Online or offline? Exploring working memory constraints in spatial updating

by

Anthony Michael Harrison

B.S. Psychology, Drexel University, 1999

B.S. Information Systems, Drexel University, 1999

M.S. Psychology, University of Pittsburgh, 2004

Submitted to the Graduate Faculty of

College of Arts and Sciences in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2007

UNIVERSITY OF PITTSBURGH

College of Arts and Sciences

This dissertation was presented

by

Anthony Michael Harrison

It was defended on

September 14th, 2007

and approved by

Stephen Hirtle, PhD, College of Information Sciences

Erik D. Reichle, PhD, Department of Psychology

Walter Schneider, PhD, Department of Psychology

Dissertation Advisor: Christian D. Schunn, PhD, Department of Psychology

Online or offline? Exploring working memory constraints in spatial updating

Anthony M. Harrison, M.S.

University of Pittsburgh, 2007

All spatial representation theories rely upon two spatial updating processes in order to maintain spatially consistent self-to-object relationships: movement-driven, automatic online updating and offline, conscious mental transformations of perspective. Theoretical differentiation based on offline updating is difficult given the equivalent predictions for many of the spatial tasks commonly used (i.e. egocentric pointing). However, representational theories do diverge with respect to the predicted working memory constraints of online updating. In experiment one participants studied groups of 4, 6, & 8 targets, engaged in a 180º rotation on half the trials and completed a series of judgments of relative direction and egocentric pointing. Set size effects for both tasks were limited to latencies alone, suggesting offline updating. Experiment two had participants study smaller (3 target) configurations and make egocentric pointing responses. On half the trials, participants engaged in either a verbal or spatial 1-back task during both retention and rotation periods. No effect of dual-task load or type were found for egocentric pointing. Both latencies and errors were significantly greater for the post-rotation pointing suggesting offline updating. The lack of evidence for online updating is surprising and contrary to previous findings that it is an obligatory automatic process (e.g. Farrell & Thomson, 1998). Multiple models were developed within ACT-R/S (Harrison & Schunn, 2003) illustrating the sufficiency of offline updating to account for the current findings. The challenges of detecting online updating and investigating its working memory constraints are discussed in the light of these results and simulations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

While this is a document of my own work, obviously I could not have accomplished it without the help of many people. Thanks go out to Dr. Susan Chipman, formerly with ONR, for having funded the early theoretical work behind ACT-R/S. Dr. Christian Schunn also has my profound gratitude and appreciation for supporting me and this work; perhaps for longer than he should have. Dr. Dario Salvucii must also be acknowledged for allowing me to finish my work from out of his lab in Philadelphia. And finally, a heart felt thank you to all my friends who had to endure the early pilot studies of this research.

1.0 INTRODUCTION

As people interact with the environment around them, their spatial relationship to it is constantly changing. Few of us are ever prepared for the occasional nighttime power failure. In these situations we must navigate through rooms and around furniture in search of the flashlight. Some of us will inch along the walls, feeling our way; others will stumble through the dark, stubbing toes and tripping over pets. Those who are confident in their memory and spatial skills may attempt something different. They will actively track the remembered locations of objects in the room as they move, retrieving the flashlight with relatively few collisions. This tracking process is referred to as spatial updating and is a necessary component in all spatial reasoning theories.

A substantial amount of research has been devoted to trying to understand spatial updating processes. While the processes, their inputs, and facilitating or interfering effects are well documented, one line of research remains contentious: trying to determine *what* is actually being updated. Studies looking at changes in spatial representation have yielded mixed results; some show spatial updating operating on individual egocentric representations, others indicate that updating merely anchors the location of the viewer within a larger allocentric (i.e. object-centered) spatial representation.

In the past year, studies have been published that take a different approach towards this problem. If spatial updating operates on individual egocentric representations, it is almost certain that the process will be subject to working memory constraints (figure 1.1). It is computationally improbable and functionally unnecessary to update the representations of all the objects in one's environment. This line of inquiry has focused on uncovering set size effects in spatial updating (Hodgson & Waller, 2006; Wang et al., 2006). If updating processes work merely to anchor the viewer within a larger integrated allocentric representation of the environment, they should be insensitive to set size manipulations (figure 1.2). The presence of set size effects for updating errors would strongly support the theory that updating operates on individual egocentric representations. However, one need not look exclusively at set size effects, interference from concurrent spatial tasks should exhibit similar effects.

Exploring the working memory constraints in spatial updating faces another challenge in that there are two different forms of spatial updating. Spatial updating can be accomplished by either an automatic path-integration process as the individual moves through space (e.g. Mittelstaedt & Mittelstaedt, 1981; Rieser, 1989) or a conscious mental transformation of perspective (e.g. Rieser, 1989; Easton & Sholl, 1995). The working memory capacity limitations mentioned previously apply only to the automatic process, conscious mental transformations are only limited by long-term memory (Hodgson & Waller, 2006). This means that if experimental methodologies cannot differentiate between the two updating processes, mental transformations' lack of working memory limitations might be misinterpreted as evidence for allocentric updating.

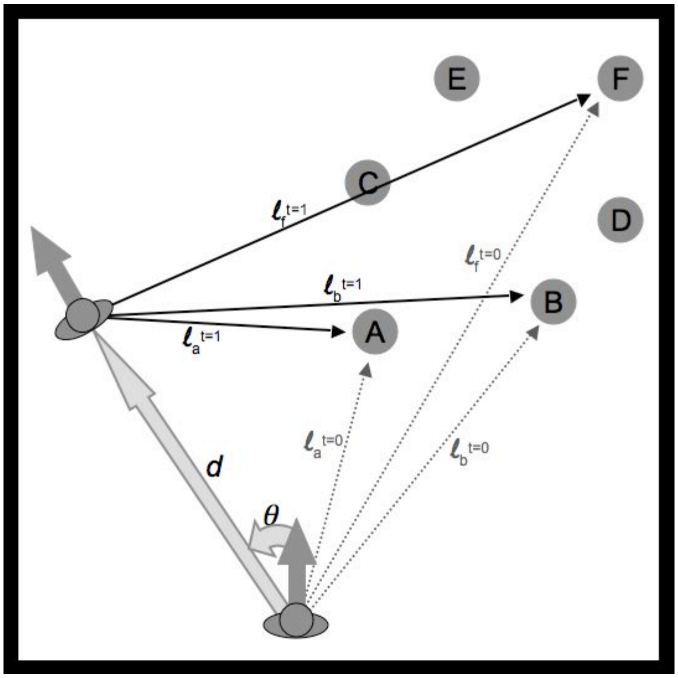


Figure 1.1 Egocentric with spatial updating's encoding of the space as egocentric vectors (ℓ) at one instance (t=0). As the subject rotates through θ and traverses across d, the egocentric vectors are updated to maintain spatial consistency, yielding a new set of egocentric vectors (t=1). In this example only the behaviorally significant objects (A,B & F) are encoded into capacity limited working memory.

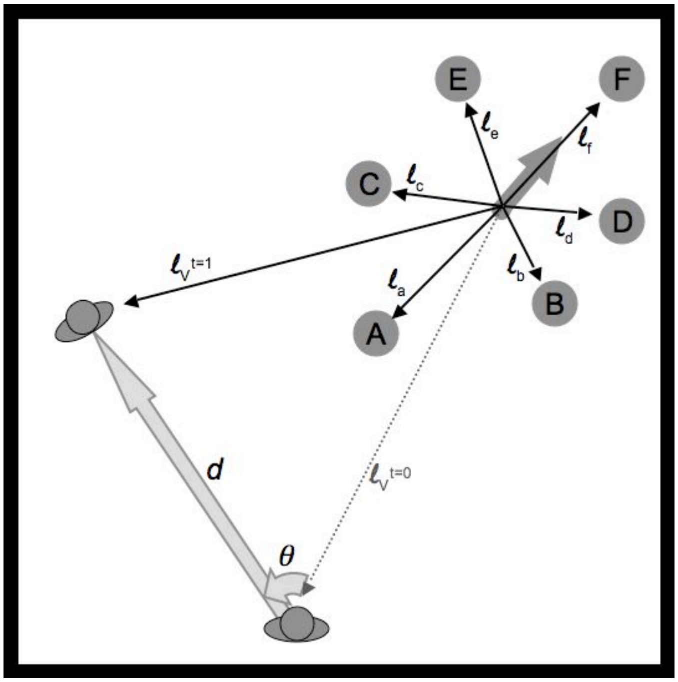


Figure 1.2 Cognitive-mapping allocentric encoding of the space. The centroid is defined as the mean of the egocentric vectors to the objects (omitted for clarity). The objects are then encoded relative to the centroid, with the reference direction (dark grey arrow) defined along the longitudinal axis of the configuration. The viewer's position within the map is represented as ℓ_V at t=0. As the viewer moves through the environment only their position relative to the centroid is updated (ℓ_V at t=1).

1.1 PREVIOUS RESEARCH

Spatial updating is performed by two separate but very similar functions: path-integration (May & Klatzky, 2000; Mittelstaedt & Mittelstaedt, 1980) and conscious mental transformations (Wraga, 2003; Wraga, Creem-Regehr, & Proffitt, 2004). Path-integration is driven primarily by idiothetic inputs (proprioceptive, vestibular, and motor efferent-copies), but does receive limited support from the experience of optic flow (Klatzky, Loomis, Beall, Chance, & Golledge, 1998), and is automatic in the obligatory sense (Farrell & Thomson, 1998; Klatzky et al., 1998; Waller, Montello, Richardson, & Hegarty, 2002). While research on mental spatial transformations has a long history dating back to the early work of Shepard & Metzler (1971), the concern here is with mental transformations of perspective, which seems to show slightly different chronometric profiles (Hegarty & Waller, 2004; Wraga, Creem, & Proffitt, 1999, 2000). The preponderance of evidence shows that mental transformations of perspective come in two flavors: rotational and translational. Both of which show chronometric profiles that depend upon the angular or linear disparity between source and target (Creem, Wraga, & Proffitt, 2001; Easton & Sholl, 1995; Farrell & Robertson, 1998; Farrell & Thomson, 1998; Jola & Mast, 2005; May, 2004; Nori, Iachini, & Giusberti, 2004; Presson & Montello, 1994; Rieser, 1989; Wraga et al., 2000). Regardless of the mechanism, spatial updating is able to facilitate spatial judgments in scene recognition (Burgess, Spiers, & Paleologou, 2004; Simons & Wang, 1998), judgments of relative direction (Presson & Montello, 1994; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Wang & Spelke, 2000), egocentric pointing (Hodgson & Waller, 2006; Sholl, 1999; Wang, 2007) and likely imaginary perspective taking as well.

Aside from differentiating spatial updating along idiothetic and conscious lines, one can also divide it in terms of when the processing takes place. Farrell and colleagues (Farrell & Robertson, 1998; Farrell & Thomson, 1999) asked participants to walk blindfolded to a previously learned location. They showed that participants modified both the number and length of steps taken to accurately arrive at the target location. This behavior persisted when subjects were able to walk with vision, but not when they were asked to walk the same distance but in the opposite direction (away from the target location). From this they concluded that subjects were updating the locations of the targets relative to themselves and adjusting their movements continuously instead of relying upon preplanned movements. Hodgson & Waller, rather succinctly, refer to this as simply *online* updating (2006). This is in contrast to *offline* updating where representations from long-term memory are transformed after a movement using the memory of an actual (or imagined) traversal (Loomis, Klatzky, Golledge, Philbeck, & Golledge, 1991).

Where as online updating is an automatic process, offline updating is not and can be influenced by task demands and instructions (Amorim, Glasauer, Corpinot, & Berthoz, 1997; Waller et al., 2002). Amorim and colleagues asked subjects to study a model of a three-dimension capital "F" and then to update both its location and orientation relative to themselves while walking. Subjects were asked to engage in one of two tasks while they moved. They either reported the number of steps they had taken or which side of the *F* was closest to them. After moving, they were to rotate and face the *F* and turn another model to indicate the *F*'s orientation relative to them. Those subjects who reported which side of the *F* was closest to them showed significantly lower pointing errors than those who counted steps. What's more, step-counters showed significantly higher instances of major orientation errors of the *F* (i.e. confusing left and right). Amorim et al. concluded that subjects who were focusing on the *F* were engaging in online updating, resulting in lower errors; whereas those that counted steps were using their memory of the path traveled to drive offline updating resulting in larger errors (Amorim et al., 1997).

These two perspectives on spatial updating: input (idiothetic or conscious effort) and time-of-processing (online or offline), are difficult to separate from each other. Within each perspective the means of differentiating is the same: magnitude of error and latency. Both idiothetic and online spatial updating show significantly lower errors and faster response times than their respective counterparts. From a computational perspective one could argue that online updating and path-integration are the same thing (using the idiothetic input to continuously update the representations), and likewise for consciously driven and offline updating. Unfortunately there has been no research in this area. For the current time, research will only be considered in terms of online and offline updating, however, the issue of input selection will be returned to in later chapters.

1.1.1 Representational perspectives on updating

While many studies have looked at the processes behind spatial updating and how it facilitates spatial judgments, few can speak directly towards *what* is being updated. The theoretical form of the spatial representations has significant bearing on how one views spatial updating, regardless of whether it is online or offline. To better highlight this consider two diametrically opposed representational forms: egocentric and allocentric.

Without a spatial updating process to maintain consistency in the face of movement, egocentric theories (e.g. Wang, 1999) would only be able to account for a small fraction of the empirical findings. These theories maintain that the spatial updating processes operate on individual egocentric representations. This enables the viewer to maintain spatially consistent representations of the objects in the environment. If this spatial updating process were disrupted (e.g. by disorientation), the representations would no longer be spatially consistent, resulting in a jumbled understanding of the environment. For egocentric theories, online updating is automatic, operating on individual attended representations, and is therefore constrained by available working memory resources. As the number of targets tracked online increases, so to should the updating errors; however, latencies will be largely unaffected since the targets will have been updated before testing even occurs (Hodgson & Waller, 2006). On the other hand, offline updating is largely limited by long-term memory as individual representations must be retrieved before they can be consciously transformed.

This is in stark contrast to allocentric spatial theories that propose that an individual encodes a representational network of locations that is independent of the viewer (McNamara, 2003; O'Keefe & Nadel, 1978; Sholl, 2001). In this representational scheme, spatial updating merely acts to anchor the viewer's location within the "cognitive map" thereby facilitating egocentric judgments (King, Trinkler, Hartley, Vargha-Khadem, & Burgess, 2004). Spatial updating doesn't act on the spatial representation of the environment, rather just the location of the viewer. Should the spatial updating process become disrupted, the viewer should just be misplaced within the "cognitive map", inter-object spatial judgments should not be affected. Since online updating only has to anchor the single representation of the viewer, it should be relatively insensitive to working memory manipulations. As in the egocentric account, offline updating permits the individual to imagine themselves at positions and orientations that they aren't currently in (King, Burgess, Hartley, Vargha-Khadem, & O'Keefe, 2002; King et al., 2004). Again, since only the self is being updated, it is largely immune to working memory manipulations.

If the spatial representations are themselves being updated then the orientation dependence of the representations should change as the subject moves (or imagines movement) through the environment. For instance, imagine an environment were encoded with a specific orientation dependency favoring views towards the north. If the representation were updated as the viewer rotated to face south, that dependency should rotate as well (Waller et al., 2002), or disappear entirely if the subject is able to encode an additional representation of the space from the new orientation (Sholl & Bartels, 2002; Sholl & Nolin, 1997). On the other hand, if updating anchors the viewer in the space, spatial updating should either not affect orientation dependency at all (O'Keefe, 1993) or simply as a function of the disparity between their actual and imagined positions (King et al., 2002; May, 2004).

With these different theoretical perspectives in mind, attention can be turned to two contrasting studies that have attempted to differentiate what is being updated. Not surprisingly, the evidence is mixed. Some show evidence that it is the position of the viewer that is being updated (or find no evidence that the representations are being updated) (Easton & Sholl, 1995; May, 2004; Mou & McNamara, 2002; Mou, McNamara, Rump, & Xiao, 2006; Mou, McNamara, Valiquette, & Rump, 2004; Sholl & Bartels, 2002; Sholl & Kenny, 2005), while others find evidence of individual representations being updated (Hodgson & Waller, 2006; Waller et al., 2002; Wang, 2004; Wang & Brockmole, 2003; Wang et al., 2006; Wang, Hermer, & Spelke, 1999; Wang & Simons, 1999; Wang & Spelke, 2000).

Mou, McNamara, Valiquette, & Rump (2004) conducted a series of experiments examining the efficiency of spatial updating using the well established judgment of relative direction (JRD) methodology. Subjects learned the locations of a series of objects from a given vantage point. They then walked into the middle of the configuration for testing. From this location, subjects were asked to engage in multiple JRDs (e.g. figure 1.3: “Imagine you are standing at the *shoe*, looking at the *clock*, point towards the *banana*”). Noticing that all previous studies had confounded actual body heading with imagined heading, Mou et al. divided subjects into two groups: those who’s imagined and actual body headings were consistent (A-I=0°) and those who were rotated 225° CCW out of alignment with their imagined heading (A-I=225°). If a given JRD trial relied upon an imagined heading other than 0°, the subject rotated (with vision) to the appropriate heading (+225° for A-I=225°) before being probed with the JRD-triplet.

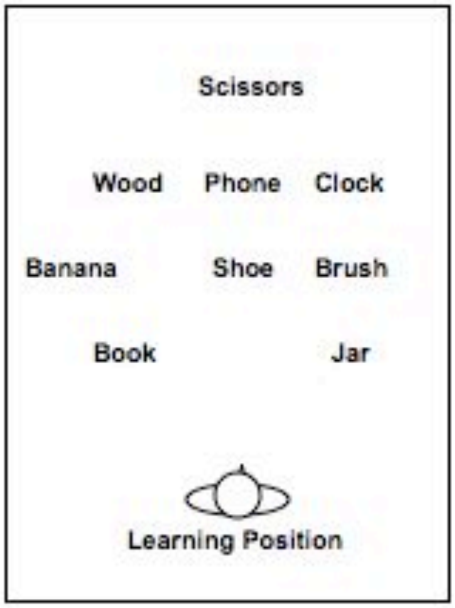
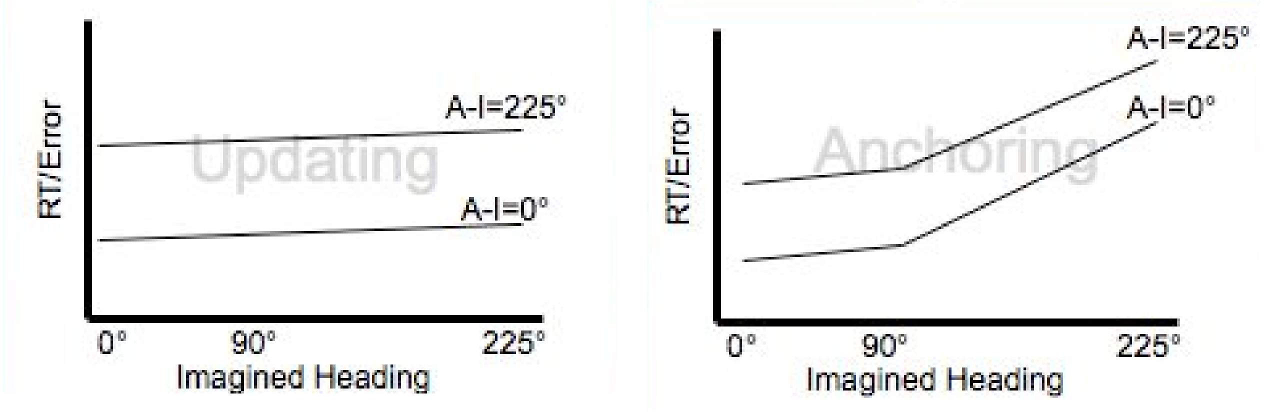


Figure 1.3 Object configuration used in Mou et al. (2004).

Mou et al. predicted that if subjects were engaging in egocentric-online updating during locomotion performance should be equivalent across the three levels of imagined heading (0°, 90° & 225°) within the actual-imagined (A-I) factors (figure 1.4a). However, performance would be best for A-I=0°, since the imagined heading was always parallel to the reference direction established by the body. Performance for A-I=225° would be less efficient than from 0°, but since the difference across the imagined headings were constant, there would still be no effect of imagined heading. On the contrary, if subjects were engaged in allocentric-online updating, neither the spatial representations nor the reference alignment would be updated and access would be most efficient when the imagined heading is parallel to the reference heading. Specifically, performance would be best for imagined headings of 0° (learned heading) and 90° (orthogonal but perceptually salient intrinsic axis), and significantly poorer for 225°, regardless of the actual-imagined heading differences (figure 1.4b).

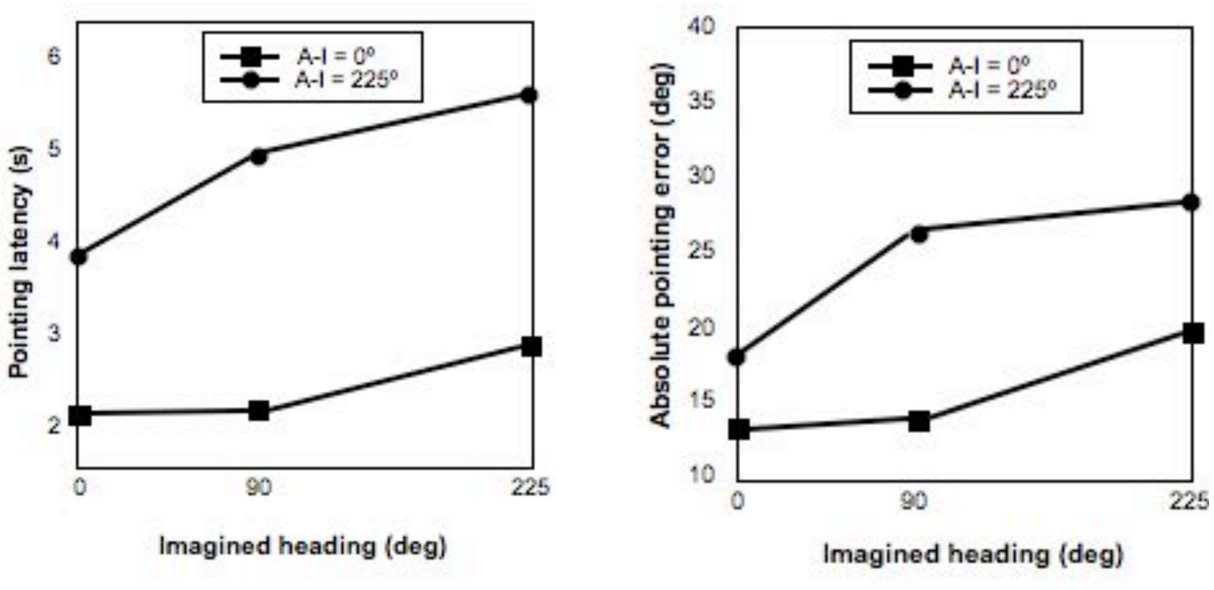


a

b

Figure 1.4 Predictions from Mou et al. (2004). A) If updating operates on individual representations, there should be no effect of imagined heading. B) If spatial updating anchors the viewer within an allocentric network, imagined heading effects should dominate.

Mou et al. found significant effects of imagined-heading (favoring judgments aligned with the 0° and 90° axes), as well as actual-imagined disparity (showing a roughly constant cost in latency and error for A-I=225°). They conclude that since the effect was not flat across imagined-headings, spatial updating was not acting upon individual representations (figure 1.5). In other words, moving to the center of the target configuration did not update the representation of the environment (2004).



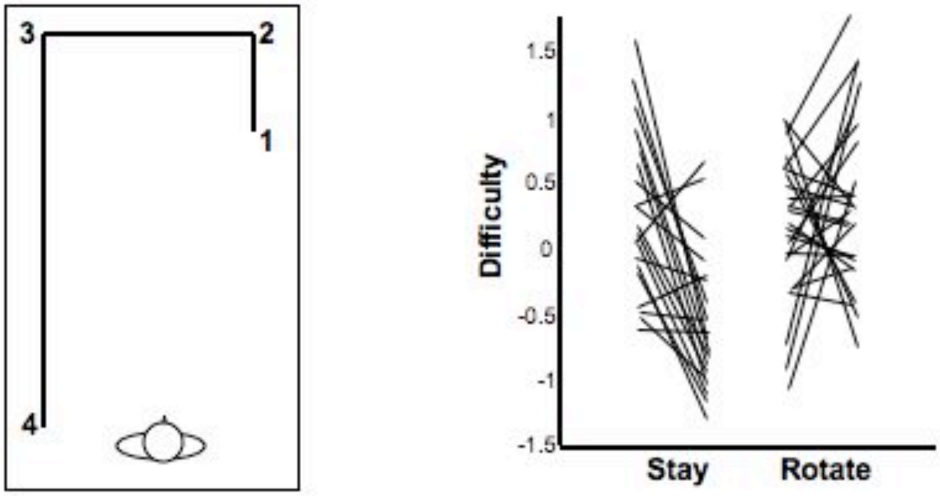
a

b

Figure 1.5 Results from Mou et al. (2004). Dominance of imaginary heading effect was interpreted as evidence for no egocentric updating.

Egocentric theories of spatial updating are not without their support, however. Waller, Montello, Richardson, & Hegarty conducted a series of experiments to see if the spatial updating processes actually influenced the representation of the space (Waller et al., 2002). In these studies subjects learned a simple path and were tested on their pointing speed and accuracy for *aligned* versus *contra-aligned* JRD-triplets. For *aligned* JRD-triplets, subjects imagined themselves at a location, facing in the same direction as they were when they studied the path; *contra-aligned* triplets had them imagining themselves facing in the opposite direction (see figure 1.6a). Given that spatial memories are strongly orientation dependent, *aligned* judgments should be both faster and more accurate than *contra-aligned* judgments.

To test the possibility that spatial updating can influence orientation dependency, they had subjects either stay in the same location after learning or rotate 180º in-place before testing (experiment 2). If the viewer's location relative to the objects was being updated (i.e. allocentric-online updating), the alignment effect should remain unchanged: *aligned* judgments should be significantly faster and more accurate than *contra-aligned* judgments regardless of the subject's orientation. However, if the spatial representations were being transformed by egocentric-online updating a reversal of the alignment effect should occur since the subjects are now in alignment with the *contra-aligned* position. The averaged data for the *rotate* condition showed a slight, but non-significant reversal. Investigating the individual data patterns revealed that approximately half of the subjects showed the reverse-alignment pattern (see figure 1.6b). Half of the subjects appeared to be updating their representation while the other half were updating their position within the representation (Waller et al., 2002).



a b

Figure 1.6 Sample four-point path and viewing location adapted from Waller et al. (2002). An aligned judgment would be to imagine standing at 4, facing 3, pointing at 2. A contra-aligned judgment would be to imagine standing at 2, facing 1, pointing at 4. Figure 4b. Half the subjects in experiment 2 *rotate* condition showed a reversal of the alignment effect, as measured by the composite difficulty measure.

To further explore this effect, Waller et al. conducted another experiment where half the subjects in the *rotate* condition were instructed to *ignore* the rotation and the other half were told to explicitly imagine the spatial configuration behind themselves (*update*). Once again the *rotate-ignore* group should show the standard alignment effect, with the *rotate-update* group showing the reverse-alignment. Waller et al. (2002) concluded that the representations were being updated and that online updating, if automatic, could be ignored (as in the *rotate-ignore* condition) or at least undone with little cost in accuracy (Farrell & Robertson, 1998; May & Klatzky, 2000). Embedded within their conclusions was the alternative that online updating may not actually be obligatory; a hypothesis that has recently received support (Hodgson & Waller, 2006) and will be discussed in the next section.

1.1.2 Set size and spatial updating

While the evidence for *what* is being updated is currently quite mixed, the theoretical perspectives underlying the previous experiments point towards another differentiating factor. If, as egocentric theorists propose, spatial updating operates on the level of individual representations it is highly unlikely that the processes can operate on an unbounded set of representations. While there is significant evidence showing spatial processing is dependent upon working memory resources (for a detailed review see Sholl, Fraone, & Allen, 2004), their have been few studies specifically looking at the role of set size on spatial updating. It should be explicitly noted that of the two forms of spatial updating, only automatic online updating should show working memory limitations and only if it is operating on individual egocentric representations. Offline updating, in service of egocentric or allocentric representations, should be relatively insensitive to working memory manipulations since it is performed after the movement has taken place.

Hodgson & Waller (2006) present an argument for egocentric-online and offline updating exhibiting different responses towards working memory manipulations. Since offline updating occurs after a movement has completed, it should be relatively immune to set size manipulations. Specifically, while there will be some latency effects, due largely to serial-search processes, updating error should be unaffected by set size manipulations. On the other hand, errors due to egocentric-online updating will be influenced by set size manipulations as the working memory resources devoted to tracking will be increasingly taxed by the increasing number of targets. With these two pieces in mind, we can look at the few studies that have explicitly examined spatial updating through set size manipulations.

Rieser & Rider (1991) examined the factors influencing children's and adults' ability to accurately point to targets after walking without vision. Participants were asked to study the locations of one or five targets. After completing baseline-pointing responses using a mounted compass pointer, subjects were blindfolded and escorted to a new test location. The path to the new test location was either 4m long with one 90º turn or 11m long with three 90º turns. They found no differences in error based on the number of targets studied. The only significant factor was the complexity of the path that subjects walked to the testing locations (figure 1.7).

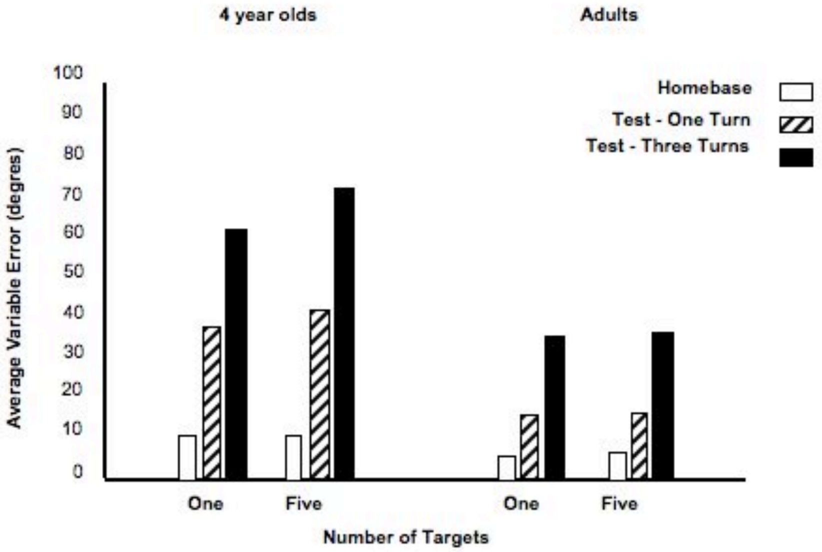
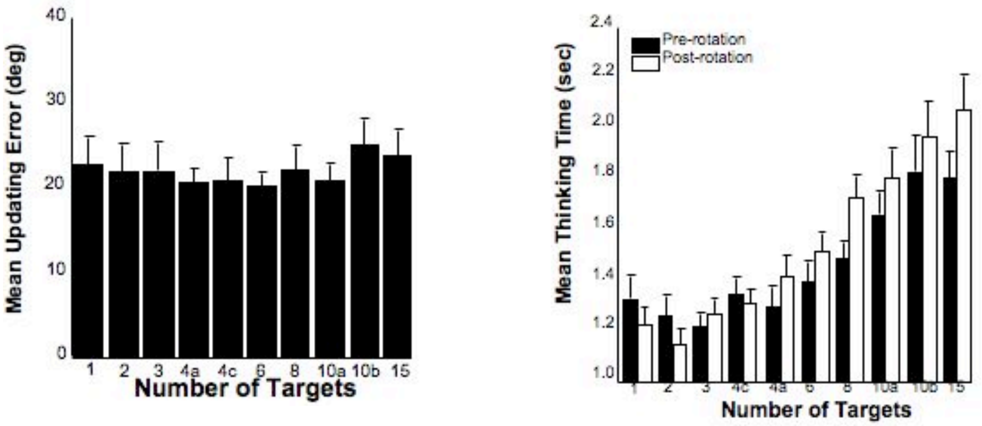


Figure 1.7 Results from Rieser & Rider (1991), experiment 3.

These findings need to be considered in light of a few key issues. First, as has been shown by other researchers (e.g. Roskos-Ewoldsen et al., 1998), merely relying on accuracy measures can be problematic, potentially hiding quite significant effects in latencies. Second, errors accumulate rapidly as the path-traveled increases (e.g. Amorim et al., 1997; Gallistel, 1990; Klatzky et al., 1998; Mittelstaedt & Mittelstaedt, 1980). The magnitude of the path complexity manipulations may have exceeding normal updating abilities increasing errors to such a point that it effectively obscured any effect set size effects. Regardless of the two previous issues, Rieser & Rider, like many other researchers, made the blanket assumption that the updating taking place was online. While this may have been warranted for the simpler path (i.e. single 90º turn), the magnitude of the complex path errors are more consistent with offline updating (Hodgson & Waller, 2006).

Rieser & Rider (1991) are not the only ones that have found no effect of set size on spatial updating. Recognizing that task instructions could influence the use of online or offline updating strategies, Hodgson & Waller were interested in what strategies subjects would engage in when left to their own devices (2006). They had subjects study sets of targets of various sizes (from one to fifteen targets). After establishing baseline-pointing responses, instead of engaging in complex translations to a new location, subjects merely rotated 135º in a random direction. As mentioned previously, they hypothesized that only egocentric-online updating should show an effect of set size on pointing error. If subjects were engaged in offline updating, while there would be an effect for latencies, it would be. If subjects were engaged in offline updating, the set size effect on latency (due to serial-search processes) would be present both before and after rotation and errors would be relatively high (around 20º). On the other hand, if subjects were engaged in allocentric-online updating, while the errors would be stable and smaller (around 10-15º), there would be no pre- post-rotation latency differences. The results of their study mirrored their predictions for offline updating: there was no effect of set size on pointing errors, and latency effects were seen in both pre- and post-rotation phases (figure 1.8). This is in stark contrast to the notion of online updating being automatic. Regardless of the instructions given, subjects should have engaged in online updating. Assuming they are correct, the question of set size effects on online updating is still left up in the air. Their conclusions are also heavily influenced by their implicit assumption that subjects will engage in one process or the other but not both. If subjects engaged in egocentric-online updating for targets up to some capacity limit and offline updating for the remaining targets, this data becomes much less clear. It is uncertain that current methodologies would be able to detect such a behavior.

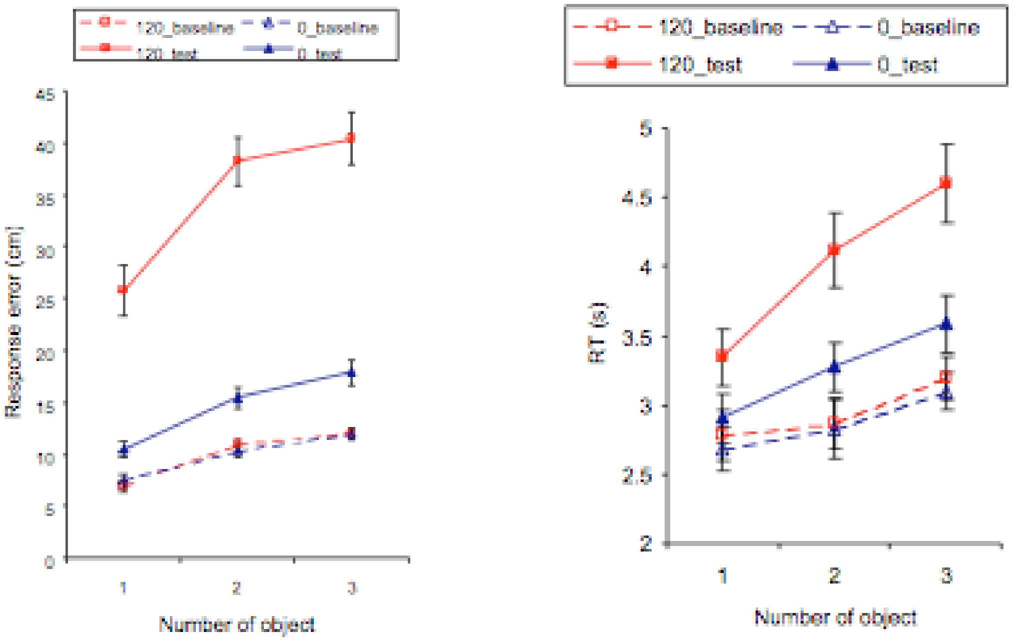


a

b

Figure 1.8 Pointing errors (a) and latencies (b) as a function of set size, adapted from Hodgson & Waller (2006).

The final set size study to be considered was conducted by Wang and associates (Wang et al., 2006). Wang et al. utilized a fully immersive virtual reality environment in order to exercise significant control over both learning and testing. Subjects entered a large projector room with digital projections on all four walls, ceiling and floor and studied the locations of one to three virtual cubes in an otherwise neutral, featureless environment. After studying, blindfolded subjects either walked the perimeter of a circle, covering a 120-degree arch, or walked in place for an equivalent period of time (around 4s). After moving, subjects used a digital wand (controlled by their hand) to place each of the studied targets in their original locations. Analyzing only the data for the first object placed, Wang et al. showed clear set size effects for both latency and positioning error (figure 1.9). Unfortunately, because they measured error with a Euclidean linear deviation and did not report subject-to-object distances, the errors in this study cannot be directly compared to those utilizing pointing methodologies. The presence of set size effects for both latency and positioning error may hint at both online and offline updating.



a

b

Figure 1.9 Object placement error (a) and latency (b) adapted from Wang et al. (2006).

1.1.3 Updating under dual-task load

Instead of manipulating spatial set size, working memory constraints can be explored by introducing a concurrent task during the movement phases. If egocentric-online updating is utilizing working memory resources, then the concurrent task should degrade performance as the two compete for limited resources (Book & Garling, 1981; Linberg & Garling, 1981; May & Klatzky, 2000). On the other hand, if subjects are engaging in offline updating, there will be little contention since the concurrent task will occur before the updating actually begins.

While there have been many studies looking at dual-task interference in other spatial tasks such as reorientation and wayfinding (e.g. Hupbach, Hardt, Nadel, & Bohbot, 2007;

Meilinger, Knauff, & Bulthoff, submitted; Ratliff & Newcombe, 2005), a review of the literature has only revealed three published studies that have looked specifically at dual-task interference in updating. The two earliest, by Garling and associates (Book & Garling, 1981; Linberg & Garling, 1981) utilized backward counting as the concurrent task as subjects walked an internal corridor while tracking target locations. From the consistent decrement in angular estimates seen in the dual-task condition, they concluded “that keeping track of the location of a reference point whilst walking is easily disturbed when the amount of central processing capacity available for the task is reduced.” However, it is uncertain whether the observed task was one of updating, wayfinding (Meilinger et al., submitted) or place-learning (Waller, Loomis, Golledge, & Beall, 2000).

May & Klatzky (2000), while not strictly using concurrent tasks, did use similar tasks within an interruption paradigm. Blindfolded subjects were guided along two legs of a triangle and then asked return to the start point on their own (triangle-completion task). During the guided traversal, they were interrupted and asked to engage in backward counting or an irrelevant (to-be-ignored movement). Not surprisingly, they found that the irrelevant movements had the greatest decrement on the accuracy of the return path. This inability to ignore the irrelevant movement is one of the key pieces of evidence for the conclusion that online updating is obligatory. While much weaker, there was also a significant effect of the backward counting on participants’ ability to return to the starting point. Like many of the previously discussed studies, this one made no attempt to differentiate between online and offline updating.

Amorim et al.’s (1997) experiment can also be viewed in light of dual-task load. In addition to step counting, they utilized a concurrent task that actually depended upon the updating. Participants who were asked to track the orientation of the “F” actually showed better updating performance than those who were counting. While it is uncertain whether the step counting was interfering or the orientation tracking was facilitating, it is worth noting that the concurrent task explicitly required the subjects to track the target.

Unlike the influence of set size, the role of dual-task loads appears to be clear. While concurrent tasks do interfere somewhat with spatial updating, some spatial tasks are much more deleterious (i.e. irrelevant movements), while others seems to facilitate performance (i.e. orientation tracking). There are two points worth considering here. First, with the exceptions of step counting and the irrelevant movements, all of these tasks are relatively complex requiring resources beyond just working memory retention. Second, and more importantly, in those studies where different concurrent tasks were contrasted, no attempts were made to equalize them in terms of the cognitive load they would introduce. It is possible that theses tasks are introducing more than just spatial interference, further undermining the conclusions drawn.

1.2 SUMMARY

Spatial updating is a complex, multi-faceted set of processes that is necessary in order to effectively maintain self-to-object spatial relationships. For every study showing that spatial updating acts upon egocentric representations there is another that shows either no spatial updating effect or that it merely anchors the viewer within a larger allocentric network. With the realization that individually updating egocentric representations should be constrained by working-memory limitations, attention has recently shifted towards exploring set size effects on online spatial updating. However, the results from many of these studies, and those that look at dual-task interference, are often interpreted with the implicit assumption that the updating taking place is entirely online. Unfortunately, the assumption of automaticity in online updating is becoming increasingly problematic (Hodgson & Waller, 2006). Combined with the fact that most tasks can be solved using either online or offline updating, attempts to differentiate the various representational theories becomes even more of a challenge. In order to effectively explore the working memory constraints of online updating, care must be taken in order to detect whether that updating is actually online or merely taking place after the fact.

With these challenges in mind, two experiments were conducted looking at set size effects on judgments of relative direction (chapter two) and 1-back interference in egocentric pointing (chapter three). At first pass, the results from these two studies could be interpreted in the light of either online or offline updating. However, analyses looking at individual differences in visualizations (chapter two) and the time course of 1-back errors (chapter three) strongly suggests that the updating taking place was entirely offline, further undermining the automaticity assumption of online updating. Models of both of the experiments were developed utilizing ACT-R (Anderson et al., 2004) and a spatial extension to the architecture, ACT-R/S (chapter four). While the results from experiment one show the hallmarks of both allocentric and egocentric updating, results from the modeling (chapter five) illustrate how such a pattern can emerge relying only on egocentric representations. Additional models explored the roles of various architectural components with respect to the tasks, illustrating inconsistencies in alternative theories and ACT-R/S itself (chapter five). The challenges to any investigation of the working memory constraints of spatial updating are discussed at length with respect to these results and models (chapter six), as well as directions for future research and theoretical development (chapter seven).

2.0 EXPERIMENT ONE

The first experiment conducted was designed to examine the role of spatial set size on spatial updating and use this information to infer how that updating was taking place. Hodgson & Waller (2006) differentiate between two different modes of updating: online and offline. Online updating is effectively an automatic[1] process driven by path-integration (Farrell & Robertson, 1998; Farrell & Thomson, 1998, 1999; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; May & Klatzky, 2000; Rieser & Rider, 1991). As such, upon the termination of the movement, the updating (egocentric or allocentric) will have already taken place and should therefore show no set size effects for latency. If the online updating is egocentric the accuracy of the updating will be influenced by set size as the updating process must be distributed over the set of representations in working memory (Hodgson & Waller, 2006). If that updating is allocentric the accuracy will be unaffected by set size manipulations since only the single representation of the viewer is being updated.

In contrast to online updating, offline is performed after the movement, typically at testing, and is controlled entirely by conscious processes. From both the egocentric and allocentric perspectives, representations currently in working memory are transformed using a

---

[1] Unfortunately, the use of the term *automatic* is somewhat problematic, while most researchers use it in the more traditional sense of outside of volitional control; others have classified the updating as automatic if subjects engage in it without explicit instructions (Wang, 2007).

representation of the path traversed or some other imagined transformation. If the appropriate representations are not available in working memory (i.e. individual egocentric representations or a different "cognitive map"), they can be retrieved from long-term memory before transformation (Hodgson & Waller, 2006; Wang, 1999). Therefore offline updating should show set size effects for latency, but only because of serial search effects (Atkinson, Holmgren, & Juola, 1969; Banks & Fariello, 1974; Flexser, 1978; Holmgren, Juola, & Atkinson, 1974). For an allocentric representation, since only the self will be updated there should be no effect of set size on accuracy. Similarly, in an egocentric framework the representations would be updated individually, exhibiting no set size effect on updating accuracy (Hodgson & Waller, 2006).

Most recently, Hodgson & Waller (2006) have presented a series of experiments looking at set size effects (one through fifteen targets) on egocentric pointing after simple rotations (135°). This extremely wide sampling of set sizes showed no effect on pointing error, and latencies that increased linearly with the number of targets. The authors concluded that subjects, in the absence of explicit updating instructions were simply relying upon an offline updating strategy.

The current experiment was interested in examining similar set size effects but from a slightly different perspective. While egocentric pointing is predominantly used to explore updating effects (Diwadkar & McNamara, 1997; Easton & Sholl, 1995; Farrell & Robertson, 1998; Hodgson & Waller, 2006; Jola & Mast, 2005; Klatzky et al., 1998; May, 2004; McNamara, 2003; Shelton & McNamara, 2004; Sholl, 1999; Wang, 2007), the predictions are often the same as those derived from allocentric or hybrid theories which rely upon processes that anchor the viewer within a stable allocentric reference frame, where the viewer is just another object in the "cognitive map." When computing self-to-object relationships for the to-be pointed-to object, the subject must perform a serial search of memory to find the target. In other words, the allocentric and hybrid theories would predict the same set size latency effect that egocentric offline updating would. The only way to differentiate the two classes of theories would be if evidence of online updating were found. Given the lack of online updating seen in numerous egocentric pointing experiments conducted by Hodgson & Waller (2006), relying upon set size effects in egocentric pointing to differentiate the theories could be challenging.

One way around this problem is to change the task. Instead of relying upon egocentric updating, this experiment utilizes judgments of relative direction (aka. JRD, "imagine you are at X, facing Y, point to Z"). Both JRD and imaginary perspective tasks (i.e. egocentric pointing from an imaginary orientation) show pronounced alignment effects, such that they are faster and more accurate when the imagined perspective is consistent with the preferred alignment of the representation (Easton & Sholl, 1995; Roskos-Ewoldsen et al., 1998; Sholl, 1999). Usually the representation's preferred alignment is that of the studied viewpoint (Diwadkar & McNamara, 1997; Shelton & McNamara, 2001, 2004), but it can also be influenced by other factors such as intrinsic salient axes defined by the environment (McNamara, 2003; Mou & McNamara, 2002; Shelton & McNamara, 2004). If spatial updating (online or offline) transforms the representations in working memory to maintain consistency, then this alignment effect should change as the representations are updated. For example, if an object's preferred alignment is straight ahead of the viewer, as the viewer rotates 180°, the preferred alignment should as well, making imaginary judgments facing 180° faster than those aligned with the initial viewpoint.

As was mentioned in the previous chapter, this alignment transformation has been found in the JRD studies by Waller et al. (2002) and others (Kelly, Avraamides, & Loomis, in pres). In their second experiment they compared JRD that were aligned with the study view with those that were contra-aligned (180° rotated) for participants who had remained in the study position and those that had also rotated 180°. Initial analyses of the averaged group data showed that after rotation the standard alignment effect favoring aligned judgments disappeared, contra-aligned JRD were just as fast an accurate. Examining the individual data they found that around half the subjects showed the standard alignment effect whereas the other half showed a complete reversal, contra-aligned judgments were faster and more accurate than aligned judgments. A follow up study, explicitly manipulated the instructions given to subjects, found that subjects who were asked to track the objects during rotation showed the reversal and subjects that were told to ignore the rotation showed the standard effect (2002).

The reversal of the alignment effect is particularly challenging for pure allocentric theories that would predict that the alignment effect arises from the preferred alignment of the stable allocentric map. Mou et al. (2004) attempt to explain this phenomenon by proposing a egocentric system on top of their allocentric encoding. They describe this system as a transient, perceptual-like egocentric system used primarily for obstacle avoidance and guiding action in space. While able to engage in limited updating with movement, representations decay rapidly in the absence of perceptual input. They argue that as the subject rotates, the egocentric system tracks the objects allowing for more rapid and accurate contra-aligned JRDs. Assuming that it can engage in the conscious transformations that are required for JRDs (e.g. “imagine you are at X, facing Y” requires an offline translation and rotation), there is still a significant problem with this explanation. While this “perceptual” system can account for the contra-aligned benefit after rotation, it can only do so for the first judgment. After that first JRD, the representations in the system will be consistent with that JRD – making subsequent judgments would require one of two things: unwinding the representations to their previous state (i.e. undoing the offline rotation and translation), or retrieving the relevant allocentric representations into the egocentric system and applying the 180° rotation. Both options would result in additional costs in terms of latency and probably error, thereby negating the savings necessary to reverse the alignment effect.

At this point, the attentive reader may realize that JRDs are solved mostly through the use of offline updating. Online updating cannot directly facilitate the process of imagining oneself at one location, facing another direction. However, it can do so indirectly, if locations are updated during rotation then they will be in a spatial consistent state before engaging in the JRD, enabling the savings seen in Waller et al. (2002). If, on average, JRDs require the same number and magnitude of offline transformations, then whatever set size effects are observed should primarily be those due to the type of spatial updating taking place before the JRDs (online or offline).

To preview, experiment one was an extension of the Waller et al. (2002) study adding a between-subjects set size manipulation, where all subjects engaged both in stationary and rotated judgments of relative direction. Like the Waller et al. study, group averaged data showed no alignment reversal after rotation. When considering the subjective quality of participant visualizations, the standard alignment effect was seen for those that reported visualizing targets from a map-like perspective. Subjects who reported visualizing the targets egocentrically (i.e. relative to themselves) did show the alignment effect reversal. Set size effects were limited to latency alone, suggesting that subjects waited until after completing the rotation to update the target locations.

2.1 METHODS

This study introduced a few changes to Waller et al.’s methodology (2002). First, a between subjects manipulation of set size was added (4, 6 & 8). Because of this, new configurations had to be generated for the six and eight target conditions. Geometrically regular configurations (i.e. grid-like configurations) were avoided in order to dissuade intrinsic alignments, which might mask changes in the alignment effect (Mou & McNamara, 2002). Additionally, Waller et al. (2002) had subjects point to each of the targets blindfolded before engaging in judgments of relative direction (JRD). This was done to ensure that participants knew the target locations sufficiently after studying. In this experiment, a training-to-criterion study phase was used instead to ensure participants knew target locations. The egocentric pointing phase was moved to the end of the JRD pointing block in case it provided an additional rehearsal or updating opportunity after rotating. Finally, the rotate-ignore group was not included; all subjects were asked to visualize the target locations relative to themselves as they rotated.

2.1.1 Participants

Sixty-one undergraduates (29 female, 32 male) from Pittsburgh and Philadelphia universities participated for course credit or pay. All participants were tested individually in one-hour sessions. Two participants were omitted due to equipment failure, and two were excluded due to insufficient samples after data cleaning, leaving a total of 57 participants (28 female, 29 male; 20, 17 & 20 in set sizes 4, 6 & 8 respectively). Analyses based on those reported below were conducted dividing the groups based on school and compensation. No significant differences between the groups were found allowing them to be collapsed.

2.1.2 Materials

Fifteen configurations of targets were generated for this study (three training sets and four testing sets for each set size) (see appendix A). Configurations were assembled from 30.5cm (1ft) tall orange cones with 7.6cm (3in) reflective letter labels. Each configuration fit within a 3m square region, with a minimum of 0.5m separating each target. The initial pointing-training configuration was an 8-target diamond pattern, labeled alphabetically clockwise, with the subject position in the center. The remaining two training configurations were four-target configurations similar to those used in Waller et al. (2002). The testing configurations were pseudo randomly generated by computer with the following constraints: there must be at least two columns with two targets each, but no row or column can contain more than two targets. Labels were assigned to targets pseudo randomly to prevent label repetition in consecutive configurations and to minimize phonetic similarity of labels.

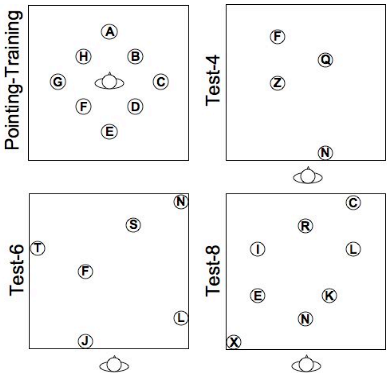


Figure 2.1 Sample training and testing configurations for experiment 1.

Participants wore a pair of blacked-out wrap-around sunglasses, a pair of passive noise-canceling headphones (for probe presentation), and held a high-precision joystick (for responding). Participants were blindfolded for the entire study except when studying the target configurations. During the duration of the study, low-level white noise was played over the headphones.

2.1.3 Procedure

After obtaining informed consent subjects were randomly assigned to one of three target set size groups (4, 6 & 8). Before testing, all participants completed the same three training configuration blocks.

2.1.3.1 Training The first training configuration (figure 2.1) gave participants practice using the joystick to respond and introduced them to the two pointing tasks: egocentric pointing and judgments of relative direction (JRD). Subjects stood in the middle of an eight-target diamond configuration and were asked to point (while sighted) to each of the targets in random order. For each target, if their pointing error exceeded 15°, they were provided with corrective feedback and asked to try again. After completing the sighted-egocentric block, participants replaced the blindfold and were prompted to point to each of the targets again. As before, if their errors exceeded 15° they were provided corrective feedback, given fifteen seconds additional study time before replacing the blindfold, and asked to try again. Upon completion of the blindfolded-egocentric block, the JRD task was explained to the participants. They were instructed that they would be provided with three target locations. They were to imagine themselves standing at the first, facing the second, and then point to the third. Like the egocentric blocks, participants were asked to engage in four sighted and blindfolded JRDs. In this case the error threshold was a more liberal 45°. After completing the egocentric and JRD training, participants received additional information. They were told that accuracy was more important than speed, but that they would have eight seconds to complete each trial. If they were uncertain of their response, they were told to just let the time expire.

Participants were next introduced to the second and third practice configuration blocks, which were structured like the actual testing configurations (figure 2.2). Subjects entered the experiment area and began the study-phase of the block. During the study phase, participants were given thirty seconds to study the configuration (figure 2.1), after which time they replaced the blindfold and were tested. The study-phase repeated itself until participants passed this test. The test prompted them to point to each of the targets randomly three times. In order to pass the study test, their pointing error to each target had to be less than 15°. Upon exiting the study-phase there was a thirty second retention interval followed by the testing-phase. The testing-phase consisted of a block of eight randomly ordered JRD trials followed by a block of randomly ordered egocentric trials (once per target) with a five second delay between each judgment. The eight JRD trials were composed of four aligned and four contra-aligned trials. The second practice configuration block introduced participants to the rotate instructions. Specifically, just before the retention interval, participants were instructed to turn 180° in-place. They were instructed to try to visualize the locations of the objects relative to themselves as they moved, since they would be asked to point to each of the targets at the end of the configuration block.

After the third practice configuration, the experimenter answered any questions and set up the first testing configuration block.

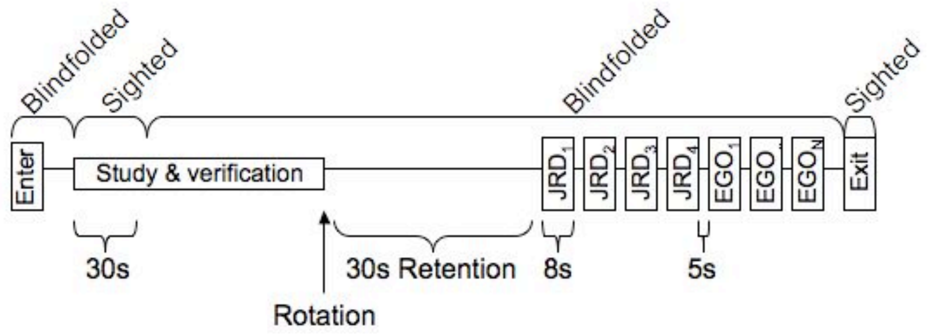


Figure 2.2 Experiment one per-configuration sequence and timings (not to scale).

2.1.3.2 Testing Having completed the training, participants were exposed to the four testing configurations presented in random order (two each in stay and rotate conditions). The testing configuration blocks were structured almost identically to the second and third practice configurations. After the configuration was in place, the participant entered the experiment area and began the study-phase. Actual initial study times were different based on set size condition. Initial study times for the three conditions were thirty, fifty, and seventy seconds for set sizes 4, 6 and 8 respectively. If participants failed the study test, the additional study time was always thirty seconds regardless of set size. The testing-phase again consisted of eight randomly ordered JRD trials (four aligned & contra-aligned) followed by a block of egocentric trials.

After the final configuration, participants filled out a brief questionnaire asking for general demographic information as well their subjective awareness of the frequency of various types of visual imagery, behaviors, and strategies (see appendix B). Of greatest interest here were the visual imagery questions. These questions were designed to probe the frequency of the use of egocentric (i.e. “When remembering the location of a target, I often saw it from the same perspective I studied it from”) or allocentric (i.e. “When remembering the location of a target, I often saw it from a top-down, map-like perspective”) visualizations. The responses for each were averaged to produce an estimated frequency of egocentric and allocentric imagery use.

2.1.4 Data cleaning

For each pointing response recorded, four data points were collected. The two latency measures looked at total response time and time to the first movement of the joystick. Deviations were measured both for absolute and signed pointing error (i.e. including the directionality of the error with negative values reflecting angular over estimations). Any responses that exceeded three standard deviations from the group mean for total latency (≤ 0.5s, ≥ 7.5s) or absolute error (≥ 120°) were excluded for that subject. 135 of 1888 (8%) responses were excluded. Responses were averaged within each primary condition for JRD (stay-aligned, stay-contra, rotate-aligned, and rotate-contra) and egocentric (stay and rotate). Any subject with less than half the possible responses per condition was excluded entirely. Two subjects were excluded by this criterion. Looking at their data individually revealed that they were frequently responding almost immediately (< 0.5s) with extremely high errors (average 105°). From all outward appearances these two subjects were not taking the task seriously. Unfortunately, their exclusion will present a problem during the set size analyses discussed later.

2.2 RESULTS

Analyses reported here were conducted on each of four measures (absolute latency, first-movement latency, absolute error and signed error). Since the first-movement latency measure showed no differences, only absolute latency is reported. Similarly, analyses of signed errors showed little significance and will only be mentioned briefly.

The core, theoretically relevant, analyses are presented first. Secondary and tertiary analyses exploring alternative interpretations and subject behaviors are included for completeness. Those interested in just the core analyses can skip to the discussion (2.3) after the egocentric pointing results.

2.2.1 Visualization style

Before delving into the various analyses it is necessary to introduce a measure derived from the debriefing questionnaires. Anticipating that the individual differences seen in Waller et al. (2002) might have been due to differences in visualization styles, questions were asked regarding the subjective quality of participants' mental visualizations of the targets. Questions probed the relative frequency of use of different visualizations along egocentric and allocentric (map-like) boundaries.

A principle component analysis of the visualization questions yielded two dominant factors. Three of the allocentric visualization questions weighed most heavily on the first factor (*allo-vis*). The second factor (*ego-vis*) consisted entirely of the egocentric questions. No other factor attained eigenvalues greater than 1.0. A frequency of visualization usage for each type was established by averaging the responses to the questions within each factor. While most participants (90%) reported using egocentric visualizations more than half the time, only half the subjects reported frequently using allocentric visualizations (50%). The frequency of allocentric visualization use was recoded into a split half, yielding two groups of roughly equal sizes. Low frequency allocentric visualizers were classified as the predominantly egocentric visualizers.

Table 2.1 Primary egocentric & allocentric questions for PCA extracted factors.

	Factor (% Variance)	
Question	**AlloVis (50%)**	**EgoVis (25%)**
01wholistic	0.62	0.23
03map	0.81	-0.32
08geometry	0.82	-0.12
04ego	-0.76	0.71
02piecemeal	-0.44	0.49

Grouping based on allocentric visualization usage is an important factor in the following analyses. While the over-all distribution of allocentric visualizers is roughly equal, in two areas it is heavily skewed. In set sizes four and eight allocentric visualizers accounted for 58% of the participants. Set size six saw a radically different distribution with only 4/17 (24%) of subjects reporting frequently using allocentric visualizations. Finally, the distribution of allocentric visualizers is significantly different when grouped by sex. Only 28% of women frequently used allocentric visualizations whereas 70% of men did, X^2 (1, 57)=10.6, $p<0.001$.

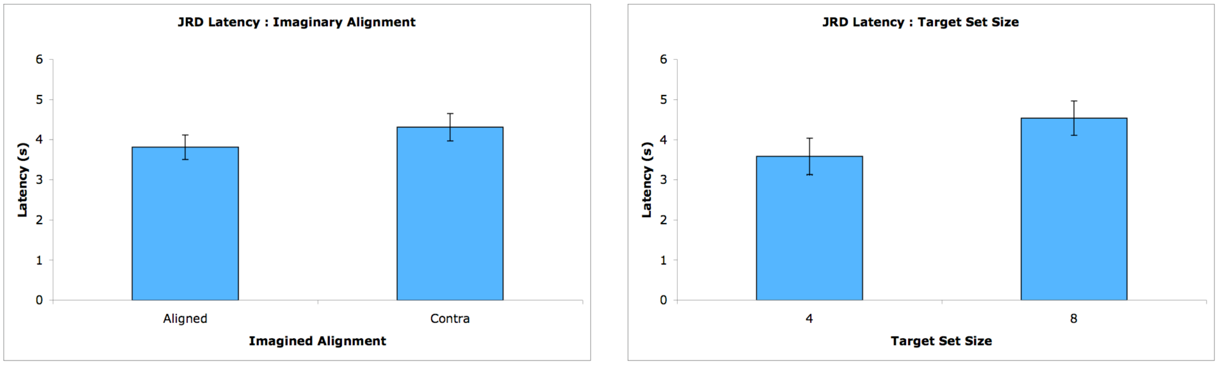
2.2.2 Judgments of relative direction

Each of the analyses reported here (absolute latency and error) are based on the same general 2x2x2x2 RMANOVA with body position (stay & rotate) and imaginary alignment (aligned & contra-aligned) as within-subject factors and visualization type (allo-vis & ego-vis) and set size (4 & 8) as between-subject factors.

It should be noted that set size 6 is being excluded from these analyses. As mentioned previously, there was an unequal distribution in the visualization self-reports, with allocentric visualizers accounting for less than a third of the sample (4/17). As it turns out, the two participants that were excluded during data cleaning also belonged to this group. Given the small sample size for set size 6 allocentric visualizers, the entire set size is omitted from these analyses, leaving an effective sample size of 40 participants.

While the main effects are interesting in their own right, the primary focus here is on the interactions, particularly of body position and imaginary alignment with the other factors. As such, while all the significant findings are reported, the interactions will receive the majority of the consideration.

2.2.2.1 Latency RMANOVA analysis on latency showed no significant effect for body position, F(1,36)=0.6, p>0.05, or visualization type, F(1,36)=0.7, p>0.05. There was a significant main effect for imaginary alignment, F(1,36)=33.6, p<0.001, with aligned judgments averaging 0.5s faster (figure 2.3, a). Set size also showed a significant main effect, F(1,36)=9.5, p<0.005, with set size 4 averaging 1s faster than set size 8 (figure 2.3, b).



a b

Figure 2.3 Main effects of alignment (a) and set size (b) for JRD latencies. Error bars are 95% CI.

The interaction of body position and imaginary alignment was significant, F(1,36)=45.6, p<0.001. When standing still the alignment effect was strong, however, after rotation it vanishes entirely (figure 2.4). All other first order interactions were non-significant or marginal and will not be discussed further.

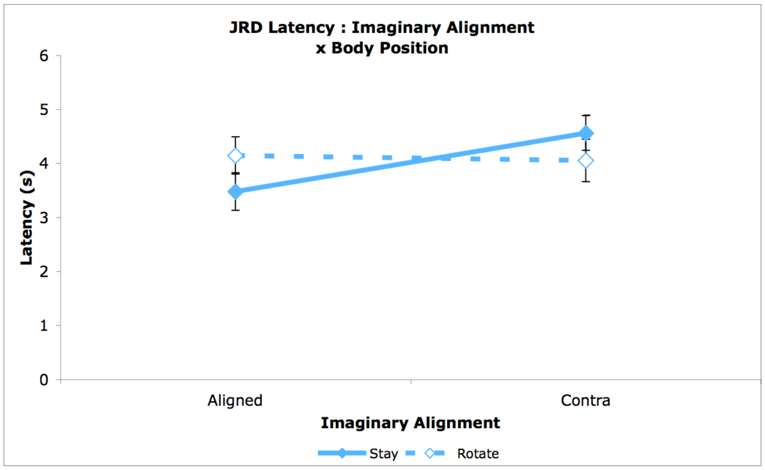


Figure 2.4 Interaction of imaginary alignment and body position for JRD latencies. Error bars are 95% CI.

The three-way interaction of body position, imaginary alignment, and visualization was also significant, F(1,36)=22.6, $p<0.001$. While both allocentric and egocentric visualizers showed the standard alignment effect when stationary, after rotation allocentric visualizers showed a reduction in the effect and egocentric visualizers showed a complete reversal (figure 2.5). The four-way interaction with set size was also significant, F(1,36)=5.1, $p<0.05$. Figure 2.6 illustrates the effect with each visualization group plotted separately. For egocentric visualizers, latencies increase with set size as the magnitude of the alignment effect (and its reversal) decreases (a). The story for allocentric visualizers is similar in that latencies are increasing with set size, but the alignment effect is decreasing (b).

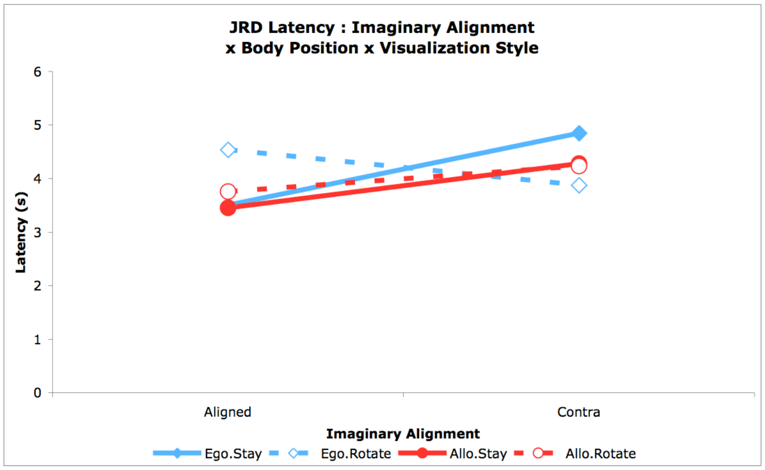


Figure 2.5 Interaction of imaginary alignment, body position, and visualization style for JRD latencies. Error bars omitted for clarity.

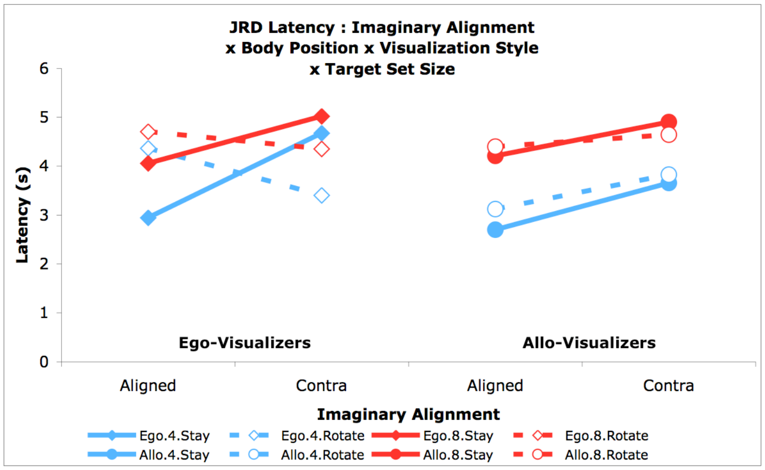


Figure 2.6 Interaction of imaginary alignment, body position, visualization style and target set size for JRD latencies. Error bars omitted for clarity.

2.2.2.2 Absolute error The same RAMNOVA template applied to the absolute pointing error found a significant main effect for body position, F(1,36)=4.8, $p<0.05$ (figure 2.7). The effects of imaginary alignment, set size and visualization were all non-significant, F(1,36)=3.1, $p>0.08$, F(1,36)=2.1, $p>0.1$, and F(1,36)=2.7, $p>0.1$, respectively.

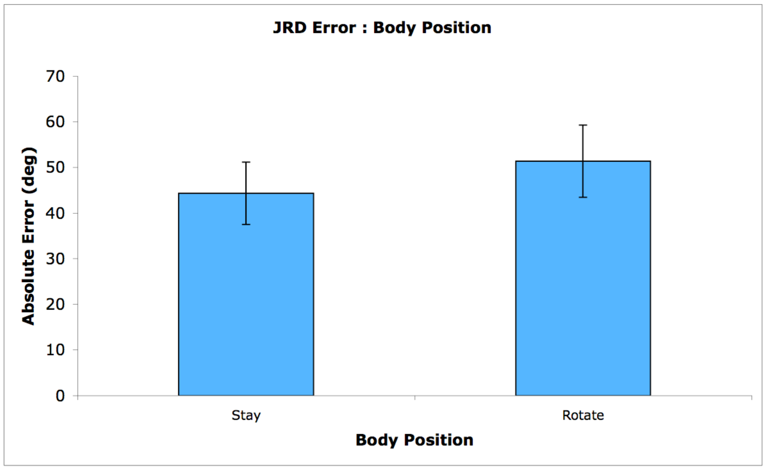
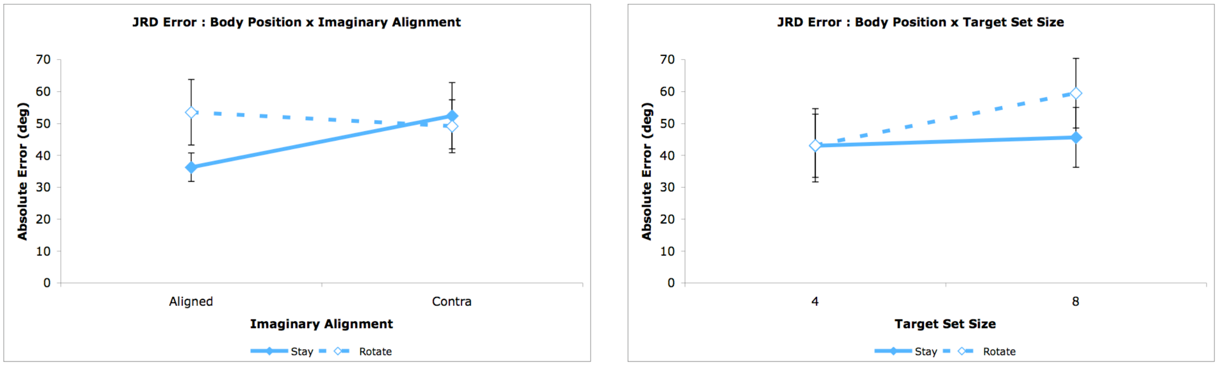


Figure 2.7 Main effect of body position on JRD pointing errors. Error bars are 95% CI.

As in the case of latency, the interaction between body position and imaginary alignment was significant, F(1,36)=11.5, p<0.005, showing a strong alignment effect when stationary and its elimination after rotation (figure 2.8, a). The interaction between set size and body position was also significant, F(1,36)=4.6, p<0.05 (figure 2.8, b). No other first order interactions reached significance.



a b

Figure 2.8 Interactions of body position & imaginary alignment (a) and body position & target set size (b) for pointing error. Error bars are 95% CI.

The three way interaction of body position, imaginary alignment, and visualization was significant, F(1,36)=7.9, p<0.01. As in the case of latency, while both visualization groups show the standard alignment effect while stationary, after rotation, egocentric visualizers show a reversal while allocentric visualizers are relatively unaffected (figure 2.9).

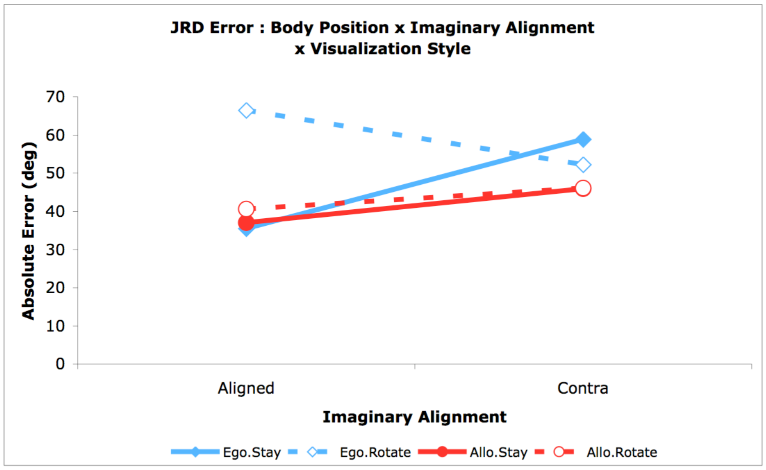
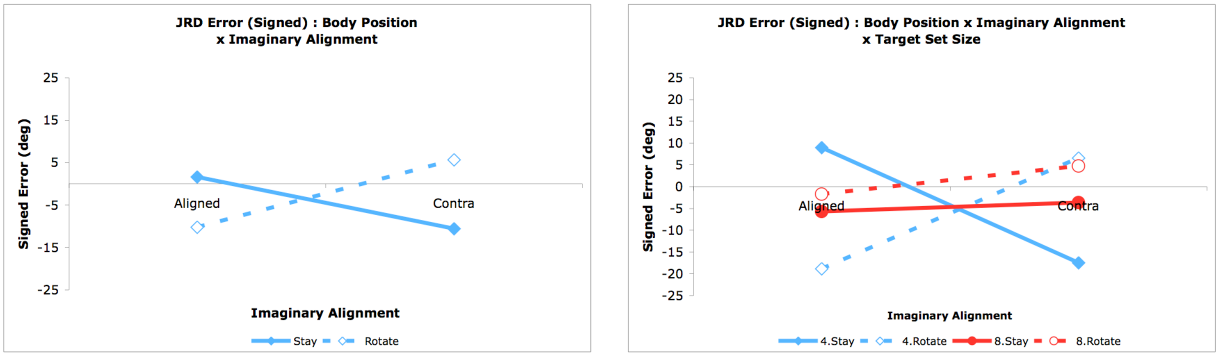


Figure 2.9 Interaction of body position, imaginary alignment and visualization style for JRD pointing errors. Error bars omitted for clarity.

2.2.2.3 Signed error Applying the same RMANOVA to signed errors showed little significant or marginal effects. However, two interactions were significant and are reported for completeness. The interaction of body position and imaginary alignment, F(1,36)=6.58, p<0.01, showed a consistent angular underestimation for stationary contra-aligned and rotated aligned judgments (figure 2.10, a). The body position, imaginary alignment and set size interaction was also significant, F(1,36)=4.68, p<0.05 (figure 2.10, b).



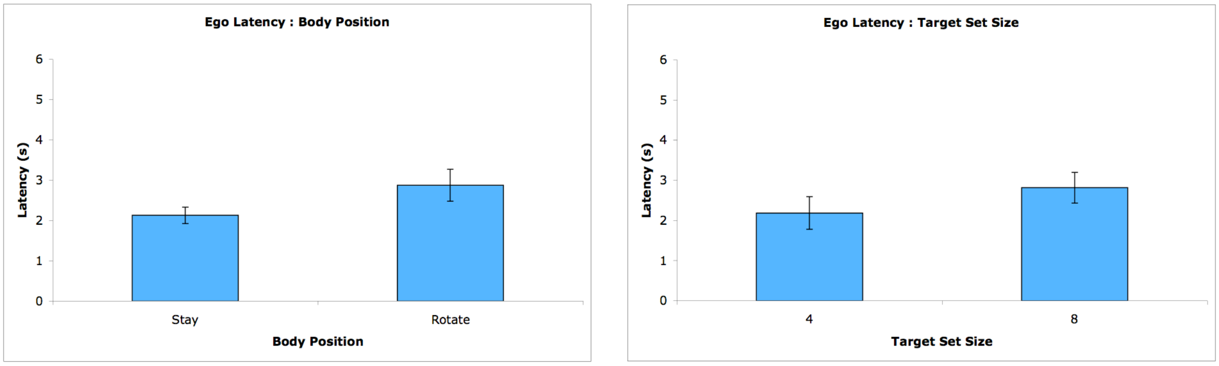
a b

Figure 2.10 Interactions for body position & imaginary alignment (a) and body position & imaginary alignment & target set size (b). Error bars omitted for clarity.

2.2.3 Egocentric pointing

For the egocentric pointing data, all analyses are based upon a basic 2x2x2 RMANOVA. Body position (stay & rotate) is the only within-subjects factor. Set size (4 & 8) and visualization type (allocentric & egocentric only) are the between-subject factors. Again, set size six has been excluded entirely since there were insufficient participants in the 6-allocentric grouping.

2.2.3.1 Latency For latency, both body position and set size showed significant main effects, F(1,36)=27.9, $p<0.001$, and F(1,36)=5.2, $p<0.05$, respectively (figure 2.11). The effect of visualization style was non-significant, F(1,36)=0.04, $p>0.05$. None of the interactions approached marginal significance.



a b

Figure 2.11 Main effects of body position (a) and target set size (b) on latency. Error bars are 95% CI.

2.2.3.2 Absolute error For absolute pointing error, only body position showed a significant effect, F(1,36)=14.9, p<0.001. Predictably, pointing error was greatest after rotation (figure 2.12). Neither set size nor visualization were significant, F(1,36)=1.9, p>0.05, and F(1,36)=1.3, p>0.05. None of the interactions were significant.

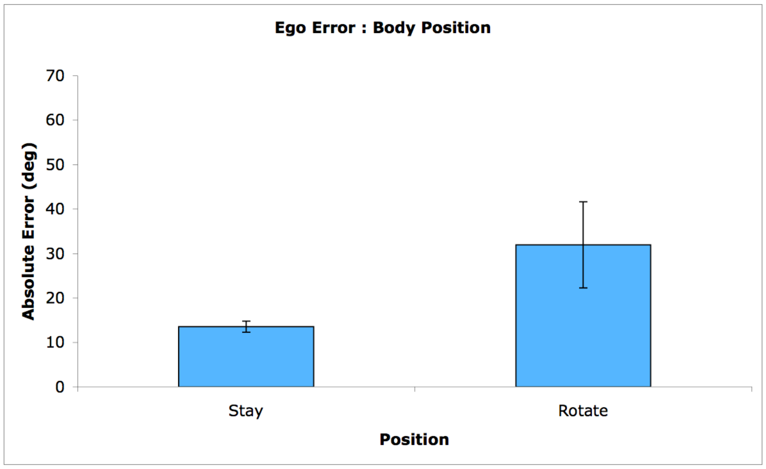


Figure 2.12 Main effect of body position on absolute pointing error. Error bars are 95% CI.

2.2.4 Trial presentation

To test for practice effects within a configuration, JRD trials were divided into halves. This temporal dimension was included with the previously discussed RMANOVAs. The temporal factor was non-significant for latency, F(1,35)=2.9, p>0.09, and pointing error, F(1,35)=2.6, p>0.1. The temporal factor did not exhibit any significant interactions with other factors.

2.2.5 Study time

This experiment used a criterion based study phase, which requires a consideration of total study time. Because the initial study time increased with set size, this analysis only looks at the total additional study time that participants received in response to insufficient pointing accuracy. Additional study time was added to the previous JRD RMANOVAs as a covariate. For latency, additional study time showed no significant main effect, F(1,35)=0.12, p>0.9. Study time showed no significant interactions with the other factors for latency. For pointing error, however, there was a significant main effect for additional study time, F(1,35)=6.2, p<0.02. Not surprisingly, those that required additional study time were less accurate in their pointing responses. Additional study time did not interact significantly with any other factor for pointing error.

2.2.6 Speed/accuracy

While participants were explicitly told to stress accuracy over speed, the fact remains that they were responding under time pressures. Speed/accuracy correlations were computed for each subject within each of the four primary cells (e.g. stay-aligned, rotate-contra). The average correlation was r=0.02. To test the possibility that subjects might exhibit different behavior in response to task demands, the individual correlations were analyzed using the template RMANOVA. Only the visualization factor was marginally significant, F(1,36)=3.6, p>0.06, showing a slight negative correlation for egocentric visualizers (r=-0.04) and a slight positive correlation for allocentric visualizers (r=0.09). While statistically significant, these differences are far from practically significant.

2.2.7 Gender differences

As discussed in the visualization results, males and females showed different distributions of reported visualization style. When gender is entered into the RMANOVAs instead of visualization type, only the interaction of body position, imaginary alignment and gender for latency was significant, F(1,36)=7.5, p<0.01. This effect mirrors the latency interaction for body position, imaginary alignment and visualization.

2.2.8 Questionnaire responses

Responses from the debriefing questionnaire were entered into the RMANOVA models as covariates (excluding the visualization questions already accounted for in the visualization style factor), as well as simple split-halves as between-subject factors. Only the latency interaction of body position and confidence (i.e. subjects reported being less confident of their responses after rotation) was significant, F(1,26)=5.3, p<0.05. None of the other questions showed any predictive value.

2.3 DISCUSSION

This first experiment was designed to highlight what, if any, effects target set size has on the reversal of the alignment effect seen when subjects engage in judgments of relative direction after a self-directed 180º rotation. Egocentric theories of spatial representation require a spatial updating mechanism to maintain a consistent spatial worldview after movement. This updating mechanism cannot be unbounded and so the efficiency and/or accuracy of the updating will necessarily decrease with increases in the number of to-be updated targets. However, one must consider the alignment effect and its reversal before delving into set size's influence upon them.

As can be seen in the main effect of imaginary alignment for both latency and error, there is a prevalent alignment effect. When participants engage in JRDs that are aligned with their original study orientation they are both faster and more accurate than when making contra-aligned judgments (figures 2.3a, 2.4 & 2.8a). This alignment effect is similar in magnitude and scope to those seen in other JRD studies (Waller et al., 2002). When body position is incorporated, the interaction is significant showing an even more pronounced alignment effect when participants do not move, but a slight (and non-significant) reversal when rotated (figures 2.4 & 2.8). Waller et al found an identical pattern in their initial rotation experiment (2002). Without either explicit instructions (as in the Waller et al study) or some other assessment of individual differences (such as the subjective visualization quality questionnaire) this pattern of results would be indistinguishable from earlier reports of orientation-independence in spatial memory (Presson, DeLange, & Hazelrigg, 1989; Presson & Hazelrigg, 1984). When subjective differences in visualization are taken into account, two qualitatively different groups emerge (figures 2.5 & 2.9). Participants who reported frequently engaging in allocentric visualizations showed a stable alignment effect regardless of their body position. Participants who reported their visualizations as being almost entirely egocentric in nature showed a similar alignment effect when in their original position, but a significant reversal after rotation. Many subjects explicitly noted at the end of the experiment that tracking the target locations during rotation was largely irrelevant. If indeed they did not track the targets or merely used their initial representations to perform the JRDs, they would show the standard alignment effect (Waller et al., 2002). That the high-low frequency of allocentric visualization resulted in a near perfect 50/50 split is interesting in its own right, but whether or not it was entirely coincidental is uncertain.

That there was a main effect of set size for latency but not error[2] is suggestive of offline updating. Serial search effects are commonplace when looking at set size manipulations; it simply takes longer to find or retrieve a given target from a larger pool (Atkinson et al., 1969; Banks & Fariello, 1974; Flexser, 1978; Holmgren et al., 1974). The four-way interaction of body position, imaginary alignment, visualization and set size bears some consideration. The interpretation of any high-dimensional interaction can be challenging, but this one can be simplified to aide in comprehension. We can eliminate the alignment factor (and the reversal) by using the absolute value of the difference score to represent the alignment effect (i.e. |*contra* – *aligned*|). What is left is a clearer picture of the alignment effect diminishing with increases in set size for both allocentric and egocentric visualizers (figure 2.13).

---

[2] As is always the case when an argument is dependent upon a null result, a power analysis had to be conducted to ensure that the experiment had sufficient power to detect a set size effect on pointing error (Cohen, 1988). Using G*Power 3.0 (Faul, Erdfelder, Lang, & Buchner, 2007) with set size $\eta^2=0.29$, the power for the study was calculated to be 0.96.

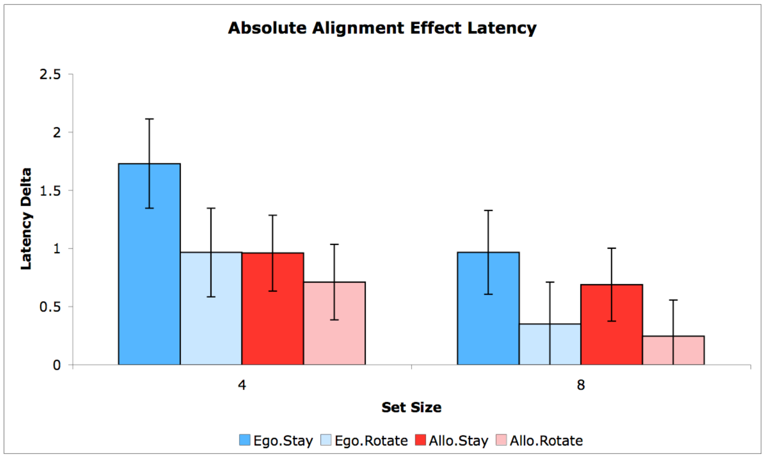


Figure 2.13 Absolute alignment effect showing decrease in alignment effect latency with increases in set size. Error bars are 95% CI.

While the latencies strongly suggest that the updating was offline, one might be tempted to ask if the same results could be the result of online-egocentric or even online-allocentric (i.e. anchoring) updating. Without a clear contrasting example of the other updating, these results could be illustrative of either. This is a viable argument until one considers the presumed automaticity of online updating for either allocentric or egocentric theories. If the updating were online then subjects should have all shown the reversal (if online egocentric) or none should have. The most viable alternative is that subjects were engaging in offline updating across the board. This is hardly surprising when one pauses to consider the nature of the task. No amount of online updating can significantly benefit a JRD without having the subject actually move to each imagined location and turn to face each orientation. The greatest benefit that online updating can provide is in establishing updated representations that are consistent with the subject's rotated position. These updated representations can then be retrieved for use in the offline transformations necessary to complete the JRD. Offline updating, while similarly constrained, only ever has to utilize at most three representations for any JRD, making it relatively immune to set size manipulations in this study.

Mou et al. (2004) proposed an alternative account for the alignment effect reversal seen in Waller et al. (2002). Their argument rests on two components: the short-lived perceptually driven egocentric system and the bidirectionality of represented alignments. Judgment of relative direction studies that measure multiple different misaligned triplets (instead of just 180º contra-aligned) routinely show errors and latencies increasing as a function of angular disparity from the preferred alignment. The one exception to that is when the judgment is 180º contra-aligned. These judgments are usually much faster and more accurate than any of the intermediary judgments. Mou et al. use this same phenomenon to explain the performance benefit seen in the rotate, contra-align conditions. This is a tempting explanation considering that this and the Waller et al. study omitted any other misaligned judgments. However, while contra-aligned judgments do show a benefit in comparison to the other misaligned judgments, they've not been shown to ever be better than those that are consistent with the preferred alignment, precisely what is seen in the reversal.

The second piece that Mou et al. use to argue against the reversal phenomenon is their perceptually driven egocentric system. As discussed in the introduction, the benefit that this system would confer would be limited to the first (or first few) JRDs, subsequent judgments would require additional offline processing to undo the previous transformation or transform retrieved representations. Either would eliminate any savings as a result of egocentric updating. Furthermore, this would predict that there would be early/late differences within a given configuration, which was not seen in this study.

Perhaps the most viable alternative account for the alignment reversal comes from May (2004). Briefly, May proposes that people can maintain two different spatial reference frames. The primary frame of reference is the one established by the body and one's awareness of their own location. People can also maintain a separate, in-the-head frame of reference. In this formulation, it is not transformations but the disparity between the two frames of reference that drives the alignment effect: the greater the angular disparity between the two, the greater the error and reaction time. This theory nicely accounts for the alignment effect reversal as well. After rotation, the body's anchoring in the primary reference frame is reversed, bringing it closer to the imagined contra-aligned judgment. Unfortunately, May's account does not speak towards the issue of where the competing representations come from and it is hard to conceive of a system that can derive the alternative representation frame without transformations. Here again, the automaticity of online updating is a challenge. May's account depends upon some form of automatic online updating in order to maintain the consistent body frame. If this process were indeed automatic, all the subjects should have shown the reversal of the alignment effect.

It is important to note that even Wang's version of the egocentric with spatial updating theory can't actually account for these results either (1999, 2007). The challenge is in the proposal that updated representations are entirely transient in nature. The only enduring egocentric representations in this model are those encoded during the initial local-view snapshot. With this constraint, online updating can only aid in tasks that occur shortly after the updating and are not disrupted by additional mental transformations (i.e. egocentric pointing and only the first JRD). While the first JRD might benefit from being able to use the transient updated representation, all subsequent JRDs will have to be based on the offline transformations of the initial local-view snapshot. Much like Mou et al.'s proposal (2004), subsequent JRDs would require additional processing, negating the benefit of updating and producing early/late differences.

These results fit squarely between two other previous studies. Waller, et al. (2002) were the first to clearly show that updating can affect the preferred alignment effect as measured by judgments of relative direction. As in their experiments, initial analyses revealed the standard alignment effect when stationary but an elimination of it after rotation. While this could be interpreted as sensorimotor awareness producing viewpoint-independent performance (e.g. Roskos-Ewoldsen et al., 1998), further analysis revealed that approximately half the subjects showed an alignment reversal. While Waller, et al. were able tease these differences out with an instructional manipulation, in this study the subjects were differentiated based on their subject visualization styles. Waller, et al. noted that their results indicated that either the automatic updating was easily ignored (c.f. Klatzky et al., 1998) or was not actually obligatory (e.g. Farrell & Robertson, 1998).

The current results can also be viewed as a JRD variant of Hodgson & Waller's extensive examination of set size effects in egocentric pointing (2006). As in this study, they found that errors were unaffected by set size increases. Latencies were affected by both set size increases and the rotation indicating that subjects were engaging in offline updating. Not surprisingly, the conclusions here parallel those of Hodgson & Waller: the lack of evidence for online updating (egocentric or allocentric) undermines earlier findings that such updating is automatic in the obligatory sense (i.e. Farrell & Thomson, 1998).

2.4 SUMMARY

This experiment was concerned with two goals: replicate the reversal of the alignment effect seen in Waller et al. (2002) and explore the role of target set size on the phenomenon. The study was framed by the predictions of egocentric updating, which posits a capacity-limited updating process that operates on individual egocentric representations. It specifically predicted that increases in set size would be met with a decrease in the alignment effect (and its reversal) for latency if subjects were updating offline, and an alignment effect decrease in error if online updating were active. If, on the other hand, an allocentric representation were at work, there would be a main effect for latency but no reversal of the alignment effect. The data showed no set size effects for pointing error, only latencies; consistent with offline updating. Furthermore, only those subjects who reported engaging in egocentric visualizations showed the reversed alignment effect after rotation.. The lack of a set size effect for pointing error could also be due to the greater magnitude of errors seen in judgments of relative direction relative to egocentric pointing. The task itself could be obscuring a set size effect on error, but only if the updating taking place is online; an assumption that is unlikely given the data.

That latency alone was affected suggests that subjects were predominantly using an offline updating strategy. This is hardly surprising given the nature of the primary task. Judgments of relative direction depend almost exclusively on offline updating. The process of imagining oneself at a different position and orientation is necessarily offline. As such, the only benefit that online updating can provide is in facilitating access to the initial representations that are consistent with the current body position. As the discussions of the modeling in later chapters will show, while this savings is small, it is sufficient to account for the effects seen.

The findings reported here closely mirror those in Hodgson & Waller (2006). Using a similar methodology they examined egocentric pointing speed and accuracy before and after rotation to targets across a wide range of set sizes. Across the set sizes, pointing errors were largely constant, but after the set size increased beyond four there was a simple main effect on latency. Attributing the set size effect to serial search processes, they arrived at the same offline-updating conclusion. In this study, even with explicit instructions for subjects to actively track the target locations, they still utilized offline updating, with some subjects not engaging in updating at all or easily ignoring it (i.e. allo-visualizers).

3.0 EXPERIMENT TWO

The first experiment showed a change in the alignment effect after subjects engaged in a 180º rotation. Combined with a set size effect limited to latencies, these results strongly suggest that participants were engaging in offline updating (Hodgson & Waller, 2006; Kelly, Avraamides, & Loomis, in press). This result was hardly surprisingly at the higher set sizes, unfortunately online updating wouldn't have been detectable had it only been used in the four target group. While it is possible to engage in JRDs with as few as three targets, it is undesirable due to the quartering of possible pointing responses. The flat latencies up through four targets seen in Hodgson & Waller (2006) might suggest that four targets represent the upper bounds in updating capacity. While JRDs provide strong evidence for the updating of spatial representations, their minimum working memory resources might already be pushing the capacity limitations of most people. Furthermore, the predominantly offline nature of the task (i.e. imagining a translation and rotation), might predispose participants to engaging in offline updating exclusively.

Instead of switching to egocentric pointing and merely repeating the set size manipulation, effectively replicating the Hodgson & Waller (2006) study, a different approach was decided upon. Instead of using set size as a working memory manipulation, a dual-task interference methodology was settled upon. Dual-tasks have been used before in spatial updating studies (Book & Garling, 1981; Linberg & Garling, 1981, 1983; May & Klatzky, 2000). As was discussed in chapter one, while concurrent tasks do interfere with spatial updating, it is taken for granted that the updating is online and automatic; there has been no consideration that the decrement witnessed might actually be due to the subjects engaging in offline updating under cognitive load. Additionally, the concurrent tasks used have been relatively complex, introducing the possibility of interference at other levels of processing. Furthermore, when multiple concurrent tasks have been compared there has been no consideration that the alternative tasks might introduce different cognitive loads. I am aware of no published studies that look at dual-task interference comparing verbal and spatial secondary tasks (but, Hodgson, 2005), and none that examines isomorphic secondary tasks.

The second experiment had subjects study three target configurations and engage in egocentric pointing before and after an experimenter controlled 135º rotation. In the dual task condition, participants engaged in either a verbal or a spatial 1-back task (see appendix C) during the retention interval before the stationary pointing and *during* the rotation. Again, participants were explicitly asked to track the target locations during the rotation. If, in the single task condition, participants are engaging in online updating there should be no latency difference across the pointing phases, but a significant difference in errors after rotation due to the updating. In the dual-task conditions it is expected that the verbal 1-back will provide minimal interference showing latencies and errors similar to the single-task conditions. However, those that are engaging in the spatial 1-back would experience significant interference, forcing participants to utilize offline updating instead, resulting in significantly greater latencies after rotation. There is another possibility that must be considered. As experiment one and Hodgson & Waller (2006) show, subjects might not engage in online updating at all. If this were the case, we'd expect to see post-rotation pointing latencies to be significantly greater than stationary pointing across all manipulations. Furthermore, if subjects are not actively updating the target locations during rotation then there will be no interference in the spatial 1-back. In other words, latencies and errors will not be affected by task-load or secondary task-type. If this is the case, then more careful analyses of the 1-back performance will likely be required.

Drawing predictions based on the other representational theories previously considered is particularly challenging for this study. The cognitive mapping theories are largely mute on the role of working memory generally, and certainly as it pertains to the interference of egocentric information (i.e. spatial 1-back cues) and the allocentric cognitive map. Similarly, while Mou et al.'s (2004) theory does incorporate an egocentric perceptual system, it is not clear if it would even be recruited for the spatial 1-back. Sholl's self-reference theory (2001) apparently would predict interference in the dual-spatial 1-back condition, similar to that predicted if subjects were engaging in egocentric-online updating. One thing to note, however, is that each of these theories proposes that the anchoring process, situating the representation of the self within the larger allocentric network, is wholly automatic. As such, the single task conditions should show equal latencies across the different pointing phases; there should be no evidence of offline updating at all. The results from experiment one and Hodgson & Waller (2006) already undermine the automatic anchoring hypothesis.

As a preview of the results, egocentric pointing performance is undistinguishable along the lines task-load or secondary task-type. Pointing performance strongly suggests that participants are engaging in offline updating across the board. Examination of the 1-back accuracies does show a measure of interference for the spatial 1-back, most significantly during the dual-task rotation blocks. The distribution of 1-back errors shows that the interference is occurring late in the 1-back trial, suggesting that subjects were starting to engage in offline updating shortly before the start of the post-rotation egocentric pointing blocks.

3.1 METHODS

3.1.1 Participants

Thirty-six undergraduates (16 female, 20 male) from Pittsburgh and Philadelphia universities participated for course credit or pay. All participants were tested individually in two-hour sessions. Three subjects were excluded due to equipment failure. Four more subjects were excluded because of difficulties understanding the task or an inability to effectively use the joystick. The remaining twenty-nine participants (13 female, 16 male) were all able to complete the study. Again, analyses showed no significant differences between compensation or university, allowing the sampled populations to be collapsed.

3.1.2 Materials

Ten configurations of targets were generated for this study (two training sets and eight testing sets) (appendix A). Configurations were assembled from 30.5cm (1ft) tall orange cones with 7.6cm (3in) reflective letter labels. Each configuration fit within a 3m square region, with a minimum of 0.5m separating each target. The initial pointing-training configuration was the same 8-target diamond pattern used in experiment one. All other configurations were comprised of three targets each, pseudo-randomly generated by computer with the following constraints: all targets must reside along the edges of the space, with no edge can containing more than two targets. Labels were assigned to targets pseudorandomly to prevent label repetition in consecutive configurations and to minimize phonetic similarity of labels.

Participants wore a pair of blacked-out wrap-around sunglasses, a pair of passive noise-canceling headphones (for probe presentation), and held a high-precision joystick (for responding). Participants were blindfolded for the entire study except when studying the target configurations. White noise was played over the headphones for the duration of the trial to mask the location and movement of the experimenter.

3.1.3 Pointing task

The primary task for this experiment was the egocentric pointing task. Generally speaking, it followed the same structure as seen in experiment one. There was a structured study phase ensuring participants know the target locations. However, this time there were three testing phases: *baseline*, *stationary*, and *rotated*. During the dual-task conditions the secondary tasks were inserted during the retention interval after study and during the rotation (figure 3.1).

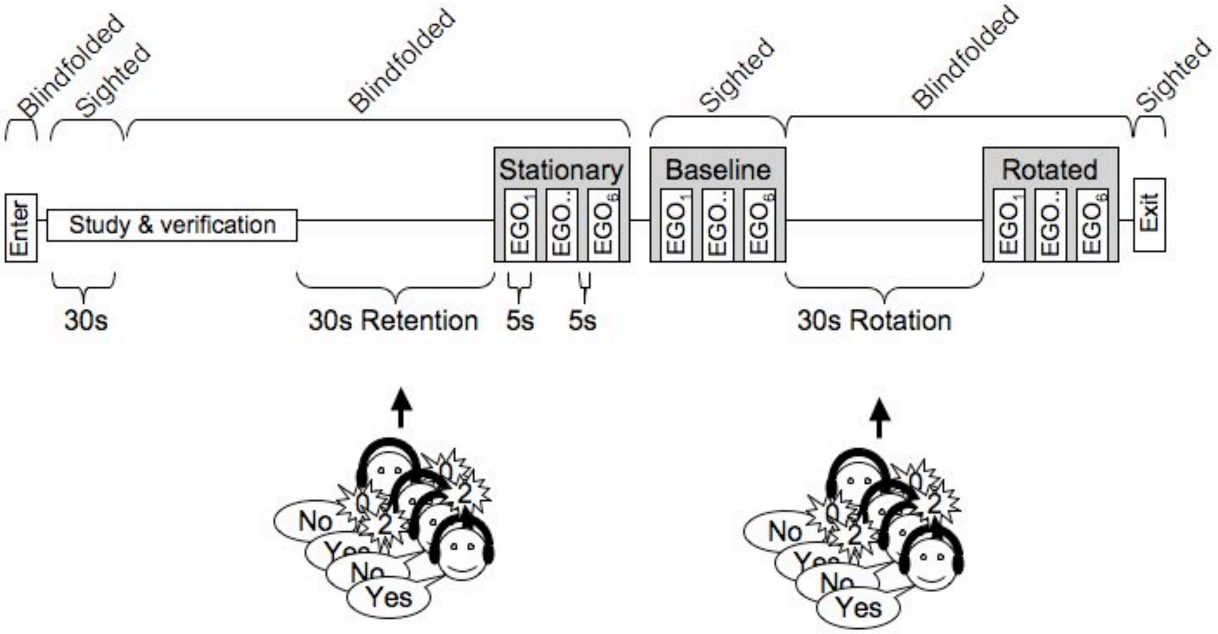


Figure 3.1 Experiment two per-configuration structure and timings. 1-Back tasks were inserted during retention and rotation intervals.

3.1.3.1 Study phase After being escorted into the experiment area subjects lifted the blindfold and were given an initial thirty seconds to study to locations of the targets. The computer then began the sighted pointing assessment stage. The goal here was to be sure that subjects could point to the targets accurately enough before actually testing their memory for the targets. This stage lasted until either two minutes elapsed or if after three iterations the subject's average pointing error for each target was less than 15°. If the sighted pointing stage exceeded two minutes the entire configuration block was aborted and a new one begun. This ejection policy was implemented to prevent subjects from languishing within a single configuration. During the sighted pointing assessment stage the computer prompted subjects to point to each target. If the pointing response given was off by more than 15° the computer provided the subject with corrective feedback (e.g. "A little more to the left") and prompted them for the next target. After completing the sighted pointing assessment, subjects replaced the blindfold and then began the blindfolded assessment stage. Like the sighted stage, it lasted until either two minutes had elapsed or the per-target average error was less than 15° after three iterations. As before, if the two-minute time limit expired, the configuration block was aborted. If at anytime during this assessment the computer determined that the subject could not pass (i.e. the average error for any given target could not be less than 15°), the subject was permitted to lift the blindfold and study the targets for an additional fifteen seconds before resuming the blindfolded assessment. Upon successfully completing the blindfolded assessment, it was assumed that subjects had sufficiently learned the target locations and the testing phase was begun.

3.1.3.2 Testing phase Immediately following the study phase subjects either received a thirty second retention interval where they were instructed to wait quietly until prompted or they performed the secondary task. Next the computer prompted them to point to each of the targets at least once for a total of six responses. This block of responses comprised the *stay-pointing* response set. Subjects were then prompted to lift the blindfold. During this sighted phase they were again prompted to point to each of the targets for a total of six responses. This was done to correct for any memory error and to provide the *baseline-pointing* response set. Subjects then replaced the blindfold and were told that they were to be rotated by the experimenter. The subject was to mentally track the locations of the targets since they would be pointing to them again after the rotation. Subjects either rotated or rotated and performed the secondary task. The experimenter's rotation of the subject was always 135° with the direction randomized. The timing of the rotation was such that it took approximately thirty seconds, equivalent to both the retention interval and the secondary task duration (approximately 5°/s). After completing the rotation, the computer prompted subjects to complete a total of six pointing responses. These responses comprised the *rotate-pointing* response set. Upon completion subjects were permitted to lift the blindfold and exited the experiment area to wait for the next trial.

3.1.4 Continuous auditory 1-back task

Two isomorphic secondary tasks, based on a general auditory, continuous response 1-back task[3], were developed in order to primarily engage modality specific processing (see appendix C for details). Stimuli had to be delivered auditorily due to the structure of the pointing task (i.e. standing with a blindfold on). In the interest of time, the tasks were continuous response (i.e. for every cue they responded "yes" or "no" depending on the match to the previous cue), as opposed to the cue-probe version (e.g. McElree, 2001). Each version utilized the same stimuli set of three numbers (0, 2 & 7) read from three different spatial locations over the headphones (left, right, and center). The difference between the two tasks was in what feature of the cues subjects were to attend and respond to. In the verbal 1-back participants were to match the number that they heard, regardless of the location. The spatial 1-back had participants respond based on the location, regardless of the actual number heard.

---

[3] It should be noted here that the 1-back is not terribly difficult and the initial hope was to use a 2-back task. However, piloting of the spatial 2-back while tracking targets during the rotation resulted in a 100% attrition rate. Subjects reported that while the dual-task 1-back was moderately difficult, the 2-back was "simply impossible".

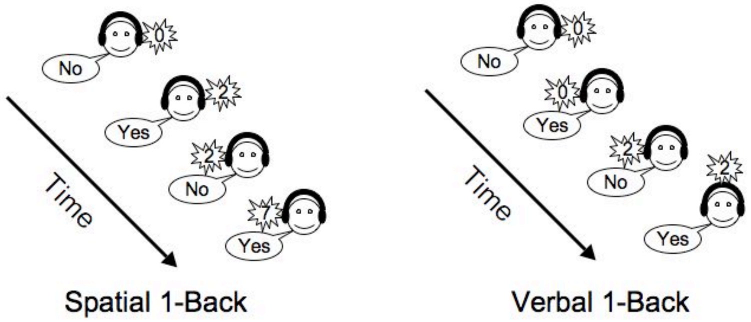


Figure 3.2 Spatial and verbal 1-back tasks. Subjects respond to the match of the current cue to the previous based on the location (spatial) or number (verbal).

Both 1-back tasks averaged twelve cues, with a two second delay between each presentation. Total 1-back trial duration averaged thirty seconds. Cue presentation was randomized with an average base rate of 0.5. The experimenter recorded subject verbal responses using a remote control device (so they could be recorded while the experimenter rotated the subject).

Participants were blindfolded during all 1-back trials. During the 1-back only blocks, participants completed three trials: practice, stationary and rotating, with the stationary and rotating trials randomly ordered. As in the pointing blocks, rotation was controlled by the experimenter at a rate of around 5°/s.

3.1.5 Experiment structure

After obtaining informed consent participants were randomly assigned to one of two groups (*spatial* or *verbal*) and were fitted with a pair of passive noise canceling headphones. The computer would deliver all the prompts and instructions for the experiment over these headphones. After an initial volume check to test levels and the ability of subjects to differentiate the three different stereo locations, the computer controlled instruction phase was begun.

Subjects were first introduced to a generalized 1-back task. After addressing any questions or confusions, the subject received more specific instructions for the specific 1-back version that they were to receive (i.e. *spatial* or *verbal*). All questions were addressed before giving them three sample 1-back trials. Participants were next familiarized with the joystick and pointing task in a procedural similar to that described in experiment one, excluding the JRD instructions. After familiarization, subjects were provided with two practice trials (single then dual), where they were introduced to the full experiment structure. All questions were addressed before data collection began.

Each participant received a different pseudorandom presentation of twelve blocks (four pointing, four 1-back, and four dual-task) such that each of four triplets contained one of each type. Participants were given a two-minute break in between each block and a ten-minute break at the halfway point. After completing the experiment, participants completed a debriefing questionnaire similar to the one from experiment one but with additional content covering 1-back and dual task performance (appendix B).

3.1.6 Data cleaning

As in experiment one, for each egocentric pointing response made four data measures were taken: absolute reaction time, time to first movement, absolute and signed pointing error. Any responses exceeding three standard deviations for latency (≤0.5s, ≥3.5s) or absolute error (≥ 52º) were excluded for that subject. Based on this criterion, 72 of 696 responses were excluded (10%). The responses within each manipulation of pointing (baseline, stay & rotate) and task-load (single-, and dual-task) were averaged together. If any subject had less than 50% (twelve pointing responses) of the data available for any given cell they were excluded entirely. No subjects were excluded from the analyses.

3.2 RESULTS

The current experiment consisted of two tasks: egocentric pointing and the continuous 1-back. For each task considered, the RMANOVA has two common factors: task-load (single or dual, within-subject) and 1-back type (spatial or verbal, between-subject). Except where noted, all analyses are based off of this basic template.

The core, theoretically relevant, analyses are presented first. Secondary and tertiary analyses exploring alternative interpretations and subject behaviors are included for completeness. Those interested in just the core analyses can skip to the discussion (3.3) after the 1-back error distribution results.

3.2.1 Egocentric pointing

Each of the four aggregate dependent measures for egocentric pointing (absolute latency, movement latency, absolute error, and signed error) were examined using a 2x2x3 RMANOVA. The two within-subjects factors were task-load (single or dual) and pointing type (baseline, stay, or rotate). The type of 1-back (spatial or verbal) performed during dual-task conditions was the between-subjects factor. As in experiment one, the differences between movement time and absolute latency were negligible. Similarly, analyses of signed errors revealed no systematic differences. Only the results from absolute latencies and errors will be reported here. As was seen in experiment one, there was no significant influence of visualization type on egocentric pointing, hence its exclusion from the general RMANOVA model.

3.2.1.1 Latency For latency there was a significant main effect of pointing type, F(2,54)=47.1, p<0.001. Post-hoc analyses using a Bonferroni correction showed no differences between baseline and stay, but a significant difference between rotate and the other two, p<0.001. Specifically, pointing after rotation took an average of 0.5s longer to complete (figure 3.3). Neither 1-back type nor task-load were significant, F(1,27)=1.46, p>0.05, and F(1,27)=0.3, p>0.05, respectively. Likewise, all of the interactions failed to approach marginal significance.

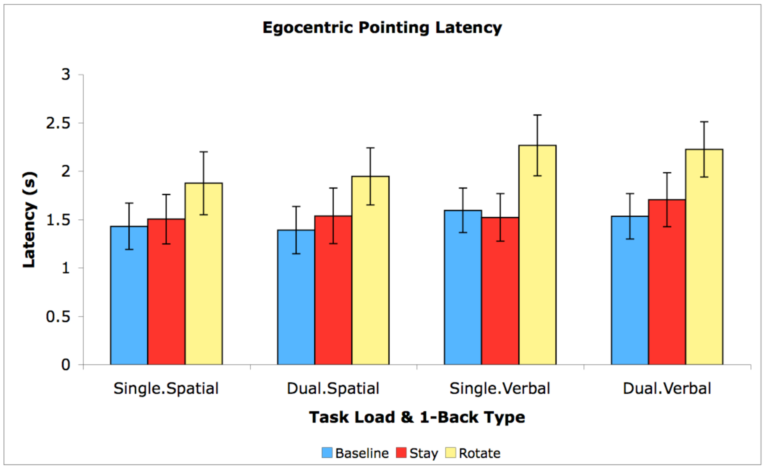


Figure 3.3 Egocentric pointing latency. Error bars are 95% CI.

3.2.1.2 Error The results of the pointing error analyses mirrored those of latency. Pointing type showed a significant main effect, F(2,54)=50.4, p<0.001, with rotate being significantly greater than baseline and stay, p<0.001. After rotation subjects erred by 24° on average, with stay and baseline both averaging a little over 14° (figure 3.4). The effect of 1-back type was not significant, F(1,27)=1.35, p>0.05; and neither was the effect of task load, F(1,27)=0.9, p>0.05. None of the subsequent interactions were significant.

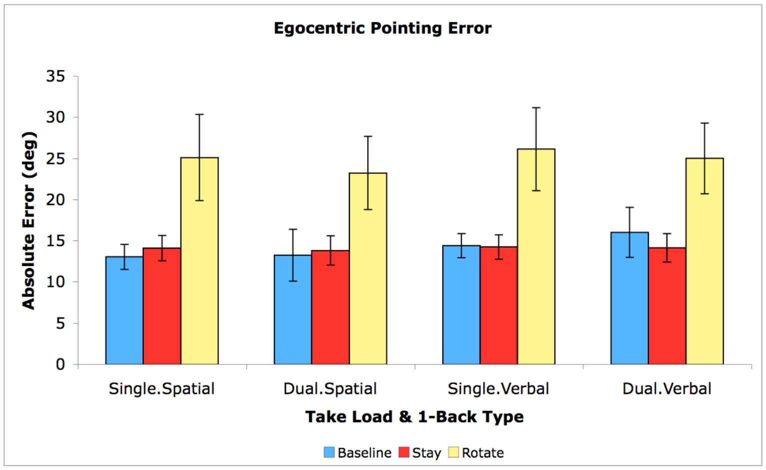


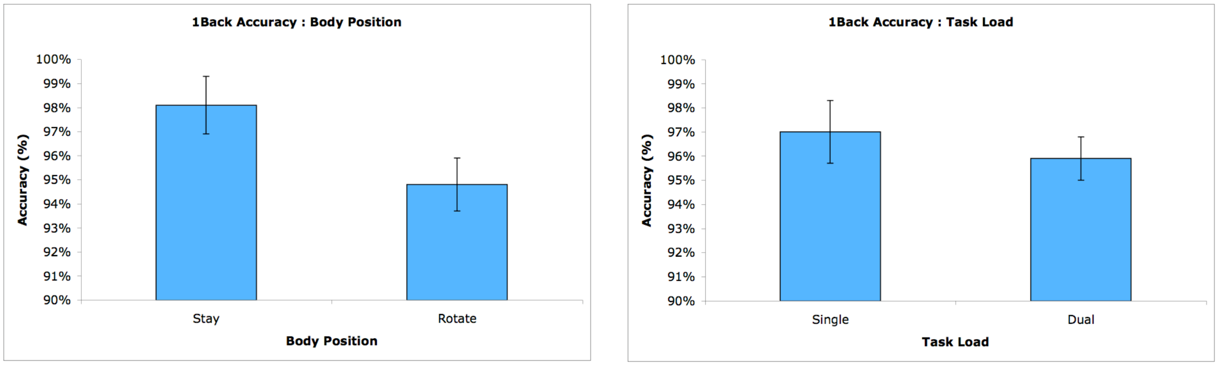
Figure 3.4 Egocentric pointing error. Error bars are 95% CI.

3.2.2 1-back performance

The structure of the continuous 1-back task eliminates the possibility of examining response latencies. Accuracy and sensitivity (d') were analyzed with a 2x2x2 RMANOVA. Body position (stay or rotate) and task-load (single or dual) were within-subject factors. The type of 1-back (spatial or verbal) was the between-subject factor.

3.2.2.1 Accuracy Body position showed a significant main effect for accuracy, F(1,27)=50.5, p<0.001, such that performing the 1-back while rotating (95% accuracy) was slightly more difficult than when stationary (98% accuracy). Task load also showed a significant main effect, F(1,27)=4.9, p<0.05, with single task performance better than dual-task performance (97% and

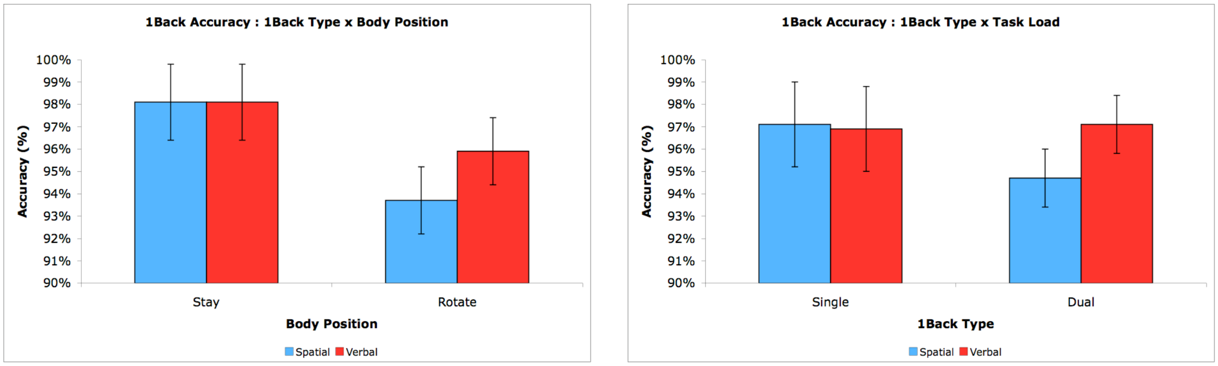
96% respectively). The type of 1-back performed was not significant, F(1,27)=1.3, p>0.05 (figure 3.5).



a b

Figure 3.5 1-Back accuracy as a function of body position (a) and task load (b). Error bars are 95% CI.

While 1-back type showed no main effects, the interaction between it and body position was significant, F(1,27)=5.6, p<0.05 (figure 3.6, a). Specifically, while there were no differences between the two groups (spatial and verbal) when stationary, rotation impaired the accuracy for the spatial group (93%) more than the verbal group (96%). A significant interaction between task-load and 1-back type was also found, F(1,27)=6.4, p<0.01. Again, little difference is seen between the spatial and verbal 1-back groups when just performing the 1-back task. When subjects perform the 1-back in the midst of the pointing block, spatial 1-back performance (95%) is worse than verbal performance (97%) (figure 3.6, b). While the interaction between task-load and position was not significant, the three-way interaction of task-load, position, and 1-back type was marginal, F(1,27)=3.67, p<0.06. Not surprisingly, dual-task, rotate, spatial 1-back showed the worst accuracy (91%) (table 3.1).



a b

Figure 3.6 Interactions of 1-back type with body position (a) and task load (b). Error bars are 95% CI.

Table 3.1 1-Back accuracy and sensitivity

1-Back Type	Body Position	Task Load	% Correct (SE)	d' (SE)
Spatial	Stay	Single	98.5% (0.9%)	3.05 (0.2)
		Dual	97.7% (0.9%)	2.69 (0.2)
	Rotate	Single	95.7% (0.9%)	2.51 (0.3)
		Dual	91.6% (0.8%)	1.68 (0.2)
Verbal	Stay	Single	98.2% (0.9%)	3.11 (0.1)
		Dual	98.1% (0.9%)	3.09 (0.2)
	Rotate	Single	95.7% (1.1%)	2.46 (0.2)
		Dual	96.1% (0.8%)	2.8 (0.2)

3.2.2.2 Sensitivity D-primes were calculated and applied to the same RMANOVA model. A significant main effect for 1-back type was found, $F(1,27)=7.76$, $p<0.01$, with the verbal 1-back showing greater sensitivity (2.87) than the spatial 1-back (2.48). There was also a significant main effect for body position, $F(1,27)=16.59$, $p<0.0001$, with 1-backs performed while rotating less sensitive (2.37) than when stationary (2.98) (table 3.1). Mirroring the accuracy results, there was a significant interaction of 1-back type and task-load, $F(1,27)=5.6$, $p<0.05$, with the dual-task spatial 1-back showing the least sensitivity. The three-way interaction of 1-back type, task-load and body position was not significant, $F(1,27)=1.7$, $p>0.1$.

3.2.2.3 Error distribution Since each response within the stream of cues provided by the subject was recorded, when the errors occurred could also be examined. Each 1-back trial contained an average of 12 responses enabling an easy temporal clustering by thirds (early, middle, late). This within-subject temporal factor was added to the previous RMANOVA model. For ease of interpretation errors were transformed into percentage points deducted from the subject's accuracy score.

The previously reported significant main effects and interactions are all largely unchanged. The temporal factor showed a significant main effect, $F(2,54)=32.9$, $p<0.001$, with errors increasing with time. The interaction of time and position was also significant, $F(2,54)=28.9$, $p<0.001$, showing a largely stable error distribution when stationary, but a skewed distribution towards the later two thirds after rotation. The interaction of task-load and time was significant, $F(2,54)=7.2$, $p<0.01$, showing skewed distributions towards the later two-thirds, but the greatest performance decrement for the final third in the dual-task condition. The interaction between 1-back type and time was not significant, $F(2,54)=2.8$, $p>0.1$.

The three-way interaction between 1-back type, time and task-load was significant, $F(2,54)=17.9$, $p<0.001$. During the final third of the spatial 1-back, dual-task performance showed the greatest number of errors (figure 3.7). A similar pattern is seen for the significant interaction between 1-back type, time and position, $F(2,54)=10.2$, $p<0.005$. Again, for the final third of the spatial 1-back, rotation performance showed the greatest number of errors (figure 3.8). The interaction of position, time, and task-load was significant, $F(2,54)=4.3$, $p<0.05$.

Finally, the four-way interaction of 1-back type, position, task-load and time was significant, F(2,54)=9.4, $p<0.005$.

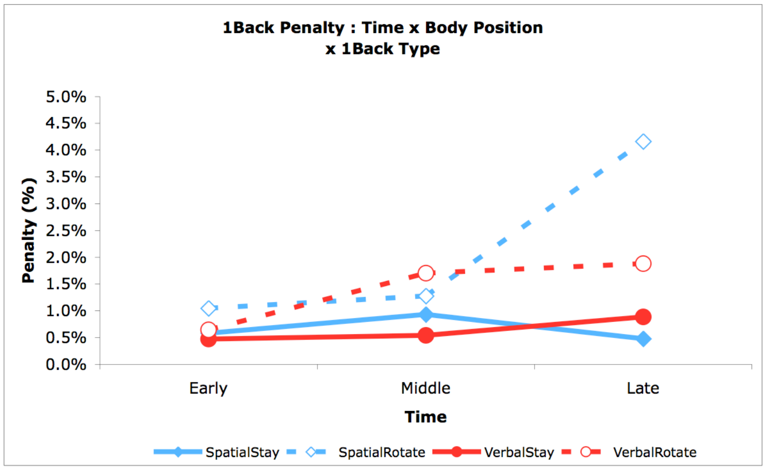


Figure 3.7 Temporal distribution of 1-back errors as a function of body position and 1-back type (plotted as decrements to accuracy score). Error bars omitted for clarity.

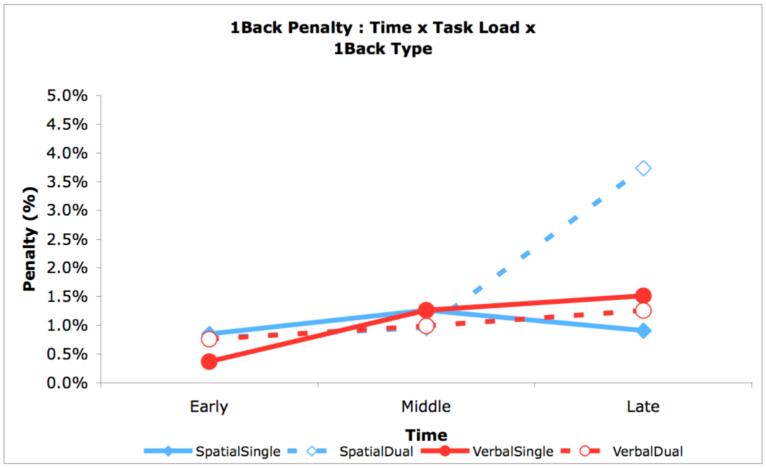


Figure 3.8 Temporal distribution of 1-back errors as a function of task load and 1-back type (plotted as decrements to accuracy score). Error bars omitted for clarity.

3.2.3 Speed/Accuracy

As in experiment one, subjects were responding under time pressures. Speed/accuracy correlations were computed for each subject within each of the condition combinations. The average correlation was r=-0.08. To test the possibility that subjects might exhibit different behavior in response to task demands, the individual correlations were analyzed using the template RMANOVA. None of the factors exhibited any significant effects on the speed/accuracy trade off.

3.2.4 Gender differences

All of the previous ANOVA models were also run with gender as an additional factor. In no case was gender a significant factor.

3.2.5 Questionnaire responses

As in experiment one, the majority of the debriefing questions probed the frequency of use of various strategies for visualization and rehearsing. Both ANOVA models with frequencies as covariates and simple split-halves failed to find any differentiating responses.

3.3 DISCUSSION

This experiment hoped to provide participants with a simpler situation wherein they would be more likely to engage in online updating. The two secondary tasks were introduced to explore how different working memory requirements would affect spatial updating. Purely egocentric theories would predicted that there would be little difference in the updating performance between the single-task and verbal dual-task conditions since there would be no overlap in working memory resources during the dual-task performance. When participants were asked to engage in the spatial dual-task, there should be a contention for spatial working memory resources forcing participants to shift from online-egocentric to offline updating. Given the previous experiment and the results of Hodgson & Waller (2006) it was hardly surprising that there was no difference in spatial updating across task load or secondary task type (figures 3.3 & 3.4). That the secondary task did not significantly impact performance strongly suggests that, even in the single task condition, participants were predominantly engaging in offline updating. The secondary task can't interfere with online updating if the subjects aren't actually engaging in it.

While dual-task interference wasn't apparent in the pointing task it was in the 1-back tasks. Having to track or maintain target locations did negatively impact 1-back accuracy slightly (97% vs. 96%). More interestingly we see effects of 1-back type here. Both the interactions between 1-back type and body position, and 1-back type and task-load were significant. The accuracy for spatial-rotate and spatial-dual-task were both significantly worse than their verbal counterparts (figure 3.6). While the type of 1-back did not differentially affect pointing performance, the type of 1-back was differentially affected by the pointing task.

Looking at the temporal distribution of errors during 1-back trials provides further evidence for subjects engaging in offline updating (figures 3.7 & 3.8). The interaction between time and task-load shows that when subjects are performing both the 1-back and tracking targets, they make most of their errors towards the end of the 1-back trial. These results are at odds with the predictions of both a high-capacity online-egocentric and online-allocentric updating process. If they were engaging in online updating the errors should be evenly distributed across the trial. This effect was even greater for those performing the spatial 1-back, suggesting some spatial modality specific interference.

Two issues with this study are readily apparent. First, the interference seen in the spatial 1-back group under dual task conditions is relatively minor (2% accuracy penalty). Presumably a strong effect would be seen if a 2-back task were used. Unfortunately, the piloting of the 2-back under dual-task conditions revealed that while the 1-back may be too easy, the 2-back is simply intractable. Not a single participant was able to complete a full spatial 2-back trial while tracking the targets; many described it as being “simply impossible”. If the pilot subjects were engaging in offline updating like the study participants, then this difficulty would have not been due to capacity limitations during online updating, but rather as they try to update the targets towards the end of the 2-back trial (after the movement).

The second issue is the actual movement manipulation. In order to fit the 1-back task into the movement period, the rotation was experimenter controlled at a rather slow rate. The rotation rate of 5º/s is simply unrealistic for normal movements. This artificiality may have been below the detectable range of the vestibular system, which in turn may have prevented the online updating process from being engaged. If this was actually the case, then dual-task manipulations may only be possible for translation studies that operate over longer timescales; natural rotations are simply too brief to insert secondary tasks into.

3.4 SUMMARY

The pointing results from experiment two showed both increased latencies and errors for post-rotation responses, the hallmark of offline updating. While the expected dual-task interference was not seen in the egocentric pointing, it was seen in the spatial 1-back performance. That the spatial 1-back errors were predominantly occurring late in the trial is suggests that those participants began to update target locations just before they would be needed in the subsequent pointing phase (i.e. they were engaging in offline updating).

These results and those from the first experiment further drive home the pervasiveness of offline updating even when subjects are instructed to actively track the targets. While previous dual-task studies have shown updating interference, they have used more demanding tasks or failed to equate alternative secondary tasks in terms of processing demands (Book & Garling, 1981; Linberg & Garling, 1981, 1983; May & Klatzky, 2000). Here we see no updating interference while using tasks that are much simpler and isomorphic. These results mirror some unpublished work by Hodgson (2005), who had compared the updating performance of subjects who engaged in backward counting or a Shepard & Metzler (1971) style object rotation task.

Why have earlier works exhibited interference, further supporting automatic online updating, whereas these later ones have not? These issues will be considered in depth in chapter six, but one element worth noting is that the earlier studies had subjects engage in complex guided locomotion as opposed to simple rotations. The duration of a physical translation is often much greater than a rotation, affording subjects with ample cognitive slack time. This extra time might permit subjects to engage in opportunistic offline updating (i.e. cognitively and incrementally tracking targets). When a secondary task is introduced, the opportunistic updating can no longer be done, forcing them to rely upon updating performed at test. However, these locomotion studies incorporate more complex movements, which introduce even greater errors. This combination of factors could produce the lower errors seen in control conditions and greater errors under load, lending itself to the online & interference interpretations.

4.0 MODELING OF SPATIAL BEHAVIOR

Despite the tremendous growth in the relevance of computational cognitive models, it is worth revisiting the core point of Newell's twenty questions paper (1973), particularly as it applies to spatial reasoning research. Looking at the state of psychological research then, Newell was distressed by the continued process of looking at micro-phenomena in isolation from the larger psychological system. While a great deal can be learned about those phenomena, a total, holistic understanding of the psychological processes involved would necessarily be lacking until they could be situated within a more unified framework. While much progress has been made on this front with generalized cognitive architectures both symbolic (e.g. Anderson et al., 2004) and connectionist (e.g. Schneider & Chein, 2003), Newell's comments can just as easily be applied to the current state of spatial reasoning theories.

A review of the article abstracts published in the journal *Spatial cognition and computation* illustrates this point quite nicely. Of the ninety-eight articles relating to human or rodent spatial reasoning published since the journal's inception[4], only twenty-one propose a formal model of any sort. Out of those, only nine are computational (i.e. mathematic or executable), and only two are situated within a larger theory of human functioning that constrains the model in terms of memory, control or perceptual processes (Gugerty & Rodes,

---

[4] Ignoring articles on geographical information systems and robot spatial processing in the absence of psychological or neurological inspiration.

2007; Gunzelmann, Anderson, & Douglass, 2004). Unfortunately, of the four major representational theories in spatial reasoning (Mou & McNamara, 2002; O'Keefe & Nadel, 1978; Sholl, 2001; Wang, 1999) only the cognitive mapping theory has been implemented as a computational system (Burgess, Jackson, Hartley, & O'Keefe, 2000; Burgess, Maguire, & O'Keefe, 2002; Byrne, Becker, & Burgess, 2007; Byrne & Becker, 2004). While the majority of the cognitive mapping models have been focused on reproducing the neurological phenomena of place- and grid-cells (Burgess et al., 2000; Byrne et al., 2007; Byrne & Becker, 2004), they have recently been used to model the rudimentary navigation behavior of rats (Burgess, Donnett, Jeffery, & O'Keefe, 1999; Burgess et al., 2000). This is not meant to downplay the significance of these published studies but rather to highlight the fact that while modeling has made successful progress into many psychological domains it has yet to really take root in the spatial domain.

Why is this the case? While human spatial cognition is likely more complex than that of rats, is it any more complex than other areas of human reasoning that have been successfully modeled? It could be the case that the core phenomena have yet to be adequately investigated (or even agreed upon), but as the evolution of any cognitive architecture can attest to, this is not a necessary constraint to make significant theoretical and architectural advances. While a few new proposals have emerged, they have yet to be implemented or applied to human data (e.g. Gunzelmann, 2006; Jones et al., 2006). I strongly suspect that another barrier to spatial modeling has been technological; it may just be that only now have the architectural and computer systems become powerful enough to begin to address models of spatial reasoning.

In an effort to fill this gap, ACT-R/S (Harrison & Schunn, 2003) was developed. It is an implementation of an egocentric with spatial updating representational theory within the broader constraints of the ACT-R cognitive architecture (Anderson et al., 2004). Before delving into the theoretical aspects of ACT-R/S, it must be acknowledged that not only does the previous empirical work reported here represent the same twenty questions that Newell was concerned with, but also that the theory is only partially specified. Every journey must start with the first steps; the work presented here are those steps.

4.1 ACT-R/S THEORY

Before introducing the theoretical perspective underlying ACT-R/S it should be noted that it has been implemented within ACT-R because of my own familiarity with the architecture. There is nothing preventing it from being implemented in most other cognitive architectures that incorporate working and long-term memories as well as a minimum level of parallelism (most likely at a working memory resource level) such as Soar (Laird, Newell, & Rosenbloom, 1987), or EPIC (Kieras & Meyer, 1997). Nor is there anything preventing it from being grounded within connectionist architectures (Just, Carpenter, & Varma, 1999; Schneider & Chein, 2003). Indeed, ACT-R/S has been theoretically applied to the phenomenon of place-cell firing patterns (Harrison & Schunn, 2003). This introduction to the theory is only concerned with behavioral evidence, those seeking some of the neurological influences are directed towards (Harrison & Schunn, 2003).

At its core, ACT-R/S is a theory of egocentric representation and processing similar to that proposed by Wang (1999). It proposes that, at the lowest representational level, spatial memories are all individual and egocentric (as opposed to holistic cognitive maps O'Keefe & Nadel, 1978). These representations arise from attending to the visual or auditory percepts of objects in the environment, typically, but not exclusively, in support of navigation and scene recognition. In order to maintain spatial consistency across time and space, currently attended representations within working memory can be updated automatically by path-integration from self-motion (Presson & Montello, 1994; Rieser, 1989) or consciously by serial mental transformations (Wang, 1999; Wraga, Creem, & Proffitt, 2000). Only the currently attended subset of spatial representations of objects in the environment can be updated, not only because it is functionally unnecessary to update all objects but also because it is computationally prohibitive. In other words, spatial updating is constrained by the working memory resources currently available to the spatial system (Hodgson & Waller, 2006; Wang et al., 2006). Whether or not those working memory resources are unique to the spatial system or shared is largely an issue for the constraining architecture, however ample evidence exists that there is a separate visiospatial working memory and possibly an entirely separate spatial working memory (Baddley, 2003; Klauer & Zhao, 2004; Lyon, Gunzelmann, & Gluck, 2004; Sholl, Fraone, & Allen, 2004).

These individual egocentric representations naturally have preferred alignments, which give rise to the alignment effects explored in experiment one. The union of two of these representations gives rise to quasi-unique locations in space, which can likewise be transformed by spatial updating processes. These location representations cannot only be used to recognize positions in space relative to landmarks in the environment, but also to compute simple traversals from one location to another. This locational representational scheme is currently underspecified in the theory, due to both a lack of data and time, and represents the immediate future direction for the theory, and will not be discussed further.

ACT-R/S takes the very firm stance that at the lowest level spatial representations are egocentric. This raises many obvious questions regarding spatial phenomena that have been taken as evidence for a fundamentally allocentric representation, such as intrinsic alignments (Mou & McNamara, 2002), or hippocampal place-cells (O'Keefe & Nadel, 1978). As mentioned previously, there is a theoretical account for the place-cell phenomenon (Harrison & Schunn, 2003) which is based largely on the work of Cohen & Eichenbaum (1991), and basically views the phenomenon as a reflection of the regular use of the same set of landmarks to define locations. The issue of intrinsic alignments, however, does present a legitimate challenge to an entirely egocentric theory. However, it is my contention that much of the data supposedly supporting allocentric representations is actually the result of higher order representations scaffolded up by the use of egocentric and other nonspatial representations. For example, Mast, Kosslyn, & Berthoz (1999) have noted that intrinsic alignment can actually arise through the use of retinotopic style visualizations without the need for actual three-dimensional representations (i.e. people are literally using a 2D map-like visualization, activating the visual perceptual systems and not this spatial system).

The most noticeable deviation from Wang's (1999) theory is in the nature of updated representations. In her original formulation of the theory, Wang proposed that updated representations were entirely transient in nature, never persisting beyond working memory (Waller & Hodgson, 2006; Wang, 1999). During the functional and computational design of ACT-R/S it became apparent that updated representations needed to be able to make the transition into long-term memory. From an activation perspective, these updated representations might decay rapidly in the absence of rehearsal, making them effectively unrecoverable relative to the original studied representations, but they do need to be accessible on the time scale of minutes in order to enable the savings seen in updating studies (Hodgson & Waller, 2006; Kelly, Avraamides, & Loomis, in press).

Inevitably this theoretical account will run into challenges as more spatial phenomena are modeled, but by putting all the cards on the table with an executable theory, it will be less amenable to vague predictions and post hoc explanations. The next section delves deeper into the details as they apply to the specific implementation within the ACT-R cognitive architecture.

4.2 ACT-R/S IMPLEMENTATION

As was mentioned previously, the implementation of this theory (and even its naming) is largely due to my own familiarity with the ACT-R architecture. While on one level all cognitive architectures are basically wrong, ACT-R presents a nice balance of explanatory breadth, cognitive penetrability, ease of learning, and speed of development. Because of these characteristics, it enables the rapid development and evaluation of additional theoretical extensions such as ACT-R/S.

While ACT-R was initially a strictly serial production system, in recent years additional levels of parallelism have been introduced through the standardized use of functional modules and buffers. While the process of production instantiation, selection, and firing is still explicitly serial, the actions initiated by the productions can execute in parallel across different modules as accessed through their respective buffers. Within this system, ACT-R/S introduces a new module that is accessed through the *configural* buffer.

4.2.1 Attending

Like ACT-R's *visual* and *aural* buffers, new spatial representations can only be encoded through an explicit request to the configural module after a preattentive search has returned a viable visual location (table 4.1, left). However, because spatial information can come from multiple modalities, the attending to a configural representation can also be driven by the detection of a spatially localized auditory event (table 4.1, right). The time it takes to attend to a configural chunk is currently controlled by the *ConfiguralEncodingTime* parameter, currently set to the default visual chunk encoding time of 0.135s.

Table 4.1 Example search and attending productions for visual and aural modalities.

```
(p search-for-configural-vis           (p search-for-configural-aural
 =goal>                                  =goal>
  isa goal                               isa goal
  ==>                                    ==>
  +visual-location>                      +aural-location>
  isa visual-location                    isa audio-event
  kind configural)                       kind configural)

(p attend-to-configural-vis            (p attend-to-configural-aural
 =goal>                                  =goal>
  isa goal                               isa goal
 =visual-location>                       =aural-location>
  isa visual-location                    isa audio-event
  kind configural                        kind configural
==>                                    ==>
  +configural>                           +configural>
  isa move-attention                     isa move-attention
  screen-pos =visual-location            aural-pos =aural-location
  +visual>                               +aural>
  isa move-attention                     isa sound
  screen-pos =visual-location)           event =aural-location)
```

4.2.2 Representations

Situated within the predominantly symbolic framework of ACT-R, the spatial representations must also be symbolic. While the slot values of the configural chunks are exact values, ideally they would actually be fuzzy values representing the egocentric vectors to the bounding edges of the object (table 4.2). The vectors represent the minimal amount of information to localize and navigate around, above or below. Normally the configural chunks don't contain any uniquely identifying information, as it is the prevue of the visual and aural systems to identify the content of the percepts. However, because of the integration of the configural system with the visual and aural systems, should the content of the percepts be identified while the matched configural representation is still active in the configural buffer, they will be linked together symbolically. This permits the model to reason about and retrieve the spatial information for identified spatial objects.

Table 4.2 Symbolic representation of a configural (spatial) chunk

```
(chunk-type configural
  top-pitch {visual degrees, 0 is eye level, increasing vertically, -90 - 90}
  top-distance {meters}
  bottom-pitch {visual degrees, 0 is eye level, increasing vertically, -90 - 90}
  bottom-distance {meters}
  left-bearing {visual degrees, 0 is center, increasing to the right, -180 – 180}
  left-distance {meters}
  right-bearing {visual degrees, 0 is center, increasing to the right, -180 – 180}
  right-distance {meters}
  center-pitch {visual degrees, 0 is eye level, increasing vertically, -90 - 90}
  center-bearing {visual degrees, 0 is center, increasing to the right, -180 – 180}
  center-distance {meters}
  where {visual-location or audio-event chunks}
  identity {visual-object or sound chunks}
)
```

4.2.3 Updating

Assuming the attending request succeeds, there will configural chunk in the configural buffer. Once it is in the buffer, it can be matched against by any production. ACT-R/S includes a series of actions that permit the comparisons of configural chunks to determine relative positions, as well as to perform mental transformations. Reflecting the differences seen in the updating literature, there are two separate mental transformations possible: rotational and translational (see table 3). Currently, only latencies are being modeled, with the transformation durations being controlled by the parameters *MentalRotationRate* (deg/s) and *MentalTranslationRate* (m/s). Error equations and parameters are currently being evaluated. These mental transformation operations represent the *offline* spatial updating. Currently ACT-R has no concept of a lower body and, while a temporary system is in the works, *online* updating is currently approximated by starting the mental transformation at the same time as the modeled movement with the parameters adjusted to take the same amount of time as the movement. Ideally, *online* updating would be computed automatically by taking the programmed motor command and applying it incrementally during the execution of the movement. It would also depend upon its own set of latency and error calculations and parameters.

Table 4.3 Sample mental transformation productions.

```
(p turn-180
 =goal
 isa goal
 =configural>
 isa configural
 :state free
 :integrator free
==>
 +configural>
 isa mental-rotation
 distance 180)
```

```
(p translate-2m
 =goal>
 isa goal
 =configural>
 isa configural
 :state free
 :integrator free
==>
 +configural>
 isa mental-translation
 distance 2)
```

Note the use of the status slots on the left-hand side to ensure that no transformations are currently active. Attempting to engage in a mental rotation and translation simultaneously will result in an error.

4.2.4 Configural Buffer

Up to this point, the implementation of ACT-R/S has conformed to the canonical ACT-R constraints. Normally the modeling of working memory resources in ACT-R depends upon the spread of activation from the current chunk in a buffer, however this is less than ideal from a functional perspective if updating is to operate on multiple chunks. Instead the configural buffer supports capacities of more than one chunk, and all chunks within the buffer are transformed during updating. While this is an architectural deviation, it is not an unheard of proposition as a recent proposal for multi-tasking applies the same principle to the *goal* buffer (Salvucci & Taatgen, in press). The capacity of the buffer is currently controlled by the *HardChunkLimit* parameter, which represents the actual number of chunks the buffer can contain. Future work will explore shifting this to an activation limit, where the buffer's source activation will be distributed among the attended chunks as a function of the recency and frequency of use within the buffer. As the activation for a chunk falls below a certain threshold, it will be removed.

Currently, the removal policy when the capacity limited is reached is to remove the chunk that was least recently matched by a production. Setting the capacity limit to a single chunk results in behavior identical to the standard buffers.

There are additional implementation details that pertain to the establishment of location representations through the combination of individual configural representations, however they are irrelevant to the goals of the work. The details, and particularly the parameters, discussed here are sufficient to permit modeling of the two previous empirical studies within ACT-R.

5.0 MODELING IN ACT-R/S

This work represents the first time that ACT-R/S has been used to model human performance data. As such, this is a vital first step in the evaluation of the formal predictions of the architecture. Instead of focusing on trying to establish the best possible model fits through parameter modification, the goal here is to derive viable initial parameter estimates and examine the consequences of ACT-R/S's constraints on the qualitative and quantitative fits.

In keeping with one of ACT-R's explicit goals, the models presented here are "end-to-end" (Anderson, 2007); they are literally inserted into the experiment in place of the normal human subject. The simulations are not based on simplified or abstracted experiments. With the exceptions of providing interpretable perceptual stimuli (i.e. polar egocentric vectors to the objects, see 4.2.2) and a mock joystick for pointing, the simulations reported here are using the exact same experiment and analysis tool chains used in the behavioral studies.

As noted in the previous chapter, currently ACT-R/S's configural system is partially implemented. The current system is able to engage in spatial updating, both online and offline, however ACT-R has no concept of movement in space beyond the hands. Without simulated legs to move on, the models presented here that rely upon online updating simulate it with the offline system and its parameters. This simplification is of little significance given the empirical evidence that subjects aren't even engaging in online updating. A more significant gap in the present implementation is that these processes currently depend only on transformation rate parameters. The only updating errors are the result of the model's occasional misretrieval of configural representations. The pointing errors from experiment two are being examined in the light of both a target's true location and the magnitude of the imagined transformation, but the error equations have yet to be derived.

Even without fitting the error data, there is sufficient data to test the current models, especially considering that both experiments incorporated two tasks. Models of the first experiment were fit to the latency data for both egocentric and JRD pointing responses. The model of the second experiment was fit to the accuracy data for the 1-back task and latency for the egocentric pointing. Multiple models of the first experiment were developed to evaluate various architectural components (i.e. online updating, multiple chunk capacity). The second model focused on illustrating the role of modality specific interference with respect to the onset of offline updating. While the same variants of model one could be applied to the second experiment model, they provide little additional information beyond what was learned and are not discussed further.

5.1 EXPERIMENT ONE MODELS

The modeling of the first experiment presented the opportunity to try out a few different model versions that rely upon different elements of ACT-R/S. These variations provide slightly different and informative perspectives on the spatial updating phenomenon while evaluating the relative merits of components of the architectural extension. Model 1a (*offline*) does not engage in any online updating and has a fixed configural capacity of one chunk, representing the smallest divergence from canonical ACT-R. Model 1b (*online*) does engage in online updating as it rotates and handles parametrically varied configural capacities, permitting it to update multiple targets at once. Model 1c (*transient*) examines Wang's proposal that spatial updating is entirely transient, with no enduring traces of updated representations (1999, 2007). Finally, 1d (*allo-surrogate*) introduces a slight modification that enables it to account for the data from the allocentric visualizers.

All of the following models (except *allo-surrogate*) focus exclusively on the egocentric visualizer data. This was done simply because the reversal of the alignment effect represents the more extreme computational situation. The stability of the alignment effect (i.e. no reversal) is easily accounted for by having the models ignore the spatial updating after the rotation (Waller et al. 2002), as will be illustrated in 1d. This is not to say that ACT-R/S denies participants' subjective accounts of allocentric visualization, but that it could just be a holistic local view snapshot of the original view (i.e. Wang & Spelke, 2002), which then feeds into the offline updating necessary to perform the judgments of relative direction.

5.1.1 Model 1a : Offline

The first version of the experiment one model is entirely offline. No configural representations are updated as the model engages in the actual rotation. This constraint permits the model to be run with ACT-R's single chunk buffer and therefore represents the smallest extension of the architecture's canonical behavior. The model proceeds through four basic phases:

1. **Attending phase**: model visually attends to all targets in the environment sequentially, linking visual, configural, and trial representations.

2. **Rehearsal/Updating phase**: model serially rehearses target locations by retrieving and reinstating relevant configural representations. If the model has rotated, configural representations are transformed to maintain spatial consistency with its current position (see 4.2.3 for details).
3. **JRD phase**: model is prompted to engage in judgment of relative direction (XY → Z). Model retrieves and verifies the configural representation (possibly transforming the representation if it is inconsistent with rotation) of the imagined location (X), orientation (Y), and target (Z). The imagined location is reinstated (i.e. inserted into the configural buffer) and the translation to it is extracted and stored in the imaginal buffer. This transformation is then applied after the orientating representation (Y) is reinstated. The bearing to the updated representation is now the necessary rotation needed to align the model's perspective with XY. The rotation is extracted and stored in the imaginal buffer. After reinstating the target location (Z), the imagined translation and rotation are applied serially, transforming the target location. The resulting target bearing is provided as the pointing response to terminate current JRD trial.
4. **Egocentric phase**: model is prompted to point egocentrically towards a particular target. Again the model retrieves and verifies the target location. The bearing to the target is extracted and provided as the pointing response to terminate the current egocentric trial.

In this variant, the updating of spatial representations is done at two points: rehearsal and test. Immediately after the targets are no longer visually available, the model begins to rehearse their locations. If, during the rehearsal phase, the model turns 180°, it will engage in effortful mental transformations, rotating the configural representations to maintain spatial consistency with its position (see 4.2.3). At test the model will update the configural representations both in order to maintain consistency (if the retrieved representation has not been rotated) and to complete judgments of relative direction.

5.1.1.1 Alignment effect and reversal In this model (and all subsequent variants), the basic alignment effect arises from the differences in mental transformations necessary to align the model's perspective with the imaginary one. Aligned judgments require a single mental translation to move the model's perspective from the learning to imaginary location. Since the mental translation operation maintains the model's current orientation, the model's perspective at the imagined location is already aligned with the orienting target. The contra-aligned judgments not only require a longer mental translation (since the imaginary locations for contra-aligned judgments were on average 1.5m further away than those for the aligned ones), but also a 180° mental rotation to face the orienting representation.

The reversal of the alignment effect depends upon the successful and rapid retrieval of spatially consistent representations. If consistent representations cannot be retrieved (because of decay, interference, or the model simply didn't update the representation), then they will have to be derived from the original, visually attended ones. This additional processing necessarily increases latencies. Assuming the updated representations are retrieved and verified in a timely manner, the reversal of the alignment effect arises from the different transformations necessary. In this case, aligned judgments require not only the short mental translation but also the full 180°

rotation to align the perspective with the original one from learning. The contra-aligned judgments no longer require a 180° rotation, but still depend upon the greater mental translation.

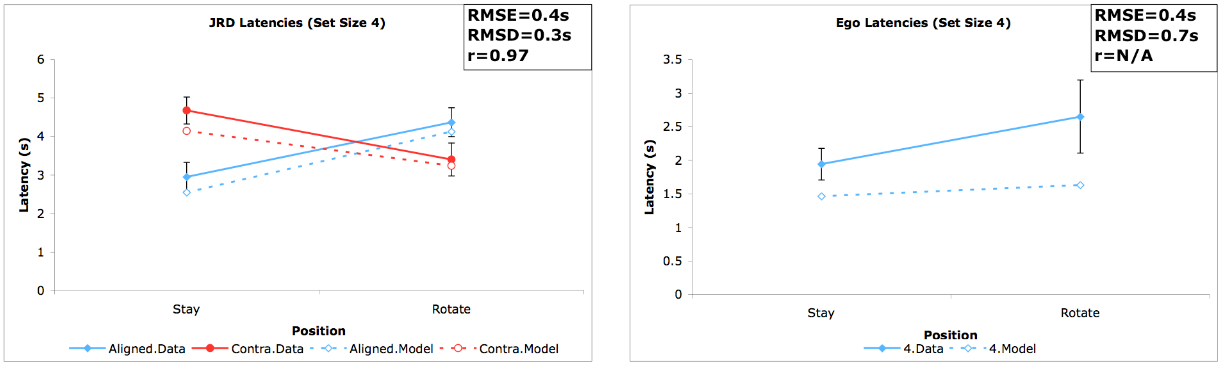
5.1.1.2 Initial fitting Keeping ACT-R's core parameters at their default values (appendix D), only two parameters were estimated for this first model. A random subsample of the set size-4, egocentric visualizer group was used to establish initial estimates for the translation (7.8 m/s) and rotation (138º/s) updating parameters (see appendix D). Simulations[5] run with these parameters yielded a fairly good fit for both egocentric pointing and JRDs, subject RMSE[6]=0.4s, RMSD=0.54s, r=0.97 (six data points[7]). Egocentric pointing responses are actually much too fast, generally weakening the fit in comparison to the JRD responses (figure 5.1, b). This arises from the model having strengthened the updated representations during the retention interval to the point that they are almost equivalent to the initially attended ones and can easily be corrected for by increasing the decay rate (below).

---

[5] All simulation were of at least 1000 iterations with activation noise (*:ans*) of 0.1.

[6] Notation: RMSE is used for subject data, RMSD for model data.

[7] For experiment one, in-text fit statistics are computed using both JRD and egocentric data. For task-specific fits, see the accompanying figures.



a

b

Figure 5.1 Initial fits to egocentric visualizer data. Combined fit for six data points (RMSD=0.54s, r=0.97). Error bars are SE.

Having established a solid foothold on the simpler set, attention could be turned towards the rest of the egocentric visualizer dataset. The quality of fit for this much larger dataset is consistent with the subsample, subject RMSE=0.35s, RMSD=0.63s, r=0.95 (figure 2, top, twelve data points), with latencies increasing with set size. Again, latencies are all somewhat faster than observed in the data, particularly for the egocentric pointing. If one insisted on a better fit, increasing the decay rate parameter[8] (*BaseLevelLearning* or *:bll*) from its default of 0.5 to 0.7, would make the updated representations less accessible, increasing latencies slightly, producing a much tighter fit, RMSD=0.41s, r=0.96 (figure 2, bottom, 12 data points).

Parameteric analyses have shown that the qualitative fit (i.e. the alignment effect, its reversal, and the reduction with set size) is stable across the majority of the tested parameter space (appendix E). While one could spend considerable computational resources searching the

---

[8] A similar effect can be achieved by increasing the latency factor (:lf) from 0.5 to 0.6, which effectively increases the average retrieval time.

parameter space for better fits, the goal here is to establish the viability of the architecture and its predictions. Instead of parameter tweaking, the subsequent models look at significant variations in the architecture and how they hold up in the light of empirical results.

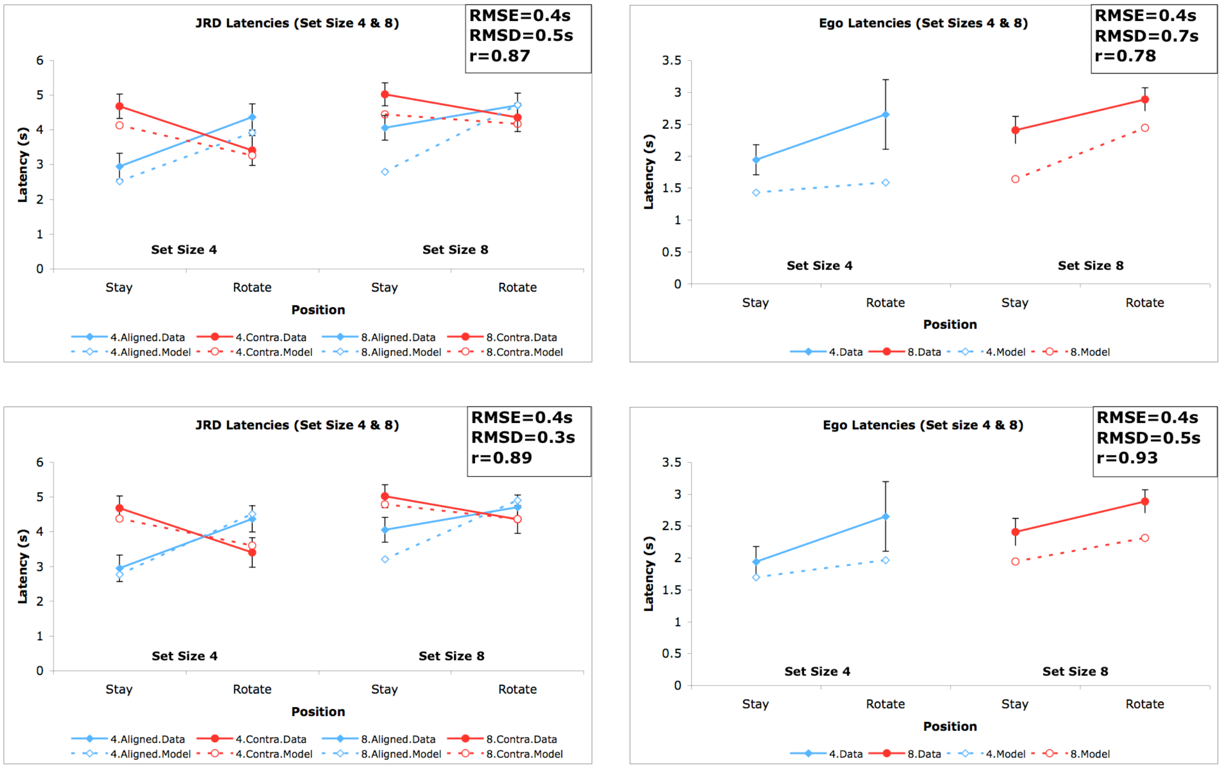


Figure 5.2 Fit egocentric visualizer fits (set sizes 4 & 8) for 12 data points. Default parameter values (top) RMSD=0.63, r=0.95. Decay rate of 0.7 (bottom) RMSD=0.41s, r=0.96. Error bars are SE.

5.1.2 Model 1b : Online

The second model of experiment one relies upon the online updating mechanism (see 4.2.3) and can support arbitrary configural buffer capacities (see 4.2.4). This allows the model to update the locations of multiple targets as it rotates, maintaining spatial consistency with little effort or cost. However, as will be shown later, given the nature of JRDs, these savings are largely irrelevant.

The model's behavior closely parallels that of the offline model. The major differences arise in the rehearsal phase and in the JRD phase (but only when capacity is ≥ 3). As the model moves, the contents of the configural buffer are automatically updated. Once it stops moving the model proceeds to rehearse the chunks in their serial order (as in the offline). If the to-be rehearsed target is currently in the configural buffer, no retrieval is necessary. As before, if a retrieved representation is inconsistent with the current position, it will be updated. However, all the other configural representations must be removed from the buffer to prevent them from being improperly transformed.

During the JRD phase, the model's behavior is largely the same as that in the offline model, until the configural buffer's capacity exceeds two chunks. At this point, the model is able to maintain all three locations (XY→Z) in memory. Instead of applying two mental translations (to get the rotation toward Y and the location of Z) and a single rotation, the model can apply a single translation and rotation to all the representations.

Explorations of the parameter space failed to yield any runs that fit better than the offline model. In fact, this is due to the model being able to access representations too quickly (even more so than in the previous model) (figure 5.3). This is because without the delay introduced by the offline updating transformations, the model is able to rehearse the target locations two to three times more frequently. Adjusting individual production firing times, decay rate or the latency factor could be used to slow down the retrievals but that would introduce additional parameters (for the production firing times) or require parameter values outside the published ranges (i.e. decay rate or latency factor would have to be above 1.1 or 1.4, respectively).

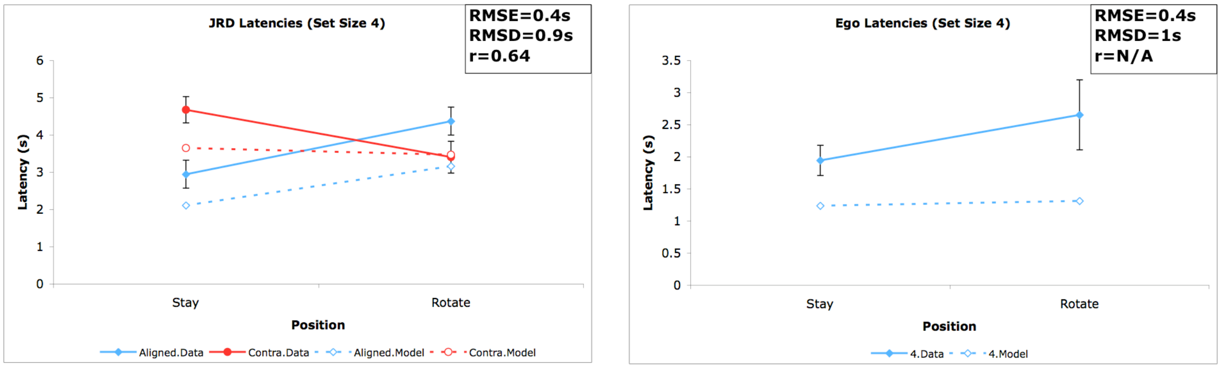


Figure 5.3 Online updating model (ChunkCapacity=3), zero-parameter fit for 6 data points (RMSD=0.98, r=0.86). Error bars are SE.

While online updating enables the (too) rapid retrieval of updated representations immediately after the rotation, the amount of time between the rotation and the first JRD allows the offline model to sufficiently update and rehearse the representations such that the online savings are largely irrelevant. The benefit for online updating (if it were being engaged in) is only going to manifest itself if there is insufficient time for offline updating and rehearsal (i.e. removing the retention interval).

5.1.3 Model 1c : Transient

Wang's egocentric with spatial updating theory proposes that updated representations are entirely transient, leaving no enduring footprint in long-term memory. The only persistent representations are the initial local-view snapshots established during attending. While it is entirely likely that most updated representations are used only briefly and decay beyond the point of accessibility after long periods of time, it is critical for the alignment reversal that they can be retrieved on moderate time scales (e.g. a few minutes) as will be explained shortly. Recently, evidence for this has actually been found, with subjects able to access updated representations after extended delays (Kelly, Avraamides, & Loomis, in press).

If updated representations were purely transient (i.e. not retrievable after a short intervening time frame of even a few minutes), then the first offline transformation would obliterate any savings for subsequent judgments. Imagine the first post-rotation JRD performed in experiment one. Let’s assume that the participant has updated the target locations (online or offline it doesn’t matter) so that the representations are behind them. If they engage in a contra-aligned JRD, the participant will perform the single offline translation necessary resulting in a relatively rapid pointing response. When they are next prompted to perform an aligned JRD they have two choices: unwind the transformations just applied (introducing further errors and eating up the latency savings) or retrieve the initial representation. If the participant retrieves the initial representation then the aligned judgment will show the standard alignment effect, not the reversal. Simply put, the alignment reversal is not possible in a purely transient system, updated representations must be weakly accessible in long-term memory or available through a long-term working-memory (Ericsson & Kintsch, 1995).

Although logically ruled out, it is worth considering the possibility that some parameter set produce the alignment reversal. Model 1c is the same as the offline model, however the encoding of updated representations into long-term memory has been disabled. Only visually attended configural representations make it into long-term memory. For this model the standard alignment effect dominates, with significant latency penalties after rotation. Not surprisingly, parameter space explorations have failed to find any values that exhibit the alignment reversal (appendix E).

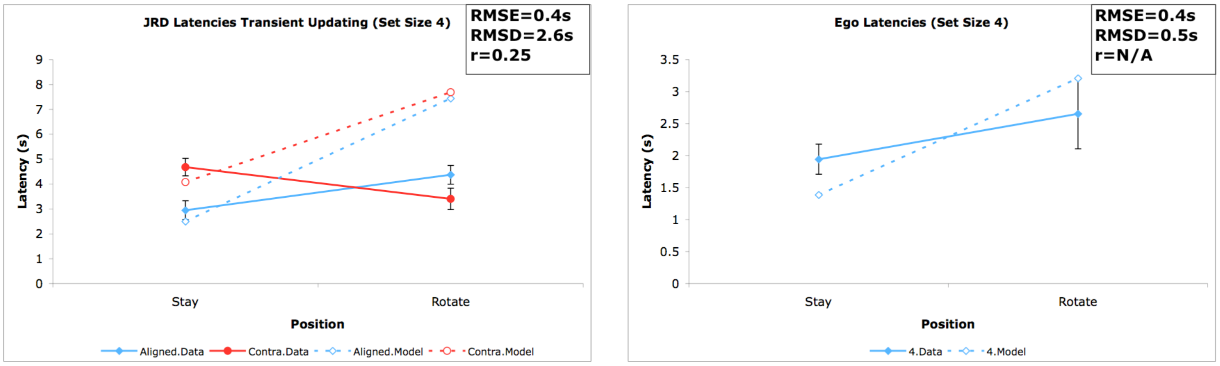


Figure 5.4 Transient model zero parameter fit for 6 data points (RMSD=2.2s, r=0.6). Error bars are SE.

5.1.4 Model 1d : Allo-surrogate

Up to this point, all of the models have been fit against the egocentric visualizer data. As has been mentioned previously, that groups data can be accounted for by postulating that they either did not update (if updating were offline) or simply ignored the updated representations (if the updating were online). The initial offline model was modified slightly so that it always preferred to retrieve configural representations of the initial view of the environment (effectively ignoring the updating). Additionally, during the verification of the target's location, it was only updated if the updated representation was explicitly required for egocentric pointing responses. Using the same parameter values (i.e. zero-parameter fit), fits with the allocentric visualizer data were in the ballpark, subject RMSE=0.4s, RMSD=0.4s, r=0.92 (figure 5.5), although significantly slower for the post-rotation JRDs.

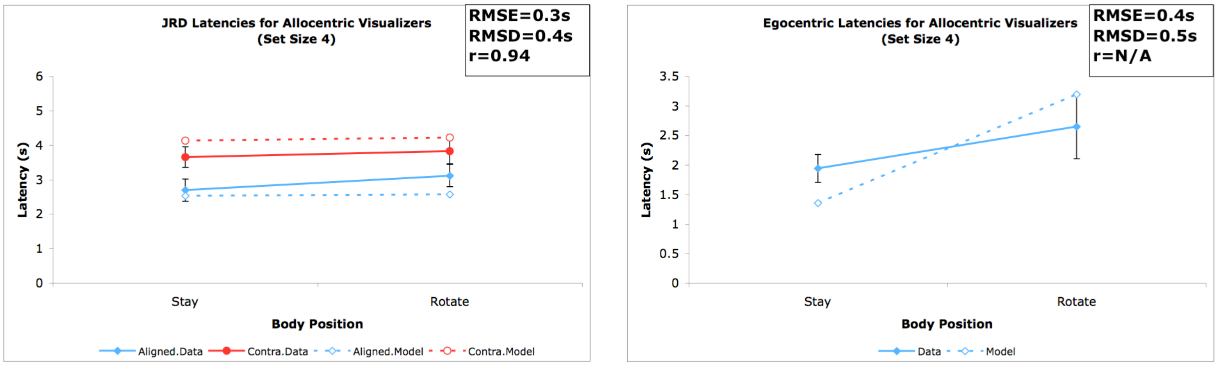


Figure 5.5 Fit to allocentric visualizer data, set size 4. Zero parameter fit for 6 data points (RMSD=0.4s, r=0.92). Error bars are SE.

5.2 EXPERIMENT TWO MODEL

The modeling for experiment two was intended to highlight the role of online updating and how it can be interfered with by modality specific secondary-tasks. Surprisingly, no evidence of online updating was found in either study. With the initial modeling revealing the simplest case as the best fitting (i.e. offline updating of single representations), can the experiment two modeling illustrate much more than modality specific interference that is dependent upon when offline updating is started?

The basic offline model (1a) was adapted to utilize Salvucii & Taatgen's (in press) threaded cognition extension, which enables ACT-R models to maintain multiple goals simultaneously. Productions were added to deal with the auditory 1-back tasks. Different productions were developed for the auditory and spatial versions but they both followed the same general pattern. When an auditory cue is detected, the model directs attention to that cue. If it is a subsequent cue, the model also makes a parallel retrieval to fetch the previous cue. Once the cue has been encoded and the previous one retrieved, the two are compared and a response given.

The differences between the two sets of productions lay in the modality that is attended to. The verbal 1-back productions use the aural system to encode the content of the cue, ignoring the location. The spatial 1-back productions use the configural system to encode the location, ignoring the content of the cue. Both sets of productions rely upon the retrieval buffer, but only the spatial 1-back productions rely on the configural buffer (table 5.1).

Table 5.1 Sample 1-back productions for verbal and spatial modalities

```
(p verbal-1back-subsequent-cue-detected
 =goal>
 isa nback-goal
 stage starting
 type verbal
 isFirst false

 =aural-location>
 isa audio-event

 ?aural>
 - state busy
 buffer empty

 ?retrieval>
 - state busy
 buffer empty
==>
 +aural>
 isa sound
 event =aural-location
 +retrieval>
 isa sound
 =goal>
 stage retrieving)
```

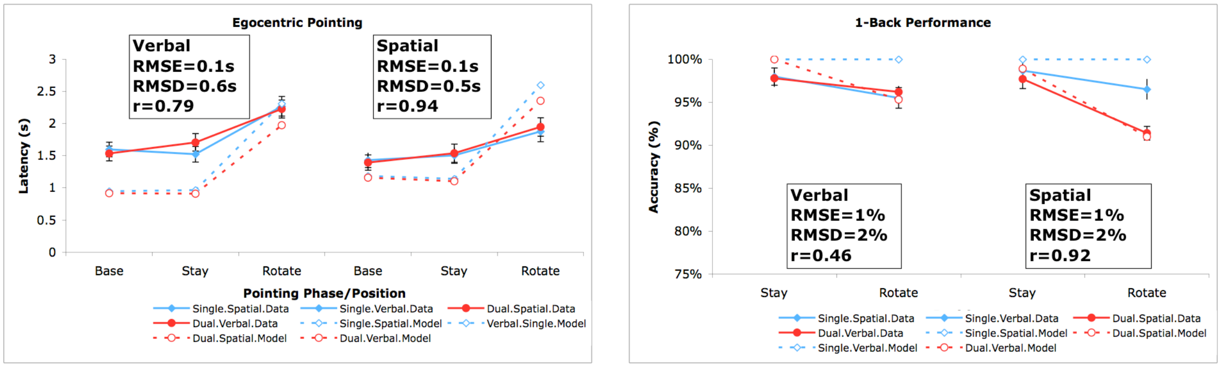
```
(p spatial-1back-subsequent-cue-detected
 =goal>
 isa nback-goal
 stage starting
 type spatial
 isFirst false

 =aural-location>
 isa audio-event

 ?configural>
 - state busy
 - integrator busy

 ?retrieval>
 - state busy
 buffer empty
==>
 +configural>
 isa move-attention
 where =aural-location
 +retrieval>
 isa sound
 =goal>
 stage retrieving)
```

```
(p verbal-1back-cues-match
  =goal>
  isa nback-goal
  type verbal
  stage retrieving

 =aural-location>
 isa audio-event

 =aural>
 isa sound
 event =aural-location
 content =content

 =retrieval>
 isa sound
 content =content

==>
 =goal>
 stage responding
 return true

 -aural-location>
 -aural>
 -retrieval>
)
```

```
(p spatial-1back-cues-match
  =goal>
  isa nback-goal
  type spatial
  stage retrieving

 =aural-location>
 isa audio-event

 =configural>
 isa configural
 audio-event =aural-location
 center-bearing =bearing

 =retrieval>
 isa configural
 center-bearing =bearing

==>
 =goal>
 stage responding
 return true

 -aural-location>
 -configural>
 -retrieval>
)
```

When the model is only performing the 1-back tasks, there is no interference. In fact, the model predicts that there should be no performance decrement due to rotation (a gap in the model since even for the verbal 1-back there is a rotation decrement). There will be interference when the 1-back tasks are performed in conjunction with rehearsing and updating of the target locations. For the verbal 1-back, interference will only arise as the two tasks contend for the retrieval buffer. There will be even greater interference for the spatial 1-back as the two tasks require both the retrieval and configural buffers. The data from experiment two points towards subjects starting to update target locations towards the final third of the 1-back trial (figures 3.7, 3.8). So, the model holds back on updating and rehearsing target locations until it is twenty seconds into the 1-back trial. In other words, it is only engaging in both tasks towards the tail end of the 1-back trial.

Using the same parameter values established for the offline model (i.e. zero parameter fit), the model does a good job of fitting the pointing and accuracy results for the spatial group, subject RMSE=0.13s, RMSD=0.54s, r=0.94 & subject RMSE=1%, RMSD=2%, r=0.92, respectively. The fit to the verbal group was much worse for both pointing and accuracy, subject RMSE=0.12s, RMSD=0.6s, r=0.76 & subject RMSE=1%, RMSD=2%, r=0.46. While the fit of the egocentric pointing data can easily be improved with parameter modifications, the poor fit of the 1-back data cannot. It is primarily driven by the model's inability to account for the performance decrement seen during the rotation trials (figure 5.6). Not surprisingly, manipulating the overlap of the two tasks also influences the amount of interference. The sooner subjects try to update and rehearse the target locations (effectively reducing the SOA), the greater the interference, with spatial 1-back performance suffering the greatest.



a b

Figure 5.6 Zero-parameter fits of both egocentric pointing (a) and 1-back accuracy (b) data. Error bars are SE.

5.3 SUMMARY

The modeling of the first experiment's results was not limited to merely fitting data, but also focused on evaluating various architectural assumptions as well as testing alternative accounts. The offline model (1a), which can only update a single target after a movement has completed, was able to account for the egocentric-visualizer data quite nicely. Combined with the evaluation of the online model (1b), it is apparent that the structure of the first experiment with its long retention interval permits sufficient rehearsal and updating time that online updating is largely unnecessary. These two models indirectly point towards a methodological issue in exploring updating processes: any significant delay between movement and probing introduces cognitive slack time that can be used for offline updating.

The transient (1c) model illustrates a potential computational flaw in Wang's (1999) egocentric with spatial updating theory. Purely transient systems cannot produce the alignment effect reversal since any savings due to updating will be lost after the first judgment is made.

Updated representations must persist in long-term working-memory (Ericsson & Kintsch, 1995), if not long-term memory proper. It is this same transience issue undermines Mou's account of the alignment effect reversal (2004). While this issue is logically obvious in retrospect, the modeling was necessary to illustrate this fact. Here the modeling not only illustrated the sufficiency of the ACT-R/S account, but also the insufficiency of transient arguments.

ACT-R/S proposes that while egocentric representations are the fundamental spatial representation, other representations can be recruited in service of spatial reasoning. Theoretically, the reports of allocentric visualization reflect the use of retinotopic imagery of the environment, which can then direct the subject to retrieve the appropriate egocentric target. While not explicitly modeling the retinotopic imagery, the allo-surrogate model (1d) does illustrate how not updating (or ignoring the updated representations) can begin to account for that group's data. Admittedly, the model's slower performance for post-rotation pointing is still a bit of a quandary.

Model two bootstraps the initial offline model and incorporates dual-task performance. Here interference is the result of modality specific resource usage and contention (Salvucci & Taatgen, in press). The model does a good job fitting the spatial 1-back results, however, the verbal 1-back fits are poor at best. This is driven primarily by the inability to account for the performance decrement during rotation. This modeling gap highlights the need for further research examining the 1-back tasks in greater depth.

Taken as a whole, these models are promising first steps towards enabling the modeling of spatial reasoning across these three areas (i.e. egocentric & JRD pointing, and spatial 1-back). Given the relative simplicity of the representational assumptions and their general implementation, the door is open to modeling a wider range of phenomena within ACT-R/S such as the imaginary perspective (Gunzelmann, Anderson, & Douglass, 2004; Hegarty & Waller, 2004) or object localization (Burgess et al., 2000; Hartley, Tinkler, & Burgess, 2004; Waller et al., 2000) tasks.

6.0 GENERAL DISCUSSION

The goal of this research has been to examine the role of spatial working memory constraints on spatial updating. While egocentric theories predict a capacity limitation for online updating, allocentric theories predict that online updating should be largely immune to working memory manipulations. The implicit assumption of this research was that subjects would engage in the obligatory online updating (e.g. Farrell & Robertson, 1998). If subjects did not engage in online updating, but relied instead upon the *just-in-time* offline updating, the working memory manipulations would be undermined. While the online updating assumption ultimately proved unfounded in both experiments, the data and models do point in some informative directions.

6.1 EXPERIMENT & MODEL ONE

In experiment one, participants engaged in judgments of relative direction based on irregular target configurations of varying set sizes from their study and 180º rotated locations. Replicating Waller et al. (2002), approximately half the participants showed the standard alignment effect whereas the other half showed a reversal. This alignment effect reversal is a better indicator of spatial updating than the traditional angular-disparity effects (Diwadkar & McNamara, 1997; Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998) as it shows a genuine shift in the preferred alignment of the spatial representations (Kelly, Avraamides, &

Loomis, in press; Waller et al., 2002; but see also May, 2004). Unlike the Waller et al. study, instructions alone were insufficient to differentiate the two groups, as all were instructed to actively track the target locations during rotation. It was the quality of participants' subjective visualizations that differentiated between those that exhibited the alignment reversal and those that did not (figure 2.5).

The set size manipulation in experiment one merely influenced latencies; pointing errors were unaffected. This points towards subjects engaging in offline spatial updating (i.e. waiting until after the rotation has completed and serially updating the targets), as opposed to actively tracking the targets online as they move (Hodgson & Waller, 2006). However, as the models (1a:offline & 1b:capacity) showed, not only is the JRD task predominantly offline, but the structure of the experiment permits ample time to engage in offline updating and rehearsals. This was anecdotally supported by a number of participants who explicitly noted that tracking the targets was unnecessary for the JRDs and could just be done when prompted to engage in egocentric pointing.

6.2 EXPERIMENT & MODEL TWO

Experiment two attempted to address a few of the first experiments shortcomings by taking a different tack. The judgments of relative direction were excluded, leaving only egocentric pointing. While egocentric pointing is a weaker illustration of alignment change, it has the beneficial property of not explicitly depending on offline updating. The set size manipulation was also replaced with a dual-task manipulation. Unlike previous dual-task studies of spatial updating, there were different isomorphic secondary tasks targeting modality specific systems (Book & Garling, 1981; Linberg & Garling, 1981; May & Klatzky, 2000). It was expected that pointing performance would have been equivalent between control and verbal-dual task conditions. The spatial-dual task condition was expected to show significant interference as the subject had to track the targets and engage in the spatial 1-back. However, pointing performance was equivalent across all conditions, with pointing after rotation taking longer and showing the greatest error (figures 3.3 & 3.4). If subjects had been engaged in online updating of any sort, pre- and post-rotation latencies should have been equivalent. Looking at pointing performance, there was no evidence of dual-task interference, modality specific or not.

The lack of interference on the primary task does not mean that there was no interference. Looking at the 1-back performance we see that while accuracy for the single-task trials was equivalent between the spatial and verbal types, both rotation and dual-task load severely impacted spatial 1-back performance (figure 3.6). Examinations of the time course of the 1-back errors revealed that they were occurring predominantly towards the end of the 1-back trial. This strongly suggests that participants were engaging in offline updating, starting it just before the end of the 1-back trials, and that updating predominantly interfered with the spatial 1-back group's performance (figures 3.7 & 3.8). If participants had been engaging in online updating (automatic or not), we would have expected to see errors evenly distributed across the 1-back rotate blocks.

Unfortunately, these 1-back tasks are apparently more complex than the pilot studies revealed (appendix C). The goal was to have secondary tasks that were relatively low cost to a central-executive and primarily tax modality specific processing, unlike the traditional spatial-updating secondary task of backward counting. While a negative influence of rotating is easily explained for the spatial 1-back, it's negative effect on the verbal 1-back is less clear (figure 3.6).

Neither the model (figure 5.6), nor the theory has any explanation for the verbal-rotate decrement.

6.3 ALTERNATIVE REPRESENTATIONAL ACCOUNTS

6.3.1 Egocentric theories

The theoretical position of ACT-R/S is most clearly aligned with that of Wang (1999). The major divergence comes in the role of updated representations. Wang proposes that updated representations are transient, never making it into long-term memory. Her reasoning is that if these updated representations were accessible then we should see viewpoint-independent performance on spatial tasks when individuals have significant experience with the environment. However, there is evidence of just that when subjects are able to view or update target configurations from multiple viewpoints (Diwadkar & McNamara, 1997; Sholl & Bartels, 2002). ACT-R/S takes the position that the updated representations must make it into long-term memory or, at the very least, a long-term working-memory store (Ericsson & Kintsch, 1995). As was shown in the offline (1a) and transient (1c) models, any savings due to spatial updating would be lost for subsequent judgments if updated representations were not accessible on a time scale of at least a few minutes. Most recently, Kelly, Avraamides, & Loomis (in press) have found evidence that updated representations are accessible after significant delays under a variety of conditions.

6.3.2 Allocentric theories

Traditional allocentric theories cannot account for the reversal of the alignment effect seen in experiment one. While the allocentric representations do have preferential alignments, the process of anchoring the viewer within that representation (the allocentric explanation for spatial updating) will not change the preferred alignments. There are three alternative allocentric interpretations that begin to address this issue: Mou et al's transient egocentric system (2004), Sholl's egocentric mediation (2001), and May's interference account (2004). As was discussed previously, Mou et al's account fails due to its transient nature. As in Wang's account, any benefit due to the transient updating of representations will apply only to the first spatial judgment. In theory, Sholl's proposal that fundamental allocentric representations are only accessible through an egocentric reference frame can possibly account for the appearance of a change in the preferential alignment. Unfortunately, the theory is vague about what is happening during the egocentric mediation making further conjectures difficult.

The most viable of the accounts comes from May (2004). He proposes that the viewpoint-dependency results do not reflect spatial transformations of representations with preferred alignments, rather the interference between the body's defined frame of reference and the mind's imagined one. Within this framework is the implicit assumption that movement through the environment is automatically tracked and used to maintain the body's frame of reference. When an individual is asked to imagine himself or herself in a new position or orientation, the latencies and errors are a function of the disparity between the body's position and the imagined one. This nicely accounts for the alignment effect and its reversal. When stationary, aligned judgments require imagined positions that are closer to the body's actual position than the contra-aligned judgments. After rotation, the contra-aligned judgments are now closer to the body's actual position. The problem, once again, lies in the automaticity of the anchoring process (i.e. online updating) that maintains the consistent body reference frame. May's account predicts that all the subjects should have shown the alignment reversal; there is no room for individual differences.

The automaticity of allocentric-online updating also predicts that the pre- and post-rotation latencies in experiment two should have been equivalent across all manipulations. Unfortunately, none of these accounts make any claims regarding the use of working memory resources as it may apply to the interaction between egocentric and allocentric frames of reference. Without this critical piece, it is hard to evaluate the rest of second experiment's results from these alternative perspectives. However, we can look at two contrasting perspectives. If the egocentric and allocentric frames do not interact with each other significantly (i.e. Mou et al., 2004), the interference for the spatial 1-back and it's unequal error distribution requires some other explanation. On the other hand, if egocentric and allocentric frames do interact with each other, but the online-allocentric updating does not require significant working memory resources (i.e. Sholl, 2001), we'd expect to see some interference for the spatial 1-back, but the unequal error distribution is still a problem. Online updating (egocentric or allocentric) predicts an equal error distribution across the duration of the 1-back trial.

6.4 SPATIAL UPDATING

If online spatial updating is indeed an automatic process as earlier research suggests (Farrell & Robertson, 1998; Linberg & Garling, 1983; May & Klatzky, 2000; Presson & Montello, 1994; Rieser, 1989), then it is extremely surprising that neither experiment shows any evidence of it.

While the first experiment's reliance upon judgments of relative direction likely predisposed participants toward offline updating, if online updating were present it would likely have manifested itself in lower absolute pointing errors for the set size four group. Even when presented with the much simpler egocentric pointing task, under single task conditions, subjects still showed no evidence of online updating. These studies and those by Hodgson & Waller (2006) seriously undermine the implicit assumption of online updating that many studies make (e.g. Holmes & Sholl, 2005; Rieser, 1989; Woodin & Allport, 1998; Wraga, 2003). While it has always been understood that offline updating could be utilized to solve spatial tasks, it has been assumed that online updating would be active when movements were actually involved. Without clear methodologies that differentiate the two updating modes, descriptions of either are likely to be confounded by the other. If online updating is not obligatory, but rather subject to individual differences (hinted at by experiment one), then the strategic use of online and offline updating becomes a possibility as well. Subjects might utilize online updating in situations of low working memory load only to switch entirely to offline or mixed strategies under increasing load. Current methodologies are simply unequipped to detect such possibilities.

Regardless of what is occurring, it is worth considering under what circumstances do we see evidence of online updating in the obligatory sense (Farrell & Robertson, 1998; Farrell & Thomson, 1998; Klatzky et al., 1998; May & Klatzky, 2000). Clearly the type of task has some influence. Predominantly offline tasks such as judgments of relative direction are likely to obscure evidence of online updating, if it is present at all. The remaining tasks have typically been basic egocentric pointing or triangle completion (accomplishable by online or offline processing), or continuous tracking tasks (requiring regular updating through the duration of the movements).

In the majority of these online updating studies, participants engaged in translations in addition to simple rotations. The physical translations in these studies all take much longer than the rotations, giving participants much more cognitive slack time than those that just rely rotations. As the modeling of the first experiment illustrated, this slack time allows participants sufficient time to engage in offline updating. One possibility is that within this slack time, participants are not updating online but rather engaging in opportunistic offline updating. Since updating times and errors are a function of the magnitude of the transformation, these incremental updates should be quite rapid and accurate (Loomis et al., 1991). When this slack time is disrupted by secondary tasks, such as backward counting (Book & Garling, 1981; Linberg & Garling, 1981), subjects may wait until the movement is completed to engage in the offline updating, resