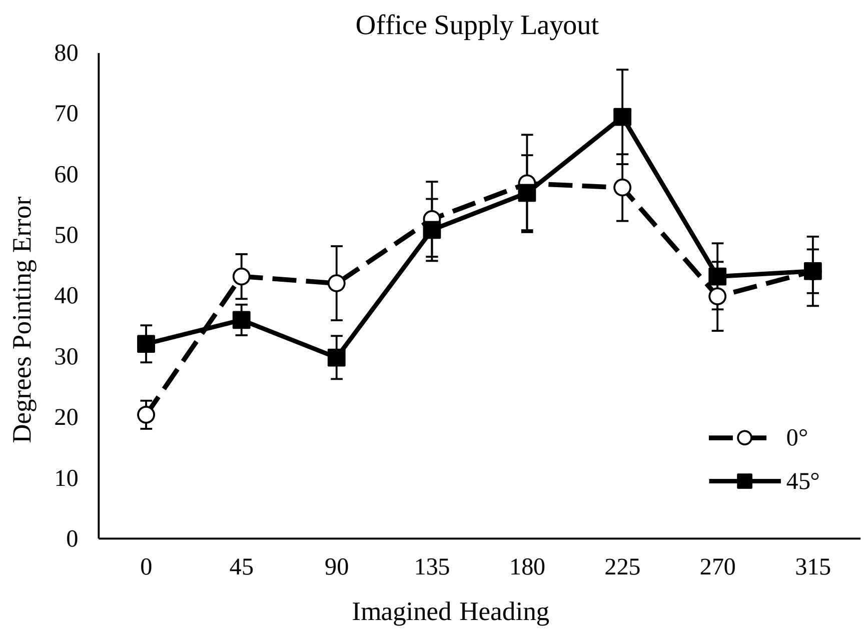

Figure 14. Experiment 2 – Average pointing error for office supply only JRDs. Standard error bars represent between subjects error.

Participants who viewed from 0 degrees utilized micro-reference frames aligned with 0 degrees for both toys and office supplies as expected as well as a macro-reference frame aligned with 0 degrees. However, the 0 degree view condition was not intended to test for the independence of macro-reference frames as the hypothesized macro-reference frame due to egocentric experience and learning order were both aligned with the 0 degree axis.

For the 45 degree viewing condition, it was hypothesized that the 0 degree axis would serve as the micro-reference frame for office supplies as a result of explicit instructions.

However, participants who viewed from 45 degrees did not perform best at the 0 degree perspective (M=32.08, SD=11.88). Rather, performance was numerically lowest when imagining the 90 degree perspective. Performance from the 0 degree heading was significantly better than the set of all other perspectives, MeanDiff = 10.60, $t(14)=2.77$, $p=.015$, but it should be noted that the differences between the 0 and 90 degree imagined perspective was not significant, MeanDiff = 6.20, $t(14)=1.56$, $p=.141$. There is significant evidence of a sawtooth pattern, where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 12.82, $t(14)=6.22$, $p<.001$.

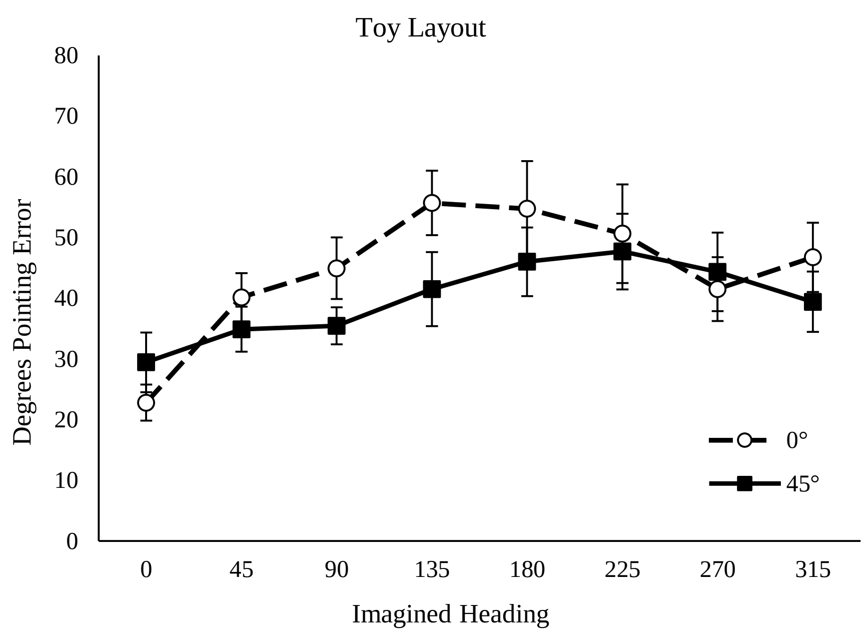

Figure 15. Experiment 2 – Average pointing error for toy only JRDs. Standard error bars represent between subjects error.

These results do not support the hypothesis that office supplies would be remembered along the 0 degree learning axis for the 45 degree view because those who learned from 45 degrees did not perform best from the 0 degree heading implied in the training. Instead, results suggest that a 90 degree reference frame fits the data better. Performance was best along the 90 degree axis (M=29.88, SD=13.77) and a two-tailed test for the 90 degree perspective shows that participants performed best along that axis compared the set of all other perspectives, MeanDiff = 17.69, $t(14)=5.99$, $p<.001$. The sawtooth pattern supports a 90 or 0 degree reference frame equally as the two perspectives are on the same side of the test.

It was also hypothesized that the 0 degree axis would serve as the micro-reference frame for toys when viewed from 45 degrees due to the explicit learning instructions. Participants who viewed the toys from 45 degrees performed best at the 0 degree perspective (M=29.43, SD=19.12). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 11.89, $t(14)=2.87$, $p=.012$. Results do not show a significant sawtooth pattern for this condition, MeanDiff = 3.71, $t(14)=1.24$, $p=.235$.

