REFERENCE FRAME DEFINITION, USE, AND INTERACTION IN SPATIAL MEMORY

BY

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DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Psychology in the Graduate College of the University of Illinois at Urbana-Champaign, 2017

Urbana, Illinois

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ABSTRACT

In order to preform actions and reason about spatial relationships in the world, a mental representation of spatial locations is needed. The exact nature of this representation has been debated among research groups with some concluding reference frames are self-based (egocentric), while others conclude spatial representations are independent from the self (allocentric or intrinsic). This research presents novel methods to assess spatial reference frame use in memory. Chapter 1 presents a framework for classifying reference frames. Specifically a distinction between reference direction and reference point is made. Chapter 2 details a novel attraction analysis paradigm to assess reference direction use. Chapter 3 details a bias distribution analysis, which can provide evidence for interacting reference directions. Chapter 4 presents a novel way to test reference point use in spatial memory. Chapter 5 combines these findings and concludes that an egocentric reference frame is encoded in memory and used during spatial tasks.
For Ethan, William, and Samantha
ACKNOWLEDGEMENTS

Many thanks to Frances Wang, Dan Simons, Diane Beck, John Hummel, and Kara Federmeier whose advice and mentorship stretched the rigor of this work. Furthermore, graduate school is a challenging time and I could not have gotten through it without the frequent moral support from other graduate students as well as the never ending help of Ashley Ramm and June Eubanks.

Most importantly, I must thank my family. My parents, Larry and Katrina Street, who raised me to know I could accomplish anything I set myself to. My maternal grandmother Wilhelmina Nesbit, who did not get to finish her degree in Psychology, but always instilled a love of education in me and every other grand and great-grand child.

During this process, I could not have continued without my husband Luke Scharf. Not only did he tirelessly support me through years and years of low paying graduate work, he did so as we expanded our family during this time. We added three children during my graduate student career which I can’t imagine as a more stressful and also perfect way to start a family. Ethan came just after my first year and gave me perspective on home and school pressures. William was born as I during the first drafts of this document and further helped define my life choices after graduate school. Finally, Samantha will make her appearance soon after this work is complete, further busying and perfecting our little family. Without these three, I likely would have given up multiple times, but they gave me reason to demonstrate the power of diving into something challenging to come out stronger.
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CHAPTER 1: INTRODUCTION

Throughout the day, we interact with objects in a spatial world. From picking up a cup to remembering the layout of a city, humans have the ability to flexibly use spatial knowledge with seemingly little to no effort. In order to perform these actions, spatial information must be stored in a mental representation and the nature of this representation has been contested. One argument could be that the eye sees the world from the viewer’s perspective, egocentrically, and therefore mental representations likely also follow that structure. However, the brain does not passively take in knowledge and instead it actively interprets the signals it encounters. Since this is the case, it is possible that spatial representations are independent of the viewer, i.e., allocentric or intrinsic.

To understand how people accomplish spatial tasks, a deeper understanding of the structure of a spatial representation is necessary. Spatial locations are inherently relative. For example, the same location might be referred to as 3.5m in front of the building, .5m to the left of you, or 40°06'28.1"N 88°13'47.8"W. To identify this location, each of these statements make use of a different reference frame which provides the structure for remembering and communicating locations as well as acting in a spatial world. Additionally, different reference frames are best suited for different tasks. While map-based applications can quickly and accurately use longitude and latitude to find any location on Earth, a person reaching for an object needs the distance and direction of that object relative to themselves. Understanding reference frame use in spatial memory is critical to understanding how we interact in the spatial world.
Within a reference frame, two components are necessary to fully define locations. A reference point specifies the origin of the reference frame. In the example, *the cup is to the right of the plate*, the plate is used as a reference point. Additionally, a reference direction is needed to act as a conceptual ‘north’ for the reference frame. Understanding ‘to the right of’ assumes knowledge of that reference direction. With these two components, all other locations can be represented as a distance from the reference point and a specific angle off the reference direction.

Research in spatial memory differs vastly on the definition and expected performance of different reference frames (Levinson, 1996; Klatzky, 1998). Furthermore, spatial reference frames are rarely fully specified by researchers and terms are often used in wildly different ways. Since reference point selection does not theoretically constrain reference direction selection and vice versa, generic terms such as ‘self-based’ or ‘environment-based’ do not specify a reference frame’s full definition.

**Reference frame definitions**

Generally, two categories of reference frames are posited in spatial memory: those based on the self, called egocentric, and those based on the external world, termed allocentric (Burgess, 2006; Feigenbaum & Rolls, 1991; Howard, 1991; Klatzky, 1998; Levinson, 1996; McNamara, Rump, & Werner, 2003; Wang & Spelke, 2000; Wang, 2003; Wang, 2012). Often egocentric reference frames are defined as those based on a person’s head, body, or hand. Allocentric reference frames often are defined as a representation external to the individual including those based on objects, geometric configurations, and any external arbitrary location or perspective. However, these are
generic categories of reference frames and a fully specified reference frame definition requires more specificity than this alone.

Since reference point and direction selection are theoretically independent of one another, either can be self or externally based. A reference direction may be based on the observer’s facing direction or based on an external direction in the environment. While self-based reference directions are likely to be a person’s facing direction or heading, external reference directions may be based on the orientation of the room, magnetic north, or any other non-self direction. A further distinction is often made between reference directions based on the properties of an object or array of objects, often called intrinsic reference direction, and those based on non-object external directions, an environmental reference direction. An intrinsic reference direction is based on the structure of the object or array (Levinson, 1996; McNamara, 2003; Mou & McNamara, 2002). That is, the object structure has an inherent ‘front’. Environment-based reference frames encompass any other arbitrary reference direction, such as magnetic north or a universally agreed upon direction such as an ascending slope (Levinson, 1996).

Similarly, the origin of the reference frame, the reference point, can also be based on the self or an external location. Egocentric reference points are based on the position of the observer (Klatzky, 1998; Levinson, 1996). Allocentric reference points are locations external to the self. There are an infinite number of possible external reference points, however some positions may be more likely than others such as landmarks or other important places. Alternatively, instead of a single external reference point, objects may be encoded relative to other objects pairwise (McNamara, 2003; Mou & McNamara, 2002). Here object A is remembered based on object B and C while B is remembered
relative to A and C, and so forth. This object-to-object encoding means each object is remembered relative to each other object in the display and direct recall of these relationships is possible from memory.

These three possible reference points paired with the three reference directions give rise to nine definitions, each of which specify a distinct and potential reference frame (see table 1.1). Research generally focuses on ‘egocentric’, ‘intrinsic’, or ‘allocentric’ reference frames which are categories of reference frames collapse across these nine cells. Though these generic terms are used widely when researching reference frames, it is important to remember that without a fully specified definition, experimental results may be difficult to interpret. Additionally, as showcased below, the same term can often have completely different meanings across different literatures/researchers so a more specified definition is critical for understanding reference frame research.

**Variety of reference frames definitions**

*Spatial Language*

A clear case of this collapsing comes from spatial language (Carlson-Radvansky & Irwin, 1993; see table 1.2). When interpreting a statement such as “above the apple”, the speaker may wish to convey the ‘above’ relative to herself, gravity, or the object itself (see figure 1.1). The intrinsic above would be relative to the stem of the apple. An intrinsic reference direction comes from the structure of the object structure (Levinson, 1996; Palmer, 1989), in this case the stem of the apples give it a natural ‘top’.

Importantly, not all objects have an intrinsic reference direction, such as a ball. In cases like these, other reference directions may more readily apply.
Beyond the intrinsic reference direction, spatial language defines two other reference frames, again by focusing only on reference direction while collapsing across reference point. Cues from the environment, such as gravity, may be used to define an absolute reference frame. An absolute reference frame may apply to objects with or without a clear intrinsic axis. Therefore “above the apple” can also be labeled with respect to gravity disregarding the intrinsic direction.

Finally, a self reference direction can be applied in spatial language, called a relative reference frame. Here “above the apple” is labeled relative to the observer’s body orientation. When the viewer stands, the relative reference frame aligns with a gravity-based absolute reference frame, however the two can conflict such as when an observer lies down. In fact all of these reference directions can conflict when they misalign (Carlson-Radvansky & Irwin, 1993; see figure 1.1).

Spatial Memory

Unlike spatial language, spatial memory researchers define an intrinsic reference frame based on the type of reference point encoded while reference direction may vary (see table 1.3). Here intrinsic encodings are a set of pairwise object vectors (Gibson, 1979; Sedgwick, 1983; Rieser, 1989; Easton & Sholl, 1995; McNamara, 2003). Reference direction on the other hand may vary with a self, object, or environmental direction selected.

Additionally, an egocentric reference frame can be defined as different combinations of reference point and direction pairs. One possible definition is one that encoded a person’s viewing direction and position. Here both the reference point and direction are based on the self and all other combinations might be defined as allocentric
reference frames. However, this is not the only possible classification. The term egocentric may be defined as a reference frame that encodes either the reference point or direction based on the individual. Here, self-motion will require the representation to update to remain accurate if either the reference point or direction are based on the self (Wang, 2012; see table 1.4). By this logic, an allocentric representation is one that includes information wholly outside the self which needs no updating after a person’s self-motion.

As is illustrated from the vastly different definitions of reference frames, the terms egocentric, allocentric, and intrinsic can describe very different spatial representations. Additionally, support for reference frame use is mixed. Some of this confusion may be due to the differences in defining reference frames however, an additional challenge in understanding how reference frames are structured in memory comes from the variety and limitations of the tasks used to test spatial memory.

**Egocentric empirical evidence**

It is generally accepted that individuals first engage the world egocentrically. Visual information is represented retinotopically in the retina as well as some cortical level of the brain (Colby & Goldberg, 1999). Additionally, acting on the world requires egocentric action vectors for movement. While allocentric reference frames have been posited for intervening cognitive steps between this input and output, there is evidence egocentric reference frames persist throughout memory.

The configuration error paradigm provides a particularly compelling test of egocentric vs. allocentric reference frames in spatial memory (Wang & Spelke, 2000). Here, egocentric representations are defined as any reference frame that uses the
observer’s position as either a reference point or direction because these representations must change after self-motion to stay accurate (see table 1.4). To test if individuals can represent locations based only on an external reference point and direction, the configuration error paradigm assumes that an allocentric reference frame should not be affected by disorientation of the observer. That is, after an individual has studied and encoded spatial locations, spinning this person until they no longer know where they are in a space should be detrimental to object-to-self encodings but not object-to-object or object-to-environment encodings. However, if spatial reference frames encode a scene egocentrically, this disorientation should affect all spatial recall.

Two types of error were used to discern what effects the disorientation had on performance. Heading error, measured by the average signed error for each object, shows if participants are accurately representing their correct heading. Disorientation should disrupt heading error as participants lose track of their position and therefore cannot accurately point to the targets. Configuration error, calculated as the standard deviations of signed errors to each target, shows how individuals represent the internal configuration of the remembered items. A correctly remembered array of objects will have no configuration error. However, this error will increase as the structure of the items deviates from this configuration. If individuals represented these object relationships allocentrically, they will not be able to correctly point directly to the objects, since they were disoriented, however, the configuration of these pointing responses should be intact.

In order to test if spatial representations of a remembered space rely on a person’s egocentric position, participants memorized several objects around a room, were disoriented, and then pointed to the remembered objects. Unsurprisingly, heading error
increased with disorientation showing that they were indeed disoriented. More interesting is whether individuals preserved the internal configuration of the objects even though they had lost their heading. Wang & Spelke (2000) found that disorientation increased configuration errors, which provides strong support that an egocentric reference frame was used in spatial memory.

**Allocentric empirical evidence**

Though spatial information enters the brain egocentrically, our brains are capable of complex spatial processing. Additionally, allocentric reference frames or ‘mental maps’ are often considered a sophisticated form of spatial memory that humans must be capable of. Additionally, subjective experience often feels like an internal enduring map of space. To support this theory, complex and difficult spatial task performance is often taken as evidence of an allocentric reference frame.

Early spatial memory research was explained in behavioral terms. Rats learned paths through mazes because of a food reward. However, Tolman (1948) and other field theorists saw more complex behavior than simple reinforcement learning. Generally researchers found that hungry rats rewarded with food at a goal location quickly decreased the number of wrong turns through a maze to a food source while those with no reward did not show learning. However, field theorists found that rats can learn in the absence of reinforcement. In a clever manipulation, Blodgett (1929) allowed a group of rats to run the maze with no food reinforcement for six days. On the seventh, a food reward was added and on the next testing day, the rats’ errors decreased to the level of the food reinforced rats. This striking performance could only occur if the rats had learned the maze without food reinforcement so they could improve immediately upon the food’s
introduction. Additionally, this finding suggests that the initial evidence that rats did not learn without food was incorrect and even these rats would have shown their hidden knowledge of the space if given a goal.

Tolman (1948) described this phenomenon as latent learning and postulated that these rats had formed a cognitive map of the maze. The term ‘map’ suggests that the rats were using a reference frame that abstracts away from any viewer-based experience to a representation based on the enduring allocentric space. When defining Tolman’s cognitive map in terms of table 1.1, an environment reference direction most closely represents a map’s use of north as its defined reference direction. Additionally, object-to-object encodings, which allow direct retrieval of pairwise object relations, mimic studying a map and knowing the locations of any configuration of objects with a single look. However, other definitions of Tolman’s mental map are possible because the original definition is underspecified.

Beyond the term ‘map’, Tolman further concluded that only ‘comprehensive’ maps allow an animal to accomplish tasks such as shortcutting to novel locations while a ‘strip-like’ map would not allow this kind of generalization. This idea of a comprehensive map suggests two properties of the reference frame. A comprehensive representation should include information broadly about the space and not only that seen in a single ‘strip’ of navigating. Furthermore, a comprehensive representation should be able to operate broadly and not only in limited situations. While an allocentric reference frame meets these criteria, an egocentric reference frame can also encode this information. In particular, an egocentric representation (as defined in table 1.4) can guide navigation, and can theoretically store and integrate information from multiple paths. Therefore,
Tolman may have intended a cognitive map to be any spatial representation that broadly guides actions meaning all possible reference frames discussed above would qualify as a cognitive map.

More recent research into reference frames makes the distinction between route and survey knowledge (e.g., Golledge, Dougherty, & Bell, 1995; Gould, 1986; Landau, Spelke, & Gleitman, 1984; Maguire et al., 2003; Thorndyke & Hayes-Roth, 1982). Route knowledge is based on the path an individual takes through a space and does not allow shortcutting as the representation only includes elements such as segments, intersections, and landmarks along a given route. With experience, route knowledge is hypothesized to combine into survey knowledge. Survey knowledge, similar to Tolman’s cognitive map, includes allocentric information about a space which allows individuals to shortcut between locations and link routes learned as distinct traversals.

A route based representation is said to be egocentric suggesting a reference point and direction based on the self. Survey knowledge, gained after many different routes are learned, is said to be allocentric and much like cognitive maps may be based on an object-to-object reference point and non-object external reference direction. Additionally, survey knowledge contains substantially more information about the environment while route knowledge is limited to include only information within a single path. If reference frames are constrained in the type of knowledge encoded in survey and route representations, novel shortcutting to new locations should distinguish between the two. Critically, successful shortcutting should only possible when using survey level knowledge.
Both animals (Cartwright & Collett, 1982; Griffin & Etienne, 1998; Lehrer & Collett, 1994; Müller & Wehner, 1988) and humans (Loomis et al., 1993; Mallot & Gillner, 2000; Wang & Brockmole, 2003) can take a novel shortcut path to a previously experienced position. For example, adults are able to return to a starting position when they are lead along a specific path blindfolded and are then asked to return directly to the origin (Loomis et al., 1993; Klatzky et al., 1998). If this performance is only possible with survey knowledge, this is evidence for allocentric representations in human spatial memory. However, shortcutting tasks may not reveal as much about the nature of spatial reference frames as originally postulated. Ants and bees are among the many animals capable of novel shortcutting (Müller & Wehner, 1988; Cartwright & Collett, 1982; Lehrer & Collett, 1994). While it is possible animals with such limited cognitive capacities represent comprehensive allocentric maps of their environment, researchers generally interpret their success as evidence of path integration, also called spatial updating.

When an ant leaves its home to forage for food, path integration allows the animal to remember the location of its nest as a homing vector from its current position to the nest (Collett, Collett, & Wehner, 1999). With each movement, this homing vector is updated by adding the new movement vector to the old homing vector. This process therefore provides accurate distance and direction information to guide the ant back to the nest regardless of where its travels take it. While shortcutting may be a sign of an allocentric reference frame, it can just as easily be interpreted as evidence of path integration which can operate over any reference frame (Wang, 2012).
Additional evidence of an allocentric spatial representation comes hippocampal place cells (O’Keefe & Nadel, 1978; Burgess, Jeffery, & O’Keefe, 1999). These place cells respond when an animal is in a particular location of space regardless of their body position. This activation is interpreted as evidence of the physical instantiation of a cognitive map. Place cells may therefore encode static map-like representations of the environment regardless of the individual’s position suggesting an allocentric reference frame with neither reference point or direction based on self position (such as in figure 1.4).

However, these cells do not simply represent an enduring, allocentric representation. A cognitive map should statically and enduringly represent space while not changing based on the observer however, these place cells can shift as the animal moves (Wang, 2003). Therefore these place cells may be encoding relationships between distances and locations of the environment egocentrically (Wang, 2012) since the hippocampus is important in relational learning (Eichenbaum & Cohen, 1988). This alternative interpretation means additional evidence is needed to fully understand how these place cells encode a reference frame in memory.

**Judgment of Relative Direction Task**

The judgment of relative direction task (JRD) is a widely used task that assesses spatial representation based on imagined perspective taking (e.g., Shelton & McNamara, 1997; Shelton & McNamara, 2001; Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998). Participants memorize a scene from one or more viewpoints. During test, they are then asked to make pointing responses from imagined headings. Some of these directions align with the studied viewpoint while others are novel. In order to identify the
imagined heading, instructions are used such as “Imagine standing at X looking at Y, point to Z”. Response time and accuracy are used to measure performance of taking particular headings.

If pointing responses are fast and accurate, then the imagined heading is thought to be encoded in the spatial representation. Slower and/or more error prone responses suggest the imagined heading required a transformation. When participants are asked to perform a heading rotation, their performance is a function of the amount of rotation required (Rieser, 1989; Easton & Sholl, 1995). Therefore, the JRD task relies on the idea that this transformational cost must occur when responding to a perspective that is not represented in memory.

Additionally, the JRD task is often assumed to require object-to-object relationships (McNamara, 2003; Mou & McNamara, 2002). JRD responses consist of the location of one object relative to another object. Object locations represented relative to a specific reference point, such as the self or an external environmental point will require a transformation for response in this task while object-to-object encodings can be directly retrieved from memory. An alternative explanation however is possible. Spatial translations, which are an imagined shift in position while maintaining the same heading direction, show little processing cost in in response time and errors (Rieser, 1989; Easton & Sholl, 1995; see May, 2004 and Wang, 2005 for more careful control of a translation task with larger effects). Therefore translating from a reference point encoding to another will not substantially affect pointing responses and the JRD task alone cannot test which reference point is used in spatial memory.
Reference direction, however, is testable through the JRD task. Experienced viewpoints almost always exhibit better performance than other perspectives (Shelton & McNamara, 1997; Shelton & McNamara, 2001; Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998; Shelton & Yamamoto, 2009). When individuals view a scene from a single perspective, they make JRD pointing responses quicker and with less error to imagined headings parallel to the learned reference direction. This orientation dependent response suggests that the spatial scene is not represented equally well from all orientations. Furthermore, this finding suggests that the default reference direction in spatial memory is egocentric.

However, not all egocentric viewpoints are equal. When participants viewed the space from two different perspectives, one that aligned with the floor and mat (0˚) and the other misaligned (135˚) and were then asked to make relative judgments of direction, their error was lowest when their imagined heading was parallel to that of the aligned orientation regardless of the order the two perspectives were viewed. However, when the aligned and misaligned perspectives were viewed individually, imagined headings to the egocentric experience won out (Shelton & McNamara, 2001; experiment 2). Therefore, Shelton & McNamara conclude that while egocentric experience may drive reference frame encoding, the aligned reference direction can replace a ‘bad’, misaligned egocentric reference direction with a better, aligned egocentric reference direction.

Beyond the viewed perspective, imagined headings at 90˚ rotations from the viewed perspective (90˚, 180˚, and -90˚ in addition to 0˚) often also show performance advantages on par with the viewed reference direction (Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998; McNamara, Rump, & Werner, 2003). This better
performance for aligned vs. misaligned imagined perspectives produces a saw-tooth pattern of performance. This pattern is taken as evidence that the aligned perspectives are also encoded in the representation and that this structure comes from the array itself, an intrinsic reference frame (Mou & McNamara, 2002; McNamara, 2003).

As a further test of how dominate this intrinsic representation is, participants were asked to study and encode a perspective they never actually saw, an imagined heading outside of their own egocentric view. Their results showed the characteristic saw-tooth pattern at the instructed reference direction and showed no evidence of encoding the egocentric reference direction at all. With this evidence, Mou & McNamara (2002) conclude that the intrinsic reference direction is the default in spatial memory. Egocentric reference directions are then the first of many possible influences, such as room geometry, array configuration, and instructions, on final reference frame encoding.

The evidence for self-based reference directions in the JRD task has shifted over time. Early evidence suggested that egocentric experience guides reference direction selection. Further research suggested that within egocentric experience, views that were aligned with an object array were preferred in spatial memory while misaligned angles are discarded. Finally, instructed directions outside of the self seem to be represented in spatial memory with no trace of the self-perspective at all. Therefore, findings from the JRD task suggest intrinsic reference directions dominate over the egocentric experience.

**Single or Multiple Representations**

Theoretically, multiple spatial reference frames can exist simultaneously in memory. In fact many theories posit an egocentric system for navigation and an allocentric representation for object-to-object relationship encoding (Burgess, 2006;
Easton & Sholl, 1995; Rieser, 1998). Alternatively, spatial memory may include only a single spatial representation for all tasks. When spatial information is needed in a different format, say object-to-object encoding for JRD judgments, the reference frame can be transformed into another format. In fact, one of the most difficult problems when testing reference frame use is that different reference frames are mathematically equivalent under many circumstances (May, 2004). A single representation that can be transformed into multiple formats would use less memory while two representations would use less processing power during a task. Either of these representations is possible resulting in different speed/storage tradeoffs.

Additionally, spatial representations may exist simultaneously due to transformations of a single encoded reference frame. When a long term reference frame in memory must be transformed, say an egocentric reference frame changed to an object-to-object pointing response for a JRD task, both the transformed and the encoded representations exist in memory during this pointing response. During this time, the more stable encoded representation may interfere with the less stable transformed version.

There is evidence for a similar type of interference in spatial memory. One theory for why imagined body rotations are difficult is that the egocentric pointing response interferes with the transformed imagined pointing response (May, 2004; Wang, 2005). Participants were positioned within the remembered array and then asked to take a different perspective either by a translation or rotation. Their physical body position interfered with the imagined pointing response resulting in slower and less accurate final responses. Similar interaction effects may occur during other spatial performance tasks.
such as between a remembered pointing response and a transformed imagined pointing response during a JRD task.

**Research Questions**

Researchers often disagree about what constitutes a specific reference frame sometimes while using the same terms. One of the goals of the following research is to more clearly discern reference point and direction use in spatial memory. Additionally, this research seeks to understand when self and external reference frames are used and how they interact in memory. If self-based representations exert a strong influence on other reference frames, self-based reference point and direction representations should occur as a default and influence task performance on any externally based representations. Alternatively, external or object based reference frames may be strongly represented in memory and bias self based reference frames. In pursuit of these goals, the following chapters test spatial reference direction and point use to better understand reference frame encoding in memory.

Chapter 2 proposes a new procedure based on signed error and an attraction analysis to uncover which reference directions are represented in memory. Generally, perspective taking tasks rely on the performance measures of response time and absolute pointing error to judge which orientations reside in spatial memory however superior performance may suggest preferential transformation as well as encoding. This new analysis assumes when a transformation is required, this transformed representation will compete with the stored representation so that final responses will be ‘attracted’ to the encoded representation.
Chapter 3 studies which reference direction is represented in memory and proposes a new method to determine if reference frame interactions lead to biases. Egocentric representations are sometimes considered a default reference direction (Shelton & McNamara, 1997; Shelton & McNamara, 2001; Shelton & Yamamoto, 2009), however there is evidence that this egocentric reference direction need not be encoded in spatial memory when participants are instructed to remember an alternative reference direction (Mou & McNamara, 2002; Chapter 2). To begin, a new method for classifying encoded response direction is proposed on the basis of signed error responses. When reference direction is held constant, signed errors will cluster around an instructed reference direction, which may be encoded or transformed, with some spread due to random noise. Therefore this distribution of errors was used to classify which reference direction was encoded within memory and if more individuals use self-based or object-based reference directions. Furthermore, signed errors show systematic bias of a reference direction. Therefore, if either a self or intrinsic based reference direction biases the final representation, those correctly representing an instructed perspective will show systematic shifts in their signed error distributions. Therefore this new analysis can both confirm that participants are representing a particular perspective and reveal if a perspective influences the encoding of others.

Chapter 4 tests reference point selection in memory with a variant of May’s (2004) interference based approach. Much of reference frame research focuses on reference direction with little research to reference point selection. Studying reference point encoding is difficult because spatial translations to new a new imagined position elicit small or no costs on performance (Easton & Sholl, 1995; Rieser, 1989). Here the
disparity between two pointing responses is used as an indicator of reference point selection. This method can directly test reference point selection to both self and external based reference points and indirectly tests object-to-object encoding. Finally Chapter 5 draws conclusions with this new research in mind.
# Tables and Figures

## Table 1.1

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## Table 1.2: Spatial Language

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## Table 1.3: Intrinsic Model

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Table 1.4: Egocentric Updating Model

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Reference Point

Figure 1.1: Spatial Language Reference Direction

Spatial language defines reference frames on the basis of reference direction. The object above the apple is the diamond if defined based on the intrinsic reference frame, the oval if defined based on the absolute reference frame, and the heart can be above in a relative reference frame if a person lies down with their head towards the bottom of the apple.
CHAPTER 2: REFERENCE DIRECTION ATTRACTION ANALYSIS

Spatial representations in memory are generally inferred from performance on experimental tasks. The judgment of relative direction paradigm (JRD) tests spatial memory first by asking individuals to remember an array of objects from a particular perspective (Shelton & McNamara, 1997; Shelton & McNamara, 2001; Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998; Rieser, 1989; Simons & Wang, 1998; Waller & Hodgson, 2006; Waller, Montello, Richardson, & Hegarty, 2002; Wang, 2007). The observer is then tested with a series of relative judgments where she takes an imagined heading and judges the location of a remembered object. Generally, instructions such as “Imagine standing at X while facing Y, now point to Z” are used to indicate the imagined heading and target object for each test. A typical interpretation of JRD results is that good performance occurs because pointing locations at some imagined heading are directly retrievable from memory while poorer performance suffers because that imagined heading required a transformation which slowed response time and increased error in pointing.

The JRD task often produces a striking pattern of performance. When observers remember a regular array from a single perspective, certain angles seem privileged in their performance (Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998; McNamara, Rump, & Werner, 2003). In particular, when participants view the scene from an aligned

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perspective relative to the primary axis of the array of objects, they show relatively good performance for the aligned axis ($0^\circ$, $90^\circ$, $180^\circ$, $-90^\circ$) while performance from a misaligned heading ($45^\circ$, $135^\circ$, $-135^\circ$, $-45^\circ$) results in poorer performance. This saw-tooth pattern of performance is usually taken as evidence that all four aligned perspectives are encoded in spatial memory while the misaligned require a transformation for response.

This chapter proposes a new logic for understanding these performance differences. Good performance for a given reference direction is generally interpreted as an encoded representation but what if there is little transformational errors for these privileged imagined perspectives? If transformations to aligned perspectives add little or no response time and/or error to responses, two or possibly even a single heading may exist in memory.

Spatial transformations can differ in their difficulty and some transformations are known to add little cost to responses. For example, imagined body rotations are considerably harder than imagined body translations (Easton & Sholl, 1995; May, 2004; Presson & Montello, 1994; Rieser, 1989; Wang, 2003). That is, if you imagine standing on a clock at the 6 looking at the 12, if you are asked to imagine standing still but turning to face the 3, your response will be more error prone and slower than imagining a move to the 3 while still facing the same direction. Additionally, under certain circumstances, these mental translations do not affect performance. When participants maintain their heading and mentally shift their location to another position that is equidistant from the observer’s actual position, this shift does not hinder performance (Rieser, 1989; Easton & Sholl, 1995). Therefore fast and accurate performance on a task may occur due to an encoding advantage or a preferential transformation advantage.
Using performance differences alone to infer a mental representation can over- or underspecify exactly what is encoded in memory. If performance at a novel perspective equals performance at the viewed perspective both headings are thought to be represented in memory. However if performance advantages result from easy transformations as well as encoding, only one heading may exist in memory with the other benefits from an easy transformation. Furthermore, a viewpoint independent representation may exist where all perspectives are encoded and performance advantages do not relate to the underlying spatial representation at all. Therefore another method of assessing spatial encoding is needed to better understand how performance relates to spatial representation.

Here we develop a novel method based on a competition model inspired by work in biases in spatial memory (Huttenlocher, Hedges, & Duncan, 1991; Sampaio & Wang, 2009) and interference that occurs during angular disparity (May, 2004; Presson, 1982; Wang, 2003, 2005). This model assumes that if using the encoded representation can solve the given task, it will be directly retrieved and used resulting in little or no error. However, if this is not possible, the encoded representation will be transformed for the task. The persistent encoded representation, still active after the transformation, may attract the transformed response towards the encoded while the transient transformed response will not attract subsequent responses. This model can distinguish between encoded representations, which will show an attraction pattern and a performance benefit, and those that are privileged transformations, which will show a performance advantage with no attraction pattern.

An example of this attraction analysis, figure 2.1a, depicts two possible test trials. Say a participant encoded a given target at -50° from the reference object when facing the
encoded direction. During test, she is asked to respond from a larger (more positive) orientation as depicted in Test 1 where the correct response would be -95°. However, if these two representations compete, a compromise angle might be chosen, say -70°. This would result in a positive signed error (bias) of 25° ([-70°] – [-95°] = 25°) for Test 1. Alternatively, some test trials ask for a response from a smaller (more negative) orientation as in Test 2, where a correct response would be -35°. Here another compromise could be made between these two values, say -45°. This trial would result in a negative signed error of -10° ([-45°] – [-35°] = -10°). Therefore responses from larger than the encoded orientation should exhibit a positive bias while smaller orientations than the encoded should exhibit negative bias.

This attraction pattern therefore should be centered at the encoded perspective. Imagined perspectives near the encoded perspective will show little bias since the maximum bias is the disparity between the two response angles (e.g. between -35 and -50° for example Test 2 in figure 2.1a). As angles move away from the encoded, if they are still biased, this disparity grows so the signed error should increase. In this way, the attraction analysis predicts a positive linear increase in signed error with zero error around the encoded perspective.

In order to do this, we asked participants to encode a perspective outside their own viewpoint similar to experiments performed by Mou & McNamara (2002). To conclude which orientations were encoded and which showed transformational advantages, we used the attraction analysis to test which of four different spatial representations exists in memory (figure 2.1b). First, all four aligned axis may be represented in spatial memory, as is traditionally concluded. Second, the main axis (both
0° and 180°), are encoded with the perpendicular axis benefiting from transformational ease. Third, a single perspective, 0°, may be encoded with all other performance benefits coming from preferential transformations. Finally, a viewpoint independent representation may exist where no attraction pattern exists suggesting all performance benefits come from transformational advantages.

**Experiment 1: Small Encoding Shift**

**Methods**

**Participants**

Twenty-five undergraduates from the University of Illinois completed the study for course credit.

**Apparatus**

Seven unique and easily identifiable objects were used and arranged in a regular array. The array configuration was constructed to match the display used by Mou & McNamara (2002). The long axis of the rectangular mat (1.8 m x 1.1 m), the long axis of the testing room (6.7 m x 4.3 m), as well as they symmetry of the object array all aligned. Participants were seated approximately 1.5 m away from the center of the mat at a -45° angle (see figure 2.2a).

**Procedure**

All participants completed a study phase followed by a testing phase. During the study phase, participants were led to a viewing chair with their eyes closed. All participants viewed the study array from a single perspective. Participants were seated -
45° from the primary axis (figure 2.2a) but were instructed to remember the objects from an imagined perspective (represented by the red arrow). An empty chair was placed at this instructed 0° heading to help understand the imagined heading. The room, mat, and array symmetry provided strong cues towards an intrinsic encoding.

Participants studied the array in 30s intervals with additional 30s study intervals given as needed. To ensure individuals correctly remembered the configuration of objects they were quickly tested after study. This was accomplished by having individuals point to each object in their own order as if the array was within reach and directly in front of them. They displayed their knowledge by pointing to objects in their configuration. The experimenter assessed visually their knowledge of each object’s location in its appropriate configuration. Additionally, individuals needed to align the primary axis of the array with their body to indicate that they had followed the instructed heading shift. Additional study time was given as needed until these criteria were met. After memorizing the array, participants were led back out of the study room with their eyes closed and to a computer where they completed the perspective taking task.

Each participant completed 160 judgments of relative direction trials. Participants encountered a screen with three words representing objects in the remembered display (figure 2.3). The center word indicated the object the individual should imagine standing at. The name directly above indicated the facing object. These two objects therefore set up the imagined heading. Finally a third name orbited the center name with movement of the computer mouse. During a trial, participants moved this name to indicate their relative pointing response. Both response direction and response time were recorded once the mouse was clicked. To create a trial, a reference object (center) was first selected
from the seven remembered objects. Next, the facing object (top) was selected from the remaining objects followed by the pointing object (orbiting). This method created sixteen different imagined perspective directions.

Finally, participants drew a map of the remembered array. Final maps were judged based on the configuration of objects represented accurately. They additionally needed to align the long axis of the array with the facing direction of the participant. Both of these criteria were used to assess a participant’s memory for the array itself as well as their adherence to the instructed reference direction.

**Data Analysis**

All participants were first screened for inclusion based on their final map performance. All participants met these criteria and were included.

Participants were evaluated in two ways. Firstly, the traditional performance based analyses were run to replicate the JRD “saw-tooth” aligned direction advantage for RT and absolute angular error.

Secondly, signed error (response angle minus correct angle) was assessed at each of four imagined headings, 0, 90, -90, and 180. In order to see these attraction patterns, four linear regression analyses were run, one for each possible encoded aligned axis, 0°, 90°, -90°, and 180°. Each analysis was based on one of the aligned perspectives and included ±45°. Testing 180° occurred from 135° through 225° by recoding -135° through -180°.
Results

Trials with absolute error above 90° were excluded as mistakes (462 trials - 12% of all trials). Absolute angular error and response time followed the saw-tooth pattern as found in previous studies (Mou & McNamara, 2002; see figure 2.4). Response time was lower for aligned (M = 11s, SE = .61) than misaligned (M = 13.3s, SE = .88) perspectives (paired t(24) = 4.4, p < .001) and the same pattern held true for absolute angular error (aligned M = 15.7°, SE = 2.5; misaligned M = 26.4°, SE = 2.2) (paired t(24) = 7.2, p < .001). From these results then, it appears there are four preferred headings in memory.

The attraction analysis found only one significant correlation centered at 0° (r = .55, p < .001) but not around any other axis that showed a performance advantage (90°, -90°, 180°) (rs < .11, ps > .27). Therefore while four angles show a performance advantage, only the instructed perspective attracts nearby responses. This finding suggests that only a single heading is encoded in memory with transformational advantages for the other three aligned axes.

Conclusion

This experiment replicated Mou & McNamara’s (2002) response time and absolute angular error saw-tooth pattern for an imagined encoded perspective. This saw-tooth pattern suggests that four different axes were encoded in spatial memory however, our attraction analysis found evidence for only one attraction pattern. This systematic attraction suggests only the instructed imagined perspective (0°) during encoding was stored in memory. All other aligned axes showed performance benefits due to a transformational advantage.
Experiment 2: Large Encoding Shift

As a further test of this finding we asked participants to imagine a larger perspective shift during the memory portion of the task. This larger shift should be more difficult to encode but once remembered correctly, signed angular errors should show the same attraction pattern as in experiment 1. If however, this more difficult encoding changes the spatial representation of the array, the attraction analysis may center around different or multiple headings.

Methods

Participants

Twenty-four new University of Illinois undergraduates completed the study for course credit. Two additional participants were excluded from the analysis due to incorrect post-test maps.

Apparatus

The study array was exactly the same as in experiment 1 however the individual’s seating position was positioned 135˚ from the 0˚ ‘front’ of the array (figure 2.2b).

Procedure

Participants followed exactly the same procedure as in experiment 1 although they were asked to imagine themselves at the 135˚ counter-clockwise position. Before moving on to the computer task, participants needed to correctly indicate the position of the objects from the imagined perspective as if they aligned their body with the instructed 0˚ imagined heading.
**Data Analysis**

Data was analyzed using the same procedure as in experiment 1.

**Results**

Responses were faster for aligned (M = 11.5s, SE = .65) (figure 2.5) than for misaligned judgments (M = 13s, SE = .74) (paired t(23) = 2.95, p = .007). Similarly, absolute angular error was higher for aligned (M = 16.1°, SE = 2.3) than for misaligned judgments (M = 28.3°, SE = 2.1) (paired t(23) = 9.3, p < .001). Even this more extreme imagined heading produced the typical “saw-toothed” pattern of performance with aligned judgments performing better than misaligned.

Additionally, the signed error analysis found a significant correlation only for the instructed 0° heading (r = .33, p = .004) but not around any other axis that showed a performance advantage (90°, -90°, 180°) (rs < .19, ps > .11) suggesting only the instructed heading was encoded in memory.

**Conclusion**

Participants were able to correctly remember the extreme 135° imagined perspective shift during encoding. Just as before, the performance data suggests all four aligned axis are represented in spatial memory however, the attraction analysis finds that only a single perspective is remembered which suggests that the other three are a result of transformational advantages.

**Discussion**

Perspective taking performance is often used to uncover a spatial representation’s structure. Better performance is generally taken as a sign that a perspective is encoded
with poorer performance a signal of mental transformations. Here we present a novel attraction analysis that suggests performance cannot always identify representation. Specifically, better performance can arise when stored information is directly retrieved from memory, if transformations are fast and accurate, or both. A new attraction analysis method was used to discriminate between these two potential interpretations for both a small and large imagined perspective shift. Regardless of the shift size, participants encoded only a single perspective even though both speed and accuracy suggested four aligned perspectives were encoded. This new measure is also more sensitive than the original performance-based measure because it is able to distinguish between an encoding versus a transformational advantage. Overall these results suggest caution is necessary when inferring representations from performance data alone.

Both of these experiments resulted in a single stored reference direction in memory. However, there may be cases where multiple perspectives are stored due to instructions, non-overlapping external reference frames (such as the room, mat, and object’s intrinsic axes), or experience with different viewpoints. Changes in these conditions may lead to further understanding about when and under what conditions perspectives are chosen and used in spatial memory.

Exactly why the attraction patterns look the way they do is unclear. The attraction appears strongest around 45 degrees from the represented heading. One factor driving this effect is that the amount of pull cannot exceed the disparity between the encoded and transformed representation. Additionally, it is possible that after about 45 degrees the attraction itself loosens its pull on the final response. Why the attraction effect falls off at this point requires further study.
Additionally, exactly where the competition among representations occurs is unclear. The attraction could occur when the transformed representation is calculated, during response selection when both representations are active, or in both places. Further research is needed to study the time course of this interference.

Finally, the mechanism of the competition between the two reference frames is unclear from this data alone. It is possible that a weighted average of the two responses is used. If so, these responses should form a distribution with a single peak. Alternatively, this data could derive from some responses coming directly from the encoded representation and others from the transformed representation. Together these two would average to represent the attraction pattern seen here. Further work on the distribution analysis in chapter 3 can shed some light on this mechanism question.

Representational form is not always apparent from performance data. With this attraction analysis, responses from an encoded representation can be separated from those that exhibit transformation advantages. This new tool, therefore, gives a clearer view of how spatial memories are formed and used while challenge the traditional analysis and interpretation of perspective taking paradigms.
Figures

(a) Attraction analysis calculation and (b) predicted attraction pattern if all axes are encoded, one axes encoded, a single perspective encoded, or a view independent encoding from top to bottom.
Figure 2.2

Study viewpoint for both the (a) -45° and (b) 135° shift condition.
Figure 2.3

Response screen. For this trial, the participant is asked to imagine standing at the pot while facing the brush and ‘point’ to the basket.
Figure 2.4

Response time (a), absolute angular error (b) and signed angular error (c) analysis for the -45° shift encoding with standard error bars.
Figure 2.5

Response time (a), absolute error (b) and signed error (c) analysis for the 135° shift encoding. Error bars represent standard error.
Spatial locations are inherently relative. That is, a location only exists in relation to a reference frame which consists of a reference point and direction. A reference point specifies an origin while a reference direction denotes the conceptual north of a reference frame. With this representation, any location can be specified as a distance from the reference point and an angle off of the reference direction. Reference direction selection has generally been the focus of spatial memory research (Easton & Sholl, 1995; Klatzky, Loomis, Beall, Chance, & Golladge, 1998; McNamara, Rump, & Werner, 2003; Mou & McNamara, 2002; Presson & Montello, 1994; Rieser, 1989; Wang, 2005, 2012; Wang & Spelke, 2000, 2002). Reference directions are usually divided into two main categories, egocentric and allocentric. An egocentric reference direction is one based on the viewer while allocentric reference directions is based on any external direction.

One of the most commonly used tasks to test reference direction in spatial memory is the judgment of relative direction (JRD) task. Here, participants memorize a scene of objects from a particular perspective. They are then asked to take an imagined heading, such as “Imagine standing at A facing B”, and respond to a target, “point to C.” Changing imagined heading require shifts in body heading, a mental rotation which produces poorer performance as the angle of rotation increases (Reiser, 1989; Easton &

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Sholl, 1995). JRD task performance generally assume that imagined headings parallel to an encoded reference direction will have lower error and faster response times since they can be retrieved directly from memory. Imagined perspectives that are not encoded in memory however, must be mentally transformed which increases absolute angular error and response time. Therefore, by testing a variety of different imagined perspectives, JRD performance is taken as distinguishing between encoded and transformed headings.

Previous studies on perspective taking have suggested an egocentric reference direction is encoded as the default reference direction in the absence of other cues or influences in the environment (Shelton & McNamara, 1997; Shelton & McNamara, 2001). Shelton & McNamara (2001) showed participants an array of objects from one perspective, and then asked them to make imagined heading shifts during test. When a heading shift aligned with the experienced view, pointing performance was better than at other imagined headings. This performance advantage was interpreted as a single reference direction encoded in spatial memory from the egocentric viewpoint.

However, an egocentric reference direction does not always seem to be encoded in memory. Mou & McNamara (2002) instructed participants to remember an array from an imagined allocentric perspective. When tested, their performance was best for imagined headings that aligned with those of the instructed perspective. Furthermore, no performance advantage existed for the experienced, egocentric perspective suggesting this viewpoint was not encoded in memory. This evidence was taken as support that the array’s intrinsic properties drive reference direction selection with no influence from an egocentric perspective.
Additionally, reference frames do not always exist in isolation and are known to interact within spatial language and attention. When judging if one object is above another, multiple reference directions are active (Carlson-Radvansky & Irwin, 1993) and these interfere if a primed and response reference direction mismatch (Carlson-Radvansky & Jiang, 1998). Similarly, egocentric and intrinsic reference directions may compete producing a biased response. If an egocentric reference direction is obligatorily encoded in spatial memory, taking an allocentric reference directions may be possible but with an influence of the egocentric perspective. To test this possibility, we developed a new distribution analysis that looks at bias instead of performance to see an effect of competing reference directions.

This new paradigm uses a modified JRD task. While typical JRD performance is interpreted by the retrieval-or-transform logic, performance on a given imagined heading may be better because it is encoded in memory, because certain transformations are easier than others, or because a transformed representation differs enough from the encoded representation such that they do not interfere with one another (chapter 2). Therefore, response time and absolute angular error can highlight differences between imagined headings but will not show any systematic shifts in pointing bias. Signed error, on the other hand, can show systematic bias in pointing responses such as those between an encoded and transformed representation. This bias can occur in two ways. Firstly, individuals may fail to represent the instructed heading and instead fall back on the stronger encoded perspective. Secondly, signed errors for those individuals who do take the instructed heading may be biased towards the competing perspective. Importantly, signed errors still cannot tell where this competition occurs as it may occur during
encoding of a spatial memory, response calculation, or response selection. This procedure can suggest which reference directions compete and bias other responses thereby highlighting which reference directions are encoded in spatial memory.

We used a modified judgment of relative direction task to classify individuals as taking an intrinsic, an egocentric, or an alternative reference direction and compared the number of individuals who accurately took the instructed heading across an egocentric instruction and an intrinsic instruction condition similar to Mou & McNamara (2002). If competition for a particular heading is low, more individuals’ signed angular errors should cluster around the instructed perspective. Higher competition may work in two ways. If an egocentric reference direction is more influential, allocentric headings should be biased towards the egocentric perspective. This bias can take the form of more individuals representing the egocentric heading and/or allocentric imagined headings showing systematic bias towards the egocentric perspective. If on the other hand an intrinsic reference direction strongly influences a pointing response, more individuals should respond with an intrinsic direction when instructed to remember the array egocentrically and those who do remember the scene egocentrically should be biased towards the intrinsic direction.

**Experiment 3: Random Array**

**Methods**

**Participants**

Fifty University of Illinois undergraduates completed the task for course credit. These included 21 males and 29 females.
**Stimuli**

Participants viewed the task on a desktop 17-inch display. For each trial, they viewed a virtual scene of four colored pegs (red, blue, yellow, and white) on a light gray floor surrounded by a cyan background. These pegs were placed at random locations on the rectangular floor for each trial. All participants viewed the array from a 45˚ offset of the intrinsic array of the floor and 30˚ above the floor plane. During study, participants could move their perspective 5˚ by moving the mouse right and left (clockwise or counter clockwise shift) or up and down (vertical shift). This slight variation in viewing angle allowed participants a greater view of the depth of the scene and allowed better viewing of any overlapping pegs.

During test, participants viewed a display with two dots. A central dot (the red dot in figure 3.1c) told participants where to imagine standing while a rotating outer dot (yellow) allowed a pointing response by moving the mouse. The color of the dots corresponded to the remembered peg identities. For all test trials, imagined heading was held constant depending on the participant’s instruction condition.

**Design**

All participants viewed this scene from an oblique 45˚ angle from the primary axis of the floor. Twenty-five participants were instructed to remember the scene from their current viewpoint, the *Self* condition (figure 3.1a, blue). The other twenty-five were instructed to remember the display as if they were viewing the array from an imagined intrinsic reference direction, the *Floor-axis* condition (figure 3.1a, red). During response, the top of the response screen (front on figure 3.1c) always corresponded to the
appropriate front during study (figure 3.1a blue for self and red for floor-axis). In this way, the response screen acted like a map for a pointing response.

**Procedure**

Each trial consisted of a study display, a brief retention period and a test display. A trial consisted of a seven second study display, a 500 ms retention blank screen followed by a test display which continued until a subject responded. This test display consisted of a single judgment of relative direction pointing response of two randomly selected pegs. After responding, the next trial began. Every twenty trials participants could take a self-paced break before beginning another trial block. Subjects completed nine blocks of twenty trials for a total of 180 trials or less if they took longer than 45 minutes to complete the test.

**Data Analysis**

For each trial signed error was calculated by subtracting the correct angle from the response angle. Negative error means participants responded in a counterclockwise direction while positive error means they responded farther clockwise than the correct answer. If participants were accurately representing the instructed reference direction, signed errors across all the trials should be centered around the instructed heading with about equal negative and positive error. Any deviation from the instructed perspective would create a biased distribution. That is if an egocentric perspective interacted with the intrinsic perspective, these responses should show a negative bias. If however the floor-axis reference direction interferes with egocentric perspective taking they should show a positive bias. With this analysis, it is possible to see how reference directions interfere in spatial memory.
However, individual differences may offer an alternative explanation. Individuals may differ in their spatial learning and perspective taking abilities (Hegarty & Waller, 2004; Wolbers & Hegarty, 2010). Some individuals may be unable or unwilling to take the instructed reference direction. These individuals might inadvertently bias the group data but not for the reason mentioned above. Therefore, we preformed an individual analysis to identify these individuals from the bias analysis.

For each subject, signed error was plotted as a histogram with a kernel curve fit to the data. Kernel curves provide a smooth curve based on the data while making no normality assumptions. Each of these curves was categorized based on the peak of the distribution. To make this classification, categories were defined in 45° segments (figure 3.2. Almost all individuals were classified as egocentric for those distributed around the experienced viewpoint or intrinsic for those centered around the heading parallel to the long axis of the virtual floor. A very few individuals were classified as taking the secondary intrinsic for those parallel to the short axis of the virtual floor or other perspectives. For both the intrinsic and egocentric instruction condition, 0° corresponds to the instructed heading so the egocentric instruction group categories were defined as egocentric from -22.5° to 22.5°, intrinsic from 22.5° to 67.5°, and secondary intrinsic from -22.5° to -67.5°. The intrinsic instruction condition was categorized either as intrinsic from -22.5° to 22.5°, egocentric from -22.5° to -67.5°, or secondary intrinsic from -67.5° to -112.5°. Two independent raters selected which category the peak of the kernel curve fit into.
To assess if the number of individuals unable to take the instructed perspective was significant, a test of equal proportion was run comparing the proportion of participants who were classified as correctly following the instructions across condition. Finally, all participants categorized as taking the incorrect perspective for each condition were removed. All other participants were included in an overall bias analysis where mean signed error for each subject was tested with a one-sample t-test to see if any systematic bias existed.

**Results**

Not all participants completed all 180 trials due to time constraints. Individuals ranged from 124 to 180 trials with a mean of 176 for the Floor-axis condition and 175 for the Self condition. However, since each trial was randomly created, all trials completed by participants were used. Trials with over 90° absolute error were removed from further analysis as incorrect trials. This removed 13% of the Floor-axis trials and 10% of Self trials.

When participants were asked to imagine an intrinsic reference direction, seventeen participants (68%) were classified as representing the instructed intrinsic heading while seven (17%) represented the egocentric heading and one (4%) was categorized as taking the secondary intrinsic heading (see figure 3.3a). When participants were asked to take an egocentric reference direction, twenty-three (92%) participants were categorized as taking the instructed egocentric heading while one (4%) responded with an intrinsic heading and one (4%) represented the secondary intrinsic heading (see figure 3.3b). The difference in the proportion of individuals who correctly complied with the instructions was significant ($z = -2.2$, $p = .03$) where the intrinsic reference direction
was followed significantly less often than the egocentric reference direction. Both raters independently rated each distribution and agreed on all individual’s classifications. Retaining only those classified as correctly following instructions for their condition, a one sample t-tests revealed that the intrinsic instruction condition contained a significant bias (mean = -8.9°; t(16) = -10.5, p < .001) while the egocentric instructions did not (mean = =-0.4°; t(22) = 0.34, p = .73) (see figure 3.4 a and b). 3

Conclusions

The Self instruction condition was followed significantly more often than Floor-axis instructions. Furthermore, if participants failed to follow the Floor-axis instructions, most took an egocentric reference direction. When those participants who did not or could not follow the correct instructions were removed, the remaining pointing responses were pulled towards the egocentric reference direction. No bias occurred in the egocentric instructions condition. Both the bias and significant difference in instruction following supports the theory that the Self reference direction automatically exerts an influence over the Floor-axis instructed perspective while the Floor-axis perspective does not interfere with the Self perspective taking.

However, this bias and lack of instruction adherence may stem from the stimuli themselves. The intrinsic axis of configuration of the pegs was not strong because the objects themselves were placed randomly on the floor. Therefore even though the floor and instructions provide a cue for the intrinsic reference direction, the array itself might

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3 Alternatively, the peak value of the kernel distribution could be used to assess bias. These peak values were found for each individual mathematically and submitted to a one-sample t-test. Here, the intrinsic instruction condition showed a significant shift towards the egocentric (mean = -8.06; t(16) = 7.8, p < .0001 ) while the egocentric condition showed no such shift (mean = .08; t (22)= .06, p = .95).
require strong regularity in order for people to represent an unbiased intrinsic reference direction. Experiment 4 tests this possibility by creating regular, symmetrical displays to see if intrinsic instruction following increased and the bias disappeared.

Experiment 4: Symmetrical Array

Methods

Participants

Fifty different (25 male, 25 female) University of Illinois undergraduate students completed the computer task for course credit.

Procedure

The procedure was identical as experiment 3 except for the placement of the pegs on the floor and which objects were possible during test. Two peg locations were selected at some distance from the center of the floor out to the floor’s edges. These two positions were then mirrored across the primary axis of the floor (figure 3.1b). This selection produced displays that were symmetrical along the primary axis but not along the secondary axis which produced an isosceles trapezoid which may simplify the memory task and make the intrinsic axis of the array itself more salient. Finally, this symmetry led to some pairs of objects to be superficially easy and therefore the two objects mirrored along the primary axis were excluded as possible test pairs.

Data Analysis

Individual histograms were classified exactly as in experiment 3 and the same bias analysis was completed.
Results

Individuals completed between 155 and 180 trials with a mean of 176 trials in the Floor-axis condition and 180 trials for the Self condition. Trials with over 90° absolute error were again removed as incorrect responses. This accounted for 12% of Floor-axis and 7% of Self condition.

Individual graphs can be found in figure 3.5a for the intrinsic instruction condition and 3.5b for the egocentric instruction condition. When instructed to take the intrinsic reference direction, sixteen (64%) responded with the correct intrinsic heading, seven (28%) responded with an egocentric heading, and two (8%) responded with a secondary intrinsic heading. In the egocentric instruction condition, twenty-one (84%) of participants represented the instructed egocentric heading while one (4%) took the intrinsic heading and three (12%) took a secondary intrinsic heading. The test for equal proportions of individuals who took the correctly instructed reference direction across condition was marginally significant ($z = -1.6, p = .1$). Both raters independently rated each individual’s distribution and fully agreed on each categorization.

Keeping only participants who correctly responded with the instructed perspective, the Floor-axis instruction condition still showed significant bias towards the Self heading (mean = -4.9°; $t(15) = -6.0, p < .001$) while the Self instruction condition showed no such bias (mean = 0.2°; $t(20) = .28, p = .78$) (see figure 3.4 C and D).

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4 A one-sample t-test on the kernel curve peaks again found a significant bias in the Floor-axis condition (mean = -2.5; $t(15) = -5.2, p = .0001$) while no significant difference was found in the Self condition (mean = 1.62; $t(20) = 1.77, p = .09$).
Conclusions

Accuracy in adhering to the instructions marginally differed in the two conditions when array symmetry was increased. However, the Floor-axis instruction group still showed significant bias towards the Self perspective. The Self instruction condition again showed no bias. Therefore, even with the more salient intrinsic reference frame provided by the array symmetry, the egocentric perspective biased responses in the intrinsic instruction condition.

Experiment 5: Bias in Real World Displays

From the previous two studies, there is evidence that bias is occurring in spatial memory towards the self. However, up until this point, this bias has only occurred in a simulated computer environment. The real world contains additional complexity not easily simulated. In particular, Mou & McNamara (2002) use a regular array aligned with a rectangular rug and room. With these overlapping reference frames, it may be possible that the intrinsic reference direction is strong enough to allow individuals to encode an allocentric representation with no bias towards the self. In this experiment, we used the Mou & McNamara (2002) array (see figure 3.6a) to see if bias occurs even in the strongest intrinsic real world scenario.

Methods

Participants

25 undergraduate students (9 male, 16 female) from the University of Illinois completed the study for course credit.

Procedure
Here, participants learned a real world array (figure 3.6a). After memorizing the object locations, they completed the modified JRD task where perspective direction was held constant to assess for bias.

Participants were first brought into the display room with their eyes closed. They were seated at a perspective -45° from the primary intrinsic axis of the room/rug/array to mirror the Floor-axis conditions of experiment 3 and 4 but with a real world display. They were then asked to remember all seven object locations as if they were at the Floor-axis direction (represented in figure 3.6a as the red arrow).

Participants were given as much time as they needed to remember all objects in the array. When ready, they closed their eyes. To test their knowledge, participants pointed in a small imaginary space in front of them to each object as if they could reach the objects and as if they were standing in the imagined location. If the participants made any mistakes more study time was given until accurate performance was possible. The experimenter judged accurate performance. Participants needed to demonstrate they knew the object locations the Floor-axis instructed direction and maintain the correct configuration of all seven objects.

After encoding the scene, participants were led from the room again with their eyes closed and taken to the computer task. Participants completed JRDs just as in the previous experiments however instead of using colors to denote different locations, object names were used (see figure 3.6b). All participants were instructed to remember the array from the intrinsic array axis direction (0°) while seated -45° from that position (see figure 3.6a) mirroring the Floor-axis instruction condition.
Data Analysis

The data analysis was performed as in the previous studies by first assessing instruction taking accuracy and then looking for bias in the errors of those correctly following instructions. Trials with error over 90° were removed as incorrect responses.

It is worth noting here that there are some differences between this and the previous studies. Unlike the random and symmetric studies, participants now relied on longer term knowledge of the array for the entire experiment rather than the relatively brief trial-by-trial memory used before. Additionally, there were far fewer unique trials due to the limited number of object locations remembered. JRD tasks usually vary the reference direction probed during test however the distribution analysis requires a large number of trials at the same reference direction. Therefore, reference direction was held constant and a single object was displayed to denote standing location with a pointing object circling it. This meant there were 42 unique trials which were randomly selected from for 160 trials. These constraints led to a fair amount of repetition throughout the testing task. Additionally answers were often 0°, 90°, -90°, and 180° due to the regular nature of the array. Either of these two changes might reduce or eliminate any bias observed for uninteresting reasons.

Results

22 out of 25 (88%) participants correctly took the instructed reference direction as judged by raters (see figure 3.7). Of those judged as incorrect, one responded with the secondary intrinsic axis while the other two respond with the 180° rotation of the instructed reference direction. These three individuals were removed from further
analysis. Generally participants did well in this task as compared with the previous intrinsic instruction conditions (68% for experiment 3 and 64% for experiment 4).

A one-sample t-test was run to assess bias in average subject response. The test showed a significant bias in response towards the self perspective\(^5\) (mean = -1.0\(^\circ\); t(21) = 2.9, p < .001).

**Conclusion**

When participants were asked to complete a real world version of the Floor-axis perspective taking task, responses showed a small but significant bias towards the self which replicates the computer tasks. Participants were overall excellent at this task most likely due to the repetition and consistency of the target trials. Furthermore, many of the trials given to participants resulted in 0\(^\circ\), 90\(^\circ\), -90\(^\circ\), and 180\(^\circ\) responses further simplifying the memory component of the task. These factors likely underestimated a true effect of bias because they make the task more easy and regular.

**Discussion**

When encoding a scene, a reference direction is needed to act as a relative ‘north’. Here we used a novel distribution and bias analysis to classify responses after a judgment of relative direction task. This method relies on interaction between multiple reference frames in spatial memory. If two reference frames compete, the more influential should bias any less influential representations.

\(^5\) A peak analysis was also completed on these data. Here, no significant bias was found towards the self (mean = -0.24; t(21) = 1.63; p = .118). The major benefit of the peak analysis is that it isn’t skewed by the tails of the distribution like a mean. In this case however participants are fairly accurate to begin with so removing the effect of the tails takes away the effect and may not accurately describe the data. The significant result from the mean analysis but not the peak analysis suggests that the bias is found in those tails.
Using a judgment of relative direction task, participants remembered the locations of objects from either their own egocentric perspective or an imagined intrinsic viewpoint. When object locations were randomly distributed, more individuals responded accurately in the egocentric instruction condition compared to the intrinsic instruction condition. Furthermore, those participants whose responses did peak correctly around the instructed intrinsic heading showed systematic bias towards the egocentric perspective. This systematic bias occurred even when the displays contained a stronger intrinsic reference frame through symmetry and when tested in the real world. This pattern of performance suggests that the self perspective exerts an automatic influence over an intrinsic representation. This occurs even in cases where overlapping allocentric reference frames strengthen the intrinsic representation.

Where this bias occurs is unclear. Individuals may encode only an egocentric reference direction in memory and transform to an instructed allocentric reference direction as needed. In this case, the bias may occur during transformation for a response. Alternatively, the instructions to remember the array from an intrinsic reference direction may have resulted in an intrinsic reference direction alone in memory which would mean the egocentric bias occurs during encoding. Further research is needed to test these possibilities.
Figures

**Figure 3.1**

The modified JRD task for both (a) the random peg locations from experiment 3, and (b) the symmetrical peg positions from experiment 4. Individuals in the Self instruction condition were instructed to remember the pegs along the blue arrow while the Floor-axis study group took the imagined heading indicated by the red arrow. Participants could shift their perspective a small amount during study. (a) and (b) show the extent of this shift. (c) Judgments of relative direction were made by consistently holding the ‘front’ constant while asking participants to imagine standing at the center peg (red) and point to the rotating dot (yellow).
Figure 3.2

*Figure 3.2*

*Categorization ranges for reference direction encoding.*
Figure 3.3
Individual participant’s signed error histograms and kernel curve fits for experiment 3 intrinsic instructions (a) and egocentric instructions (b) with categorization cut-off boundaries. Those outlined in red were judged by both independent raters as not following the specified instructions for their condition and were removed from further analysis.
Figure 3.3 (cont.)
Figure 3.4
Histogram and kernel curves for all participants excluding those who did not take the instructed reference direction for experiment 3 (random array) with (a) Self and (b) Floor-axis instructions as well as experiment 4 (symmetrical array) with (c) Self and (d) Floor-axis instruction conditions. A rightward shift in A and C would mean the egocentric shifting towards the array’s intrinsic perspective. For B and D, a leftward shift indicates an intrinsic perspective shifting towards the egocentric viewpoint.
Figure 3.5
Individual participant’s signed error histograms and kernel curve fits for experiment 4 (a) Floor-axis instructions and (b) Self instructions with categorization cut-off boundaries. Red boarders indicate individual’s judged as not following the instructions for their given condition by the raters.
Figure 3.5 (cont.)
Participants viewed the array from an off centered perspective but were asked to remember the scene as if they were facing the Floor-axis direction indicated by the red arrow. (b) When responding, participants were instructed to use their imagined perspective throughout the test. They then were asked to judge the relative direction of one object relative to the other. In this case they are asked to ‘point’ to the brush as if they were standing at the vase.
Figure 3.7
Individual participant’s signed error histograms and kernel curve fits for experiment 5 with those judged not following to instructions boxed in red.
CHAPTER 4: REFERENCE POINTS IN SPATIAL MEMORY

Locations are inherently relative and require a reference frame in memory. A cup on a table may be one meter from you, at the center of the table, or .25 meters from the plate. In each of these instances a different origin, also called a reference point, is used to define the location of the cup. A reference point can be the observer, often called an egocentric reference point, or one outside the self, an allocentric reference point. To fully specify a reference frame, a conceptual ‘north’ or a reference direction, is also needed.

Most research on reference frames focuses on which of these reference directions are used in spatial memory and under what circumstances. However, to fully understand how reference frames operate in memory, reference point selection requires further study.

Often reference frames in spatial memory are tested with the judgment of relative direction (JRD) task. Individual are asked remember a scene from a single perspective, imagine different headings, and then point to remembered objects. Lower response times and absolute pointing errors suggest an imagined heading is encoded in spatial memory however if performance is worse, a mental transformation is inferred.

The JRD task tests reference frames by imagined heading shifts that are changes in reference direction. Furthermore, shifts in reference direction are spatial rotations that elicit a cost as the imagined rotation increases (Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989). However, shifts of reference point are spatial translations, shifts forward, back, and side-to-side while facing the same direction. Spatial translations produce little to no performance costs when people imagine shifts to
equidistant locations around regular shape such as a circle or square (Rieser, 1989; Easton & Sholl, 1995). However, some translations do elicit a performance cost such as non-regular distance shifts (Easton & Sholl, 1995; May, 2004; Wang, 2005). Because JRD tasks often do not have equidistant object shifts, reference point could be studied with this task however typically object locations are close together meaning any translation cost would be minimal.

Generally the difference in difficulty between a mental rotation and mental translation is taken as evidence that mental rotations require individuals to mentally ‘turn’ their body to an instructed direction which are thought to be more costly to performance than mentally ‘moving’ while maintaining a heading. This transformational hypothesis comes from the object mental rotation literature where the amount of rotation drives the time a mental rotation takes (Cooper & Shepard, 1973). May (2004) however, used a different methodology to test weather these differences in performance were due to differences in transformations or if they were from an interaction during response selection. That is, the pointing response from the individual’s actual position may interfere with the imagined pointing angle required for the task. May theorized that if this interaction occurs, pointing performance should increase as the disparity between the imagined and real pointing direction increased (figure 4.1).

In a series of carefully controlled studies, individuals stood in the center of an array of objects and were asked to remember a set of objects and locations. They were then asked to take imagined translations, ‘imagine standing at location A’, or rotations, ‘imagine looking at location A’, and were then instructed to point to a remembered object. When they did, pointing errors and response times varied as a function of object disparity.
regardless of whether the instructed transformation was a rotation or translation. This object disparity effect supports the interaction account where individuals’ poorer performance comes not from difficulty imagining rotations but where physical pointing angle interacts with the transformed pointing angle.

May’s (2004) original experiment pitted an individual’s physical position with that of a mentally transformed representation. He found that performance costs came not from the difficulty of the transformation but because these two representations conflicted when individuals stood in the center of the remembered array during test. The following study extends this hypothesis and studies if this interference among different translations may also operate between a remembered reference frame and a response location.

While a typical JRD task is not ideal to test reference point selection, this chapter uses the disparity interaction paradigm with a modified JRD task to assess reference point encoding. Reference points and directions are theoretically separable (chapter 1) so it is possible people encode the scene relative to some external reference direction with an egocentric reference point or vice versa. To test this hypothesis we held reference direction constant throughout the following task so that any performance cost or advantage must be due to shifts of reference point alone. We then tested if object disparity from two possible reference point encodings explained pointing performance. When the encoded pointing response is similar to the imagined pointing response, little or no interaction should occur (such as figure 4.1b). However as the disparity increases, the interaction between the two angles should also increase (figure 4.1a). If interference occurs, response time and/or absolute pointing error should correlate with the disparity between the remembered and transformed pointing angle.
This procedure for identifying the reference point of a spatial reference frame makes specific predictions depending on which reference point is encoded in spatial memory. Potential reference points fall into three categories. First, a reference point can be egocentric, one that encodes all objects relative to the viewer’s position in space. Secondly, allocentric reference points are possible where all object locations are remembered relative to a landmark or position outside the viewer. This disparity interaction procedure can test any position, allo- or egocentric, as a possible reference point in memory.

The self reference point, positioned at the viewer’s virtual location in the scene, was tested using the disparity procedure along with an environment reference point. Because the virtual display was sparse in landmarks, the most likely other reference point was a location on the virtual floor. We chose to test the center of the floor as an additional possible reference point. While many other spatial locations are possible and testable, these two locations are the most likely options in this virtual environment.

Some researchers have suggested reference points are substantially different than those discussed above and that locations are stored as object-to-object relationships (Rieser, 1989; Easton & Sholl, 1995; McNamara, 2003; Mou & McNamara, 2002) Here, one object is remembered in relation to all other objects. A pure object-to-object relational encoding would posit a null effect for these experiments since object locations would be retrieved directly from memory with no translation shift and therefore no correlation with disparity. While this task cannot directly test object-to-object encoding, effects of disparity on performance would suggest some specific reference point is being
used in spatial memory even if object locations are also redundantly remembered in object-to-object relationships.

Experiment 6

Methods

Participants

Twenty-five University of Illinois undergraduate students completed the experiment for course credit.

Materials

Displays, sized approximately 30 degrees of visual angle, consisted of a computer generated rectangular floor with four pegs. All pegs were the same height, located randomly, and differed in color. These colors were used to identify pegs during the test displays so were important for participants to remember during study. Participants viewed this scene from -45° off the main axis of the floor and 30° above the floor plane (figure 4.2a). Furthermore, they could shift their perspective 5° side to side and vertically with the mouse which allowed participants to view partially obscured pegs as well as give more depth to the scene. Test arrays consisted of two colored circles representing two of the four pegs previously presented (figure 4.2c). Participants moved the outermost dot with the mouse to indicate the correct pointing response and clicked to record their response. Reference direction was held constant throughout the experiment and used the same instruction and method as the Floor-axis condition from Chapter 3.
Procedure

Participants studied the four pegs for seven seconds. All participants were instructed to remember the scene from an imagined 0° perspective. This imagined perspective shift during encoding dissociates the reference direction from the egocentric heading of the observer. The disparity interaction analysis does not require that participants imagine a reference direction outside themselves however, this separation may lead participants to encode the scene relative to an intrinsic or allocentric reference frame if possible. Chapter 3 and previous research (Shelton & McNamara, 1997; Shelton & McNamara, 2001; McNamara, 2003) suggest that egocentric encoding is a privileged spatial encoding. Therefore, we encouraged intrinsic representations to 1) see if no self or external reference point was encoded in spatial memory suggesting object-to-object encodings were used and 2) produce a situation where multiple encodings may occur to see if there is evidence for multiple representation encoding.

After learning each display, the participant completed a single test trial. During test they were asked to complete a modified judgment of relative direction task where the imagined reference direction always remained constant. The test display consisted of two items, a center dot, where participants imagined standing, and an outer dot which participants imagined pointing to. Participants were instructed to imagine facing the instructed 0° reference direction while standing at the center dot and point to the outer dot. Pointing occurred by moving this outer dot around an orbit and clicking when satisfied. Participants were instructed that distance did not matter while responding and only to respond as if they were pointing to the orbiting color peg.
Analysis

Only participants who were able to take the imagined perspective were included in the analysis. In order to determine this, each participant’s signed error was fitted with a kernel curve. A distribution’s peak and overall shape was evaluated as in chapter 3. Eight participants had signed errors either centered at their actual perspective (315°), showed a bimodal distribution around both the actual and imagined perspective, or a uniform distribution of errors. These participants were removed from further analysis leaving seventeen remaining participants.

For each trial, two disparities were calculated based on a reference point of self (figure 4.1a) and the center of the virtual floor (figure 4.1b). For both disparities two angles were calculated. Angle A reflects the angle from the reference direction to the target object at the encoded reference point. Angle B is the angle from the reference direction to the target object from the response reference object. For both self disparity and environment disparity, angle A is subtracted from angle B. A disparity of zero means both angles are the same and present no interaction in response. As this disparity increases however, larger interactions should occur for an encoded reference point.

The purpose of this analysis is to observe how response time and absolute pointing error change as these disparities increase. Therefore, for each participant two linear regressions were run, one on RT and the other absolute error. Both regressions included self and environment disparity as factors. The standardized coefficients for each factor were then used in a one-sample t-test. If either disparity predicts performance, the one sample t-test on that disparity will have a significant effect. Furthermore, if the self or environment disparity increase as absolute error and/or response time increases, then
that location is a possible reference point for the remembered scene. However, if objects are only encoded as object-to-object relationships, then neither response time nor absolute error should increase as disparity increases.

Results

Four one sample t-tests were performed to test weather the standardized coefficients from the linear regressions were significant. Tests were run for self disparity for both the RT and absolute error as well as the environment disparity for both RT and absolute error (figure 4.3). Self disparity did not significance increase as absolute error increase (t(24) = 1.51, p = .14) but it did increase as RT increased (t(24) = 4.58, p < .001). The reverse was true for environment disparity. Here as absolute error increase, so did environment disparity (t(24) = 2.876, p = .008) but this increase did not occur for RT (t(24) = 0.24, p = .81).

Conclusions

Response time increased as self disparity increased while increases were found in absolute error with increases in environment disparity increased. This provides evidence that both self and the environment reference object were encoded in memory as significant interactions were found for both possible reference points. While the two disparities acted on different measures, there is no a priori reason why disparity should affect accuracy or speed. It is possible that there is a reason why these two response points target one or the other response measures however equally likely is that these effects may appear in either absolute error or RT depending on the subject population and their speed/accuracy trade-off.
A pure object-to-object reference point encoding would predict neither of these interactions to appear. Therefore a strong claim that only object-to-object encodings occur in spatial memory cannot be true. However, it is possible that other reference points were found because the intrinsic reference frame was not strong enough given the sparse virtual environment presented. To strengthen the intrinsic reference frame, the following experiment increases the salience of the internal layout of objects by making the peg positions symmetrical across the primary axes of the floor. If object-to-object encodings only occur under these more salient environmental conditions we would expect the self and environment effects to disappear.

Experiment 7

Methods

Participants
Twenty-five new University of Illinois undergraduate students completed the experiment for course credit.

Materials
Participants completed the same task as experiment 6 except two peg locations were chosen at a random distance from the center of the rectangular floor along an oblique angle (figure 4.2b). These two pegs were then mirrored across the long axis of the floor resulting in a symmetrical array. For test, pairs of pegs were chosen at random excluding the mirrored pairs due to the trivial response required.

Procedure
The procedure was identical to experiment 6.
Data Analysis

Each participant’s signed errors were plotted and fit with a kernel curve. Using the same criteria as in Chapter 3, participants were excluded if they did not or could not take the imagined 0° perspective. Sixteen participants met this criterion for correct instruction following and were included in the further linear regression and one sample t-test analysis.

Results

As in experiment 6, RT increased as the disparity between the response and encoded angle increased with a reference point of self (t(24) = 2.43, p = .022) however no increase in absolute error was found (t(24) = 1.39, p = .17). As environment disparity increased, absolute error increased (t(24) = 4.06, p < .001). There was a marginal effect of RT with external disparity (t(24) = 1.83, p = .08) however this effect is opposite to the expected effect. That is as external disparity increases response time decreases with a marginal significance (see figure 4.3).

Conclusions

Changing the symmetry of the array did not substantially change performance. Even with a regular array, theoretically increasing the intrinsic reference frame of the array, disparity from the encoded representation and response angle increased for both the self and external reference point. This evidence suggests reference points other than object-to-object relationships exist even when the intrinsic reference direction is stronger.
Discussion

When encoding reference frames, a reference point and direction are needed to code spatial locations. While reference direction has received the vast majority of study, which reference point(s) are remembered in memory has not elicited much study. In two experiments, three possible reference point encodings were tested using an interaction paradigm that directly tested two potential reference points, the self and the center of the array and indirectly tested object-to-object relations that would predict no effect. Experiment 6 found evidence for both an egocentric and an external reference point. Experiment 7 presented a stronger array, intrinsic reference frame with symmetrical displays and again found evidence for both proposed reference points.

The strong model of only object-to-object relationships encoded in spatial memory cannot be true. If the participants had encoded each object’s relation to all other objects, responses should be directly recalled from memory resulting in no interaction effect between a stored and response representation. While these experiments cannot directly test if object-to-object encoding occurs, they do cast doubt on the necessity of this kind of representation since there is evidence for other encoded reference points. Two possible options exist given these findings. Spatial memory may encode object arrays in multiple ways with object-to-object encoding as well as reference frames with other reference points. Alternatively, egocentric and allocentric reference points alone may encode spatial relationships in memory with no need of object-to-object encoding. Future study is needed to directly test object-to-object encodings to fully explain reference point encoding.
These experiments found direct evidence for two different reference points within spatial memory when only one reference point is necessary. Mental translations in spatial task are generally precise and accurate compared to other spatial transformations such as object rotation. So why might spatial memory include both of these reference points? Egocentric reference points may be crucial to acting on the world. Picking up a cup on a table or navigating to a building requires viewer-centered coordinates. Even though there is a minimal cost to mental transformations required in converting between reference points, we may encode these viewer-centric reference points for use when acting in the world. If this is true, then finding the egocentric reference points here is particularly interesting. Participants in this task did not directly act on the objects they remembered from their own perspective as they were instructed to take the intrinsic reference direction throughout the test. Therefore, this finding might speak to an automatic encoding of an egocentric reference point regardless of final intent. Since we often encounter scenes before deciding what actions, if any, to take, this automatic encoding may be obligatory even in cases where participants knew ahead of time they would not act on their own viewpoint.

However, we also found evidence that we encode a scene with an environment reference point. One possible reason for this second encoding is that the environment influences the encoding of this reference point. Even in this sparse virtual world, environmental cues from the pegs and floor may influence the encoding of an external reference point. If true, a sparser environment may remove this reference point. However, it is also possible that regardless of the environment, some external reference point is encoded. In this case, spatial memory may encode a reference point for other use
such as identifying objects that may require understanding how multiple parts or objects relate to each other. Future studies will be required to fully understand what is and is not encoded in spatial memory as well as the full extent of the function of these representations.
A large (a) and small (b) object disparity. Object disparity was calculated as the difference between stored and imagined pointing response. In both cases, the blue location represents a possible encoded reference point, the yellow represents the imagined translation location during response, while the red dot represents the target object. In panel (a), the disparity between encoded pointing response a and calculated pointing response b is large while this disparity is smaller in panel (b).
Figure 4.2

Individuals studied an array of pegs located randomly (a, experiment 6) or symmetrically (b, experiment 7). Participants were instructed to remember the array as if viewing the scene from a perspective along the imagined black arrow. During study (c) individuals imagined standing at the center peg (red) while facing the constant ‘front’ of the scene. They then used an orbiting peg (yellow) to indicate pointing direction.
Figure 4.3

Mean coefficient values for absolute error and response time as a function of self and external disparity. Error bars represent standard error.
CHAPTER 5: CONCLUSIONS

In spatial memory, we use reference frames to represent and remember spatial locations. However the nature of this representation has been hotly debated. Information comes into the eyes egocentrically so a reasonable hypothesis is that reference frame use would be represented egocentrically. However, as with all other aspects of vision, the brain actively interprets the signal it receives so it is possible locations may be represented in a viewer-independent way. Introspectively, our spatial memory often seems like a stable map-like representation. Tolman (1948) wrote about a ‘mental map’ that guides the actions of humans and animals and this idea of a mental map seems intuitive. We can reason about objects and their relationship to other objects even when we are not near them. We don’t need to consciously include our own location when giving directions to someone. However, does our ability to complete tasks like these mean we must have a mental representation that is independent of our own location?

Some of the evidence Tolman considers for a mental map is an animal’s ability to shortcut. When rats escaped their mazes, they were able to follow a straight line on the roof of their maze to their food reward without any prior experience with this open space (Tolman, 1948). This certainly can be done with a map but does it require a map?

African ants traverse a very difficult and deadly environment. They must search long distances through the desert for food with the risk that too much time outside the nest means death. These ants are therefore motivated to find food and return home in the most efficient way possible given their mental constraints. Ants leave the nest and wander in a seemingly random path until they find a food source. On the return trip however, they walk directly home disregarding their original path (Müller & Wehner,
1988). This path integration ability has been taken as evidence that the ant is not directly representing its path but instead encoding and updating a vector (a distance and direction representation) directly home. The twists and turns the ant takes are not ultimately important. All the ant must do is return home in the most efficient way possible and this homing vector can accomplish this goal efficiently. Because shortcutting can be accomplished without a mental map, it alone isn’t sufficient to presume allocentric mental maps are required for human spatial representations. The sense that we have a ‘mental map’ might purely be an illusion and when forced to draw a map for directions, we transform an egocentric representation into an allocentric map view.

If allocentric map-like representations can be generated from egocentric mental models, what about performance on tasks? Research provided here tries to answer this question with three novel methods. When using a judgment of relative direction task (JRD), responses are attracted to an instructed reference direction (chapter 2). Previous research and those presented here does suggest that given time to encode, people can fairly accurately represent a location outside of themselves. In both a near and far instruction case, individuals were able to perform accurately and their responses were attracted to the instructed encoded reference direction.

However, if people are able to take a perspective other than their self location, are they doing so accurately? Chapter 3 presented experiments that challenged this idea. Even though participants largely took an instructed imagined perspective outside of their own viewpoint, they still showed bias towards the self-location while there was no bias towards an intrinsic viewpoint when participants were instructed to take their own perspective.
When these experiments were replicated in the real world task from chapter 2 using the bias analysis in chapter 3, again, participant’s responses biased towards their actual viewpoint even when instructed to ignore that self perspective. Even when overlapping reference frames strengthened the intrinsic axis of the scene responses were pulled by the self position. Additionally, this experiment makes clear that bias is not just an artifact of single trial study on a computer display since the finding was replicated when the participant’s were tested on a real world display with strong intrinsic cues.

Finally, chapter 4 found evidence for both self and environment based reference points. While only a single reference point is necessary it is possible our spatial system encodes multiple representations to quickly and accurately respond regardless of the task at hand.

This research suggests that the egocentric reference frame is the default in spatial memory. The egocentric perspective is so strong that it biases performance even when people are specifically instructed to take an intrinsic perspective and when no egocentric responses are needed. The nature of this default status however is unclear. Spatial tasks often require a direct action on the world. Because of this, the egocentric reference frame may always be encoded in memory because it provides the most accurate and fastest response for daily tasks. Alternatively, the egocentric perspective may be the default because spatial information enters the brain from an egocentric perspective.

When spatial transformations are required, the egocentric default may produce a biased allocentric or intrinsic reference frame due to an error-prone spatial transformation process. Alternatively, accurate representations of both egocentric and intrinsic reference frames may be stored in memory and compete during response. The current research
cannot distinguish between these possibilities and further research would be necessary to tease apart why we see this persistent self-bias.

Regardless of why spatial representations contain egocentric information when they do not need to, the implications are clear. When a person needs to complete a task that has no relationship to themselves, such as judging the distance between two buildings, or whether two cars on the street will hit each other, a person’s position will bias their performance. In normal daily life this bias may be insignificant because people are able to correct their actions due to visual feedback or the bias may be small compared to the precision required for correct task performance. However, there are some situations where this bias may be harmful. Driving a car down a highway leaves little time for responses and increases the risk of a wrong judgment if biased incorrectly. Additionally extreme jobs, such as firefighting, may require both accuracy in judgment and speed in execution while understanding the locations between hazards, such as in a burning building during a rescue.

In addition to understanding better how the human spatial memory system works, this research may aid technological advances. As technologies progress, computers are likely to take over more and more tasks for humans. Understanding the limitations and benefits of the human spatial system can guide technology development to aid, and not inhibit, a human’s inherent abilities. This research suggests humans could benefit from technology that assists during speeded or precision spatial tasks that require judgments outside their own perspective. This assistance appears less necessary when those same judgments involve the individual’s position. This knowledge can help engineers
prioritize their efforts to maximize the helpfulness of new technologies given time and cost constraints.
REFERENCES