Similar to Experiment 1, instructing participants to learn the two sub-layouts along the 0 degree axis did not fully control micro-reference frame selection. Those who viewed from 45 degrees utilized micro-reference frames aligned with 90 and 0 degrees for office supplies and toys respectively while the macro-reference frame was aligned with the environmental cue at 45 degrees. These findings do not exclude the possibility that macro-reference frames are independent of the constituent micro-reference frames, they only fail to reject the alternative that the macro-reference frame is an average of the two micro-reference frames. Both Experiments 1 and 2 failed to confirm that the macro-reference frame is independent, but it should be noted that the alternate explanations that could be supported by those two experiments are not compatible with one another. Experiment 1 could alternatively be explained by selecting one micro-reference frame while this experiment's alternate explanation is an average of the two. However, both the results of Experiment 1 and 2 could be explained by an independent macro-reference frame. Independent macro-reference frames are necessary in order to replicate reference frame findings that utilize a single layout. If the macro-reference frame were determined based on the constituent micro-reference frames, studying how different cues affect macro-reference frame selection would be pointless. An independent macro-reference frame is a separate representation in memory and could therefore be selected based on egocentric experience, environmental cues, or intrinsic layout structure without regard for how the micro-reference frames are stored.

CHAPTER 5: EXPERIMENT 3

Experiment 3 follows up on the results of Experiment 2 and was modeled after Shelton and McNamara (2001) Experiment 3 to test the hypothesis that environmental cues are an important cue for macro-reference frame selection that can also override an earlier reference frame selection that was based on learning view. Participants learned the layout from both the 0 and 45 degree perspectives. This experiment utilized the same virtual room and floor mat from Experiment 2 as environmental cues for reference frame selection. Condition was defined by counterbalancing the order the learning perspectives were experienced (0 then 45 degrees or 45 then 0 degrees).

This experiment serves as the second step in determining the specific effect of environmental cues on macro-reference frames. If environmental cues influence macro-reference frame selection, and supersede a reference frame derived solely from egocentric experience, participants should select a macro-reference frame that overrides the egocentric reference frame selected initially (0-45 condition) or remains robust despite being exposed to a new perspective (45-0 condition). Valiquette, McNamara, and Smith (2003) demonstrated that when participants were allowed an unlimited number of viewing perspectives, participants settled on a single reference frame (with benefit for the corresponding orthogonal axes) rather than developing a reference frame associate with each possible perspective. According to Valiquette et al. (2003) as well as Shelton and McNamara (2001), it appears that spatial memories are encoded based on the most salient cue made available to the viewer and that multiple viewpoints only increase the number of cues available to be used when selecting a single reference frame for storing spatial memories. The environmental cue is expected to be the most salient in this experiment based on the results of Shelton and

McNamara (2001), and thus the 45 degree axis should serve as the macro-reference frame for both conditions, irrespective of learning order.

Method

Participants

Thirty-six participants (20 female) were recruited from the Iowa State SONA system in exchange for course credit. Participants were randomly assigned to condition with gender approximately balanced. Three participants were dropped and replaced for having average error greater than 80 degrees on the JRD test. Three participants did not finish the entire test, and all three were replaced. In total, the data from 30 of the 36 recruited participants was kept for this study.

Stimuli and Design

All of the stimuli for this experiment were identical to that of Experiment 2. The virtual environment consisted of the same 5m room and 4m carpet, both aligned with the 45 degree axis. The layout itself was identical to Experiments 1 and 2 and participants learned toys and office supplies separately using the lame learning order as the previous 2 experiments. The JRD trials were identical to those presented in Experiments 1 and 2.

Procedure

The learning procedure in Experiment 3 was modified from Experiments 1 and 2 so that participants could study the layout from both the 0 and 45 degree location. After donning the HMD, participants were guided to the first study position via an irregular path and then proceeded to learn both groups of objects until they successfully named and pointed to each object in order 3 times per layout. After reaching the initial criteria, the experimenter guided participants to the second viewing location (0 or 45 degrees depending on initial position).

No irregular path was used at this point because the participant never took off the HMD during transit and therefore could not see the real world. Additionally, the HMD was blank during transit to ensure participants did not have a view of the layout other than 0 or 45 degrees. After reaching the new position, participants again studied and tested their ability to name and point to both groups of objects until they succeeded 3 more times. After reaching criteria in the new location, participants were moved to the start via an irregular path and then took off the HMD before going to the adjacent room and completing the 144 JRD trials.

Results & Discussion

Responses were processed in the same manner as Experiments 1 and 2. Participants performed 6 JRDs at each imagined perspective (0, 45 … 315) for each layout type (between, office supply, toys) which were then collapsed to provide 24 total data points for each participant (3 layout * 8 imagined perspectives).

Response time was collected for all experiments, and used to determine whether participants sacrificed accuracy in order to complete the JRD trials faster. A negative correlation between speed and accuracy would indicate such a tradeoff. No individuals showed a significant negative correlation and the mean correlation across all participants in the experiment was significantly positive, $\rho=.05$, $t(29)=3.19$, $p=.003$, and there is no evidence of a speed-accuracy tradeoff. Response time does not contribute further to understanding macro-reference frame selection, so only the pointing error results are reported and discussed in the body of this paper. Response time data can be found in Appendix C (Figures 26-28).

Distribution of responses

Overall, performance on the JRD trials was very high. Figure 16 shows the proportion of responses equal to or below the designated amount of error, increasing in 5 degree increments. The figure includes all 4320 JRD responses collected from both the between- and within-layout judgments. Error was measured in absolute distance from the correct answer, therefore, 4.8 degrees of error clockwise and 4.8 degrees counterclockwise would both be counted as less than 5 degrees of error. The 5 degree increments in Figure 16 represent 5 additional degrees of error both clockwise and counterclockwise.

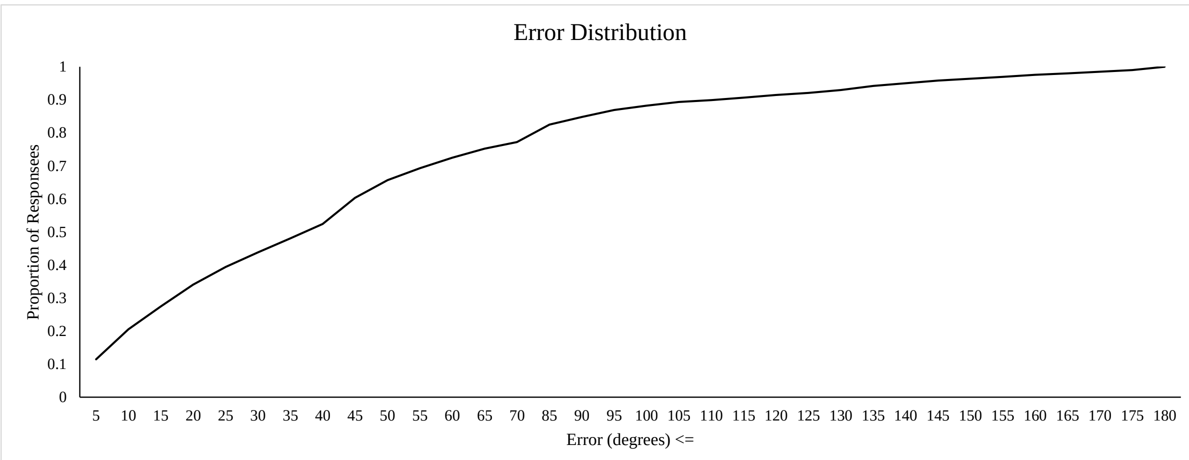

Figure 16. Experiment - 3 Proportion of total responses less than or equal to the specified degree of error.

Of the 4320 total responses collected across the entire experiment, 11% were within 5 degrees of the correct answer (either clockwise or counterclockwise). Furthermore, over 50% of responses were within 40 degrees of error in either direction. These results again suggest that participants learned the layout well despite viewing from two locations and were able to respond accurately using the joystick.

Macro-reference frame selection (between-layout judgments)

The response graphs for between-layout JRDs (split by condition) can be seen in Figure 17. One-tail tests were used for a priori planned contrasts consistent with the results of Shelton and McNamara (2001). For the 0-45 degree viewing condition, it was hypothesized that the 45 degree axis would serve as the macro-reference frame as a result of viewing the environmental cues (walls and carpet). Participants who viewed 0 degrees first performed best at the 45 degree perspective (M=45.28, SD=14.54). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 10.76, $t(14)=2.37$, $p=.032$. There is a unexpected, significant sawtooth pattern, where participants performed worse when imagining perspectives orthogonal to the 45 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 8.02, $t(14)=3.64$, $p=.003$. There is no explanation for why a sawtooth pattern would exist opposite the reference frame, but all other evidence seems to support a 45 degree reference frame.

For the 45-0 degree viewing condition, it was hypothesized that the 45 degree axis would also serve as the macro-reference frame due to the environmental cues (walls and carpet). Participants who viewed from 45 degrees first performed best at the 45 degree perspective (M=45.18, SD=18.31). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 12.79, $t(14)=2.75$, $p=.016$. No significant sawtooth pattern exists for this condition, MeanDiff = 3.68, $t(14)=.92$, $p=.371$.

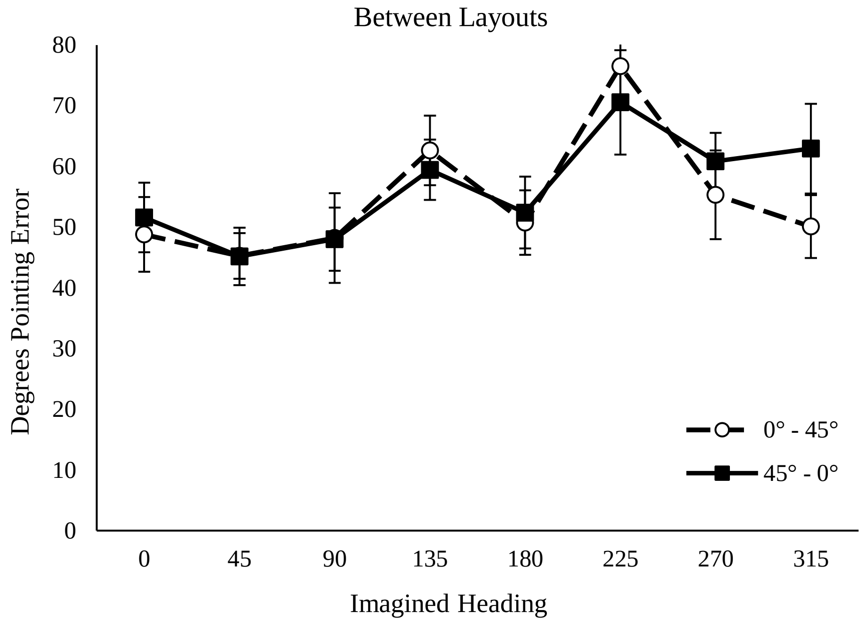

Figure 17. Experiment 3 – Average pointing error for between layout JRDs. Standard error bars represent between subjects error.

Participants in both conditions selected a macro-reference frame aligned with the room walls and carpet. Compared to the results of Experiment 2, it is clear that giving all participants the opportunity to view a perspective aligned with the walls allowed the environmental cue to determine the reference frame, even if another view had been learned first. A reference frame will be formed based on the initial learning position (0 or 45 degrees). At this point, the experiment is identical to Experiment 2 and, theoretically, participants are utilizing a 0 and 45 degree reference frame respectively. However, after viewing from the second position (45 or 0 degrees), both groups utilize a 45 degree macro-reference frame. The 0-45 group appears to have dropped the original 0 degree reference frame in favor of 45 degrees while the 45-0 group did not give up the initial 45 degree reference frame despite viewing from a new perspective.

These results replicate Shelton and McNamara (2001) showing that order of experience does not matter when selecting a reference frame. Instead, whichever cue is most useful will serve as the reference frame, with the others seemingly overwritten.

Micro-reference frame selection (office supply and toy layout judgments)

The response graphs for office supply and toy layout JRDs (split by condition) can be seen in Figures 18 and 19. One-tail tests were used for a priori planned contrasts consistent with the results of Mou and McNamara (2002) as well as Siegel et al. (2013). For the 0-45 degree viewing condition, it was hypothesized that the 0 degree axis would serve as the micro-reference frame for the office supplies due to the explicit training instructions. Participants who viewed from 0-45 degrees performed best at the 0 degree perspective (M=27.65, SD=18.42). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 16.68, $t(14)=4.21$, $p=.001$. There is a significant sawtooth pattern where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 10.59, $t(14)=4.56$, $p<.001$.

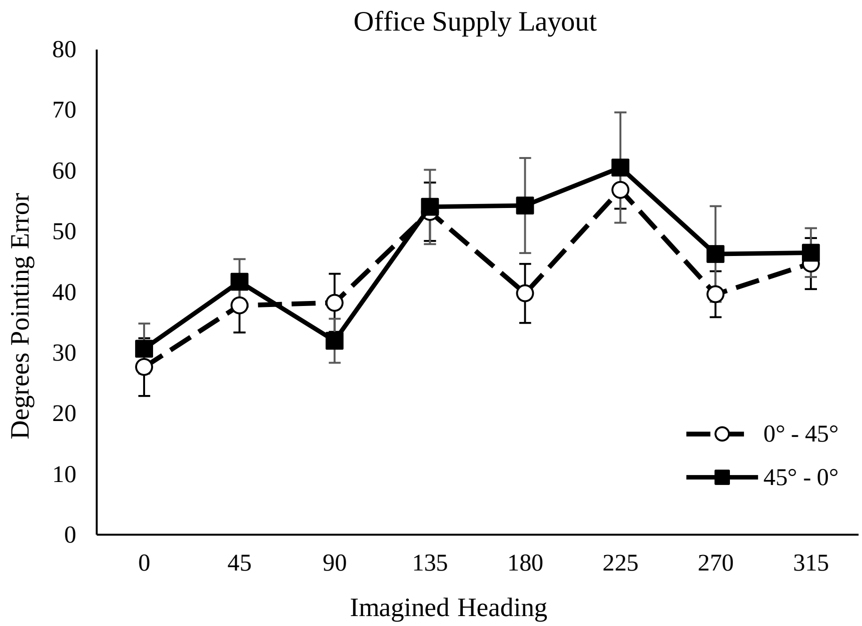

Figure 18. Experiment 3 – Average pointing error for office supply only JRDs. Standard error bars represent between subjects error.

Similar to the office supplies, it was also hypothesized that the 0 degree axis would serve as the micro-reference frame for the toys due to the explicit training instructions. Participants who viewed from 0-45 degrees performed best at the 0 degree perspective (M=37.24, SD=21.52). Performance from this heading was significantly better than the set of all other perspectives, MeanDiff = 11.01, $t(14)=3.49$, $p=.014$. No significant sawtooth pattern exists for this condition, MeanDiff = 2.27, $t(14)=.93$, $p=.367$.

Both micro-reference frames in the 0-45 degree condition were aligned with the 0 degree axis while the macro-reference frame was aligned with 45 degrees. This condition replicates the findings in Siegel et al. (2013) and provides solid evidence that the macro-reference frame is independent of the micro-reference frames. If the macro-reference frame was not independent, this discrepancy (45 vs 0 degree reference frame) between the two levels should be impossible.

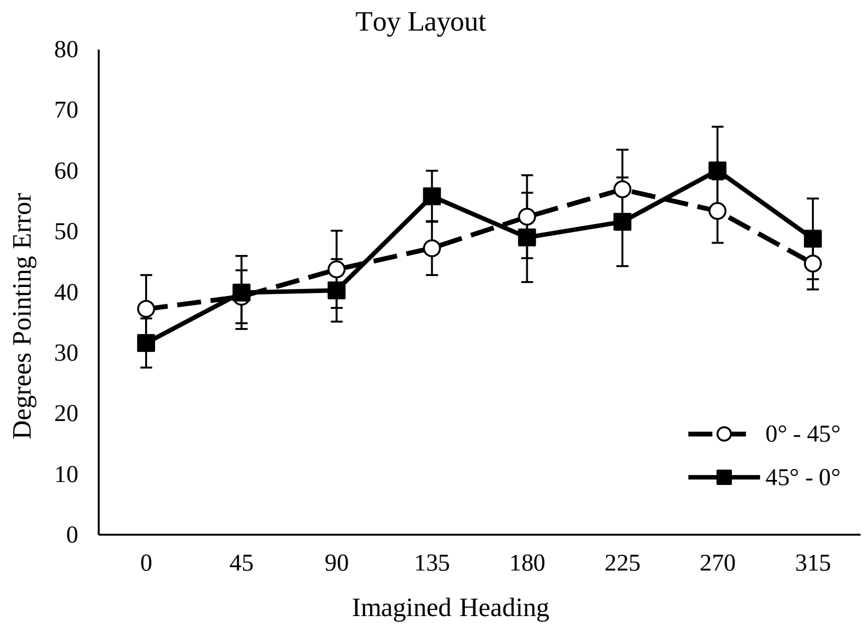

Figure 19. Experiment 3 – Average pointing error for between layout JRDs. Standard error bars represent between subjects error.

For the 45-0 degree viewing condition, it was hypothesized that instruction would cause the 0 degree axis to be selected as the micro-reference frame for the office supplies. Participants who viewed from 45-0 degrees performed best at the 0 degree perspective (M=30.68, SD=16.02). Performance from the 0 degree heading was significantly better than the set of all other perspectives, MeanDiff = 17.22, $t(14)=4.10$, $p<.001$. There is significant evidence of a sawtooth pattern, where participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 11.84, $t(14)=4.99$, $p<.001$.

It was also hypothesized that the 0 degree axis would serve as the micro-reference frame for the toys when participants viewed from 45-0 degrees due to the learning order. These participants performed best at the 0 degree perspective (M=31.60, SD=15.70). Performance from the 0 degree heading was significantly better than the set of all other perspectives, MeanDiff = 17.75, $t(14)=3.49$, $p=.004$. There is significant evidence of a sawtooth pattern as participants performed better when imagining perspectives orthogonal to the 0 degree heading than when imagining the non-orthogonal perspectives, MeanDiff = 3.85, $t(14)=2.05$, $p=.059$.

The 45-0 degree condition also demonstrates that the macro-reference frame must be independent from the constituent micro-reference frames. Unlike the previous two experiments, explicit training was again successful in constraining both office supply and toy micro-reference frames to 0 degrees while the macro-reference frame was aligned with 45 degrees. This experiment is the best evidence of the three presented here for the independence of the macro-reference frame from the constituent micro-reference frames.

CHAPTER 6: GENERAL DISCUSSION

It was hypothesized that macro-reference frames are selected using the same egocentric, environmental, and intrinsic cues and that have proven influential for individual layouts (Shelton & McNamara 2001, Mou & McNamara, 2002). The three experiments presented here, along with the results of Siegel et al. (2013), give strong support for all three types of cues. Siegel et al. demonstrated that the symmetry axis of a layout was an intrinsic cue capable of defining the macro-reference frame, even when the macro-reference frame was misaligned with both the learned view and the constituent micro-reference frames. This finding replicates the findings of Mou, Zhao, and McNamara (2007) where three different views were learned, but a reference frame aligned with the symmetry axis was selected irrespective of learning order. Macro-reference frames are impacted by intrinsic axes, just like micro-reference frames.

Experiment 1 demonstrated that the perspective viewed during training influenced macro-reference frame selection, even though the viewing perspective did not necessarily align with the eventual reference frame. This differs from Shelton and McNamara (2001) because egocentric experience did not define the macro-reference frame, it merely affect which perspective was selected. The overall layout for this study was designed to minimize intrinsic cues; it was not symmetrical and did not have a strong principal axis. Despite teaching participants to learn the objects in a specific order along the 0 degree axis, participants seemed to have identified different cues, such as long rows of objects (ball to boat, robot to train, and block to bear), depending on their viewing position to serve as intrinsic cues for macro-reference frame selection. It is possible that the findings of Shelton and McNamara (2001) were coincidental in that the salient portion of the layout and the learned view happened to overlap. In this case, the effect of learned view on reference frame selection requires a slight modification reflecting that learned view affects, rather than defines the eventual reference frame. The theory that learned view influences the salience of other cues does not necessarily have to apply to studies involving a single layout such as Shelton and McNamara (2001) or Mou, Zhao, and McNamara (2007). It is possible that learned view only defines the reference frame when all objects are intentionally learned as a single group. Macro-reference frames must be learned through incidental means (otherwise there would not be two separate groups to integrate). Learned view may define the reference frame only for single groups, and not in these incidental learning scenarios.

When applying this explanation to the results of Greenauer and Waller (2010), it is possible a long line formed by the two spatially distinct groups served as a strong reference frame cue instead of learned view itself defining the macro-reference frame. The theory that learned view influences the salience of intrinsic cues is compatible with past findings, but also fits the current data in a way that learned view serving as the reference frame cannot. To confirm this, the results of Experiment 1 should be expanded to single layout reference frame selection by having the same overall layout learned as a single unit from a 0 and 45 degree view. As long as no instructions were given about learning order, participants viewing from 0 and 45 degrees should utilize 0 and 90 degree reference frames respectively if egocentric experience affects reference frame selection rather than defining it. Alternatively, it is possible that macro- and micro-reference frame selection differs in this regard with memory of the egocentric experience serving as a cue that is impossible to replicate with in macro-reference frame selection. This episodic memory may cause participants to utilize 0 and 45 degree reference frames aligned with the learned view similar to previous findings with single group layouts. Egocentric view can influence macro-reference frame selection (given that no other cues are present), but the exact mechanism for influence should be further investigated in the light of the discrepant findings between Experiment 1 and Shelton and McNamara (2001).

Experiments 2 and 3 extend the finding that environmental cues influence micro-reference frame selection to macro-reference frame selection (Shelton & McNamara, 2001). The long lines from robot to train and block to bear appear to be particularly weak cues compared to the environmental cues provided by the walls and carpet because participants in Experiment 2 utilized the environmental cues for macro-reference frame selection when viewing from 45 degrees. Given the existing literature, it should not be surprising that environmental cues are stronger than an egocentrically-influenced cue. Though participants unexpectedly utilized 90 degrees as their reference frame when viewing from 45 degrees in Experiment 1, the change between experiments gives clear evidence for the power of these environmental cues. Once both conditions were able to view the layout aligned with the environment in Experiment 3, the 45 degree macro-reference frame dominated and there is no evidence that the 0 degree macro-reference frame for the 0-45 layout was preserved.

In addition to showing the efficacy of egocentric view and environmental cues, these experiments demonstrate that the macro-reference frame exists independent of the constituent micro-reference frames. The results of Greenauer and Waller (2010) left the door open for the macro-reference frame to be a simple average of the reference frame for the near and far array. While true independence was not demonstrated in every experiment, Experiment 3 shows that neither an average of the micro-reference frames nor selecting one of the two sufficiently explains macro-reference frame selection. These results replicate the independence finding from Siegel et al. (2013). Experiments 1 and 2 do not preclude the possibility that macro-reference frames are independent, they only fail to exclude the alternate explanations for macro-reference frame selection and the alternate explanations supported by these experiments do not agree with one another. Experiment 1 could be alternatively explained by selecting one of the micro-reference frames while Experiment 2 could theoretically be explained by some combination of the two micro-reference frames. Therefore, the conclusion should be that the macro-reference frame is truly a unique construct in memory, as that is the only explanation consistent with results of Greenauer and Waller (2010), Siegel et al. (2013), and the 3 new experiments discussed here.

The experiments included here are limited to Montello's (1993) vista space (requiring head rotation, but not locomotion). However, these results can be generalized to environmental space thanks to evidence from Marchette et al. (2011) where reference frame effects were observed for a large college campus. It is possible, but not guaranteed; that these results would generalize to geographical space as learning through maps may not be subject to the same cues. Anecdotally, it is easier to make judgments about relative city locations when the imagined perspective is aligned with a northerly axis. Learning maps north-up is similar to an egocentric cue and may hold promise that separate geographic layouts might be affected by the same reference frame cues observed in vista and environmental space. Future work on this question could utilize overhead maps of the layouts from this project and constrain viewing direction to the 0 and 45 degree angles used for the in-person experiment.

Taken together, these experiments demonstrate that the current understanding that egocentric, environmental, and intrinsic cues all impact micro-reference frame selection should be extended to the selection of macro-reference frames as well. Additionally, macro-reference frames are unique representations in memory that are not influenced by micro-reference frame selection. This has important implications for spatial memory research because it allows macro-reference frame research to continue without needing to control or test the constituent micro-reference frames. It does not appear that macro-reference frame selection is subject to the same sort of hierarchical effects seen in distance judgements (Hirtle & Jonides, 1985; McNamara, Hardy & Hirtle, 1989). With this understanding in mind, future work should move forward to examine how mental representations of two distinct sub-layouts are integrated. It is not yet known if the macro-reference frame is calculated at decision time or if the relationship between sub-layouts is learned incidentally during training for the two separate layouts. Evidence for incidental learning has already been demonstrated for spatial information, (vanAsselen, Fritschy & Postma, 2006) but accuracy suffers compared to the information learned intentionally. While the lack of accuracy may increase overall pointing error, the reference frame selected should still be detectable. Valliquette, McNamara, and Smith (2003) confirm this assumption by demonstrating that incidental learning can establish a reference frame for a single layout of objects, however, the nature of incidental learning for macro-reference frames may be different as the two layouts are stored separately in memory. Though the layouts are never intentionally associated prior to test, incidental learning might still establish a reference frame for the whole set of objects during the learning phase that is then utilized later.

The fact that relationships between sub-layouts must be learned incidentally raises the question as to which sub-layouts are included when selecting a macro-reference frame. So far, the research considered has only included two different layouts, but it might stand to reason that the macro-reference frame takes into account the entire set of objects, even if there are 3 distinct learned categories. Alternatively, the macro-reference frame may be formed individually for each combination of sub-layouts. An unpublished experiment conducted after Siegel et al. (2013) investigates this question, but the results are not reported here because the layout used was not particularly well suited to the question and the results do not favor any particular theory.

In summary, macro-reference frames are selected independently from micro-reference frames with selection based on egocentric, environmental, and intrinsic cues. The exact method for egocentric influence on macro-reference frame selection may or may not differ from the way egocentric cues affect micro-reference frame selection. However, environmental cues appear to work in exactly the same manner, determining the reference frame only if the individual has had the chance to view an aligned perspective. With this understanding, the nearly two decades of ground work on reference frame selection should generalize to studies examining how multi-layout spatial knowledge is remembered and how portions of more complex environments are associated with one another. Future research in this area can continue forward to answer new questions about macro-reference frames, confident that the existing literature is safe to build upon.

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APPENDIX A

EXPERIMENT 1 RESPONSE TIME DATA

The response time (seconds) for between-layout JRDs (split by condition) can be seen in Figure 20. Participants who viewed from 0 degrees responded most quickly from the 90 degree imagined perspective (M=10.26s, SD=2.83s). Responses from this heading were marginally faster than the set of all other perspectives, MeanDiff = .97s, *t*(14)=1.82, *p*=.091. There is no evidence of a significant sawtooth pattern where participants respond more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .13s, *t*(14)=.33, *p*=.747.

Participants who viewed from 45 degrees responded most quickly from the 90 degree perspective (M=8.10s, SD=2.29s). Responses from the 90 degree heading were not significantly faster than the set of all other perspectives, MeanDiff = .78s, *t*(14)=1.63, *p*=.126. There is also no significant evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were faster than perspectives orthogonal to 45 degrees, MeanDiff = .37s, *t*(14)=1.93, *p*=.074.

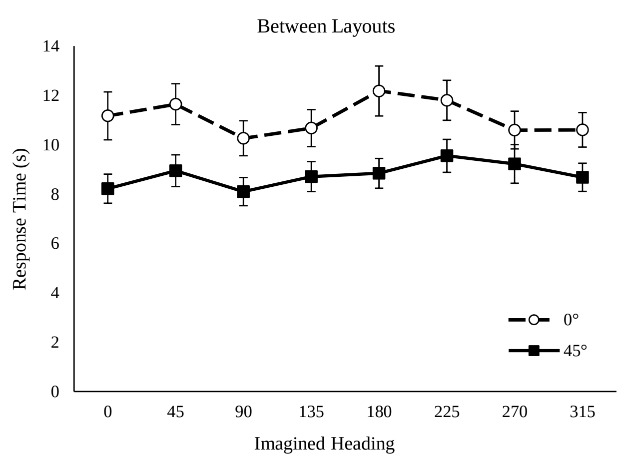

Figure 20. Experiment 1 – Average response time for between layout JRDs. Standard error bars represent between subjects error.

The response time (seconds) for office supply JRDs (split by condition) can be seen in Figure 21. Participants who viewed from 0 degrees responded most quickly from the 0 degree imagined perspective (M=8.56s, SD=2.18s). Responses from this heading were significantly faster than the set of all other perspectives, MeanDiff = 2.09s, $t(14)=3.94$, $p=.001$. There is marginal evidence of a significant sawtooth pattern where participants responded more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .90s, $t(14)=2.07$, $p=.058$.

Participants who viewed from 45 degrees responded most quickly from the 90 degree perspective (M=7.79s, SD=1.98s). Responses from the 90 degree heading were not significantly faster than the set of all other perspectives, MeanDiff = .824s, $t(14)=1.26$, $p=.226$. There is also no significant evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were faster than perspectives orthogonal to 45 degrees, MeanDiff = .17s, $t(14)=.70$, $p=.496$.

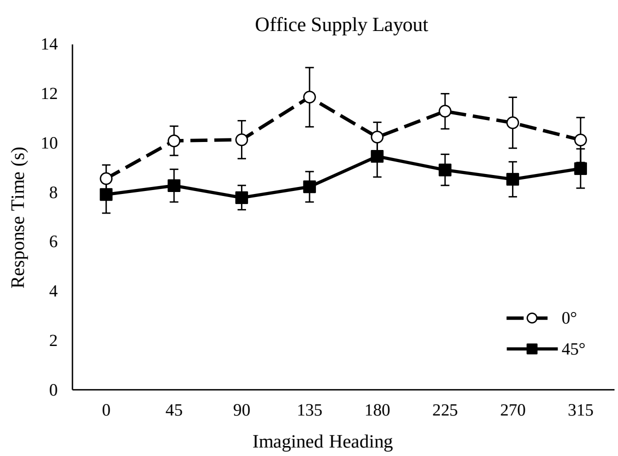

Figure 21. Experiment 1 – Average response time for office layout JRDs. Standard error bars represent between subjects error.

The response time (seconds) for toy JRDs (split by condition) can be seen in Figure 22. Participants who viewed from 0 degrees responded most quickly from the 0 degree imagined perspective (M=10.90s, SD=3.17s). Responses from this heading were marginally faster than the set of all other perspectives, MeanDiff = 1.38s, *t*(14)=2.10, *p*=.054. There is no evidence for a sawtooth pattern where participants respond more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .80s, *t*(14)=1.72, *p*=.108.

Participants who viewed from 45 degrees responded most quickly from the 90 degree perspective (M=7.56s, SD=1.82s). Responses from the 90 degree heading were significantly faster than the set of all other perspectives, MeanDiff = 1.20s, *t*(14)=2.54, *p*=.024. There is no significant evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were faster than perspectives orthogonal to 45 degrees, MeanDiff = .68s, *t*(14)=1.85, *p*=.086.

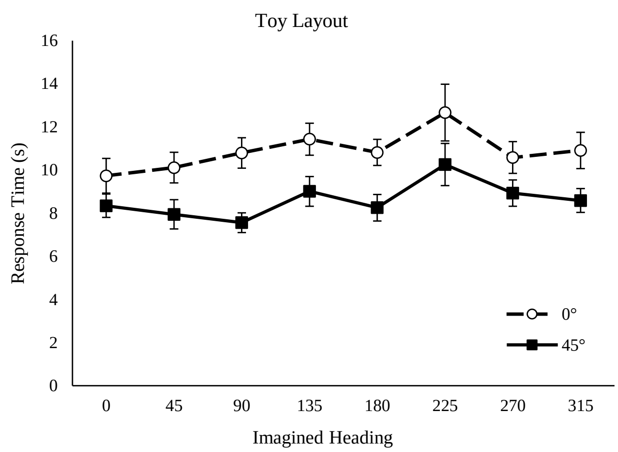

Figure 22. Experiment 1 – Average response time for toy layout JRDs. Standard error bars represent between subjects error.

APPENDIX B

EXPERIMENT 2 RESPONSE TIME DATA

The response time (seconds) for between-layout JRDs (split by condition) can be seen in Figure 23. Participants who viewed from 0 degrees responded most quickly from the 0 degree imagined perspective (M=10.90s, SD=3.17s). Responses from this heading were significantly faster than the set of all other perspectives, MeanDiff = 1.38s, $t(14)=2.20$, $p=.045$. There is evidence of a significant sawtooth pattern where participants respond more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .91s, $t(14)=2.18$, $p=.047$.

Participants who viewed from 45 degrees responded equally fast (within rounding error) to both the 90 degree perspective (M=8.84s, SD=2.91s) and the 315 degree perspective (M=8.84s, SD=2.26s). Responses from the 90 degree heading were significantly faster than the set of all other perspectives, MeanDiff = .93s, $t(14)=2.25$, $p=.029$. Responses from the 315 degree heading were also significantly faster than the set of all other perspectives, MeanDiff = .93s, $t(14)=2.25$, $p=.041$. There is no evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were slower than perspectives orthogonal to 45 degrees, MeanDiff = .48s, $t(14)=1.19$, $p=.253$.

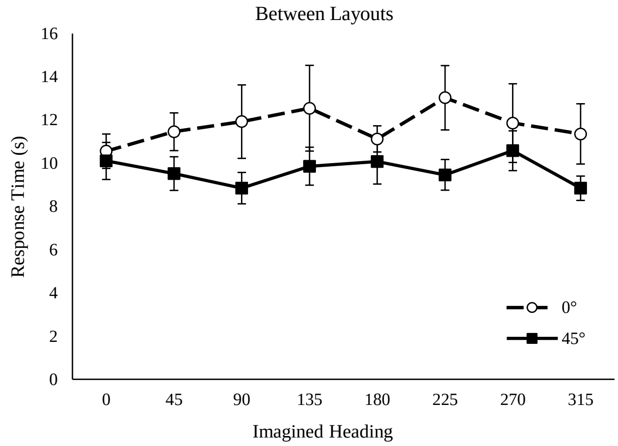

Figure 23. Experiment 2 – Average response time for between layout JRDs. Standard error bars represent between subjects error.

The response time (seconds) for office supply JRDs (split by condition) can be seen in Figure 24. Participants who viewed from 0 degrees responded most quickly from the 0 degree imagined perspective (M=9.45s, SD=2.92s). Responses from this heading were significantly faster than the set of all other perspectives, MeanDiff = 1.20s, $t(14)=2.92$, $p=.011$. There is no evidence of a sawtooth pattern where participants responded more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .91s, $t(14)=.74$, $p=.473$.

Participants who viewed from 45 degrees responded most quickly from the 90 degree perspective (M=8.00s, SD=2.57). Responses from the 90 degree heading were not significantly faster than the set of all other perspectives, MeanDiff = 1.40s, $t(14)=3.76$, $p=.002$. There is evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were significantly faster than perspectives orthogonal to 45 degrees, MeanDiff = .66s, $t(14)=2.92$, $p=.011$.

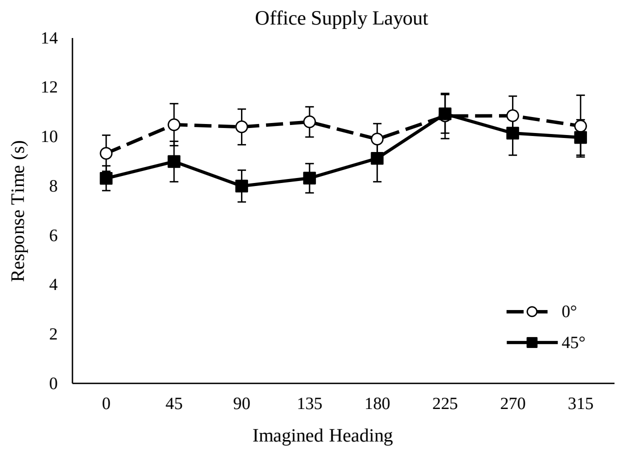

Figure 24. Experiment 2 – Average response time for office layout JRDs. Standard error bars represent between subjects error.

The response time (seconds) for toy JRDs (split by condition) can be seen in Figure 25. Participants who viewed from 0 degrees responded most quickly from the 0 degree imagined perspective (M=9.41s, SD=3.05s). Responses from this heading were significantly faster than the set of all other perspectives, MeanDiff = 1.93s, $t(14)=2.09$, $p=.055$. There is no evidence for a sawtooth pattern where participants respond more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .15s, $t(14)=.32$, $p=.754$.

Participants who viewed from 45 degrees responded most quickly from the 45 degree perspective (M=7.65s, SD=2.25s). Responses from the 45 degree heading were significantly faster than the set of all other perspectives, MeanDiff = 1.18s, $t(14)=2.91$, $p=.011$. There is no significant evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were faster than perspectives orthogonal to 45 degrees, MeanDiff = .26s, $t(14)=.54$, $p=.589$.

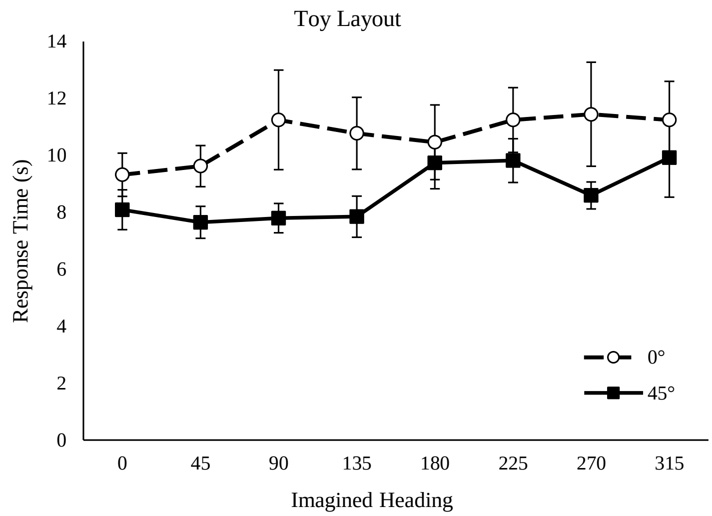

Figure 25. *Experiment 2 – Average response time for toy layout JRDs. Standard error bars represent between subjects error.*

APPENDIX C

EXPERIMENT 3 RESPONSE TIME DATA

The response time (seconds) for between-layout JRDs (split by condition) can be seen in Figure 26. Participants who viewed from 0 degrees responded most quickly from the 180 degree imagined perspective (M=8.04s, SD=2.04s). Responses from this heading were not significantly faster than the set of all other perspectives, MeanDiff = .55s, $t(14)=1.65$, $p=.121$. There is no evidence of a significant sawtooth pattern where participants respond more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .19s, $t(14)=.96$, $p=.356$.

Participants who viewed from 45 degrees responded most quickly from the 45 degree imagined perspective (M=7.44s, SD=1.40s). Responses from the 45 degree heading were not significantly faster than the set of all other perspectives, MeanDiff = .28s, $t(14)=.94$, $p=.364$. There no evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were slower than perspectives orthogonal to 45 degrees, MeanDiff = .04s, $t(14)=.20$, $p=.848$.

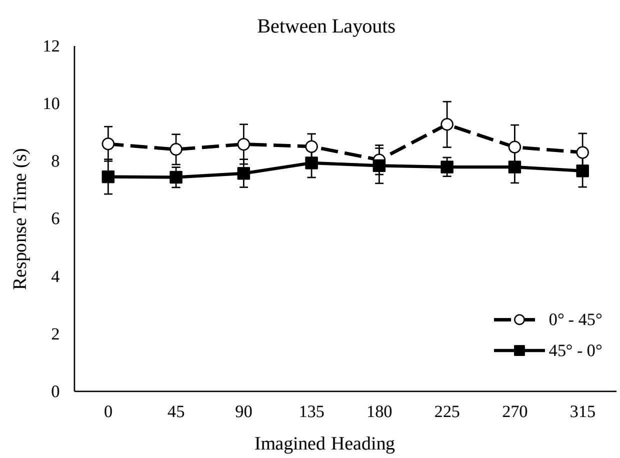

Figure 26. Experiment 3 – Average response time for between layout JRDs. Standard error bars represent between subjects error.

The response time (seconds) for office supply JRDs (split by condition) can be seen in Figure 27. Participants who viewed from 0 degrees responded most quickly from the 0 degree imagined perspective (M=6.82s, SD=1.59s). Responses from this heading were significantly faster than the set of all other perspectives, MeanDiff = 1.39s, $t(14)=5.16$, $p<.001$. There is marginal evidence of a sawtooth pattern where participants responded more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .56s, $t(14)=1.79$, $p=.095$.

Participants who viewed from 45 degrees responded most quickly from the 45 degree imagined perspective (M=6.57s, SD=1.87). Responses from the 45 degree heading were not significantly faster than the set of all other perspectives, MeanDiff = .76s, $t(14)=1.61$, $p=.129$. There is no evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were significantly faster than perspectives orthogonal to 45 degrees, MeanDiff = .24s, $t(14)=1.03$, $p=.320$.

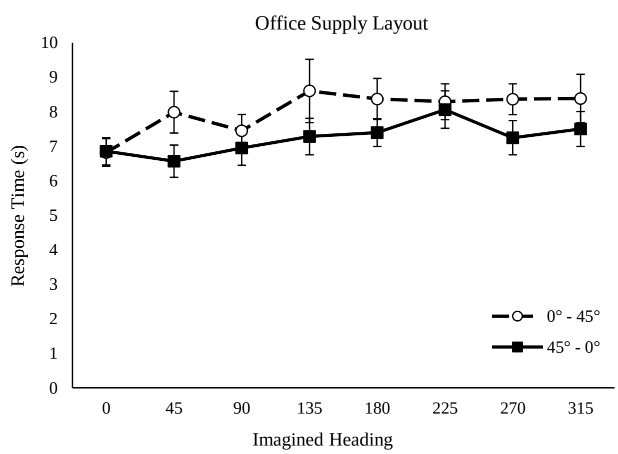

Figure 27. Experiment 3 – Average response time for office layout JRDs. Standard error bars represent between subjects error.

The response time (seconds) for toy JRDs (split by condition) can be seen in Figure 28. Participants who viewed from 0 degrees responded most quickly from the 0 degree imagined perspective (M=7.77s, SD=1.86s). Responses from this heading were marginally faster than the set of all other perspectives, MeanDiff = .67s, $t(14)=1.91$, $p=.077$. There is no evidence for a sawtooth pattern where participants respond more quickly when imagining perspectives orthogonal to the 0 degree heading (0, 90, 180, and 270) than when imagining those orthogonal to 45 degrees (45, 135, 225, 315), MeanDiff = .16s, $t(14)=.43$, $p=.672$.

Participants who viewed from 45 degrees responded most quickly from the 45 degree perspective (M=6.86s, SD=1.81s). Responses from the 45 degree heading were marginally faster than the set of all other perspectives, MeanDiff = .50s, $t(14)=1.81$, $p=.092$. There is no significant evidence of a sawtooth pattern where responses to perspectives orthogonal to 0 degrees were faster than perspectives orthogonal to 45 degrees, MeanDiff = .26s, $t(14)=1.29$, $p=.218$.

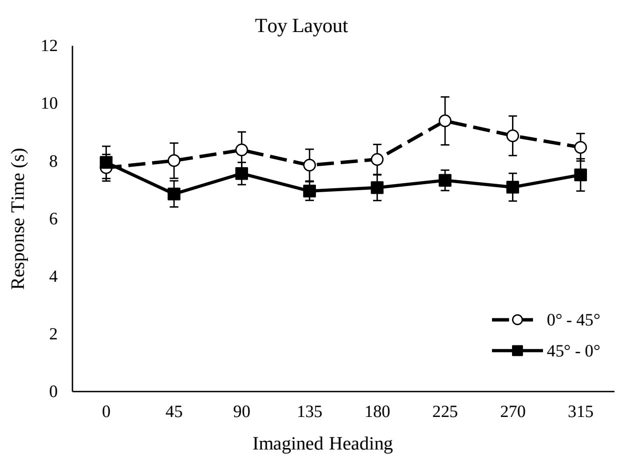

Figure 28. Experiment 3 – Average response time for toy layout JRDs. Standard error bars represent between subjects error.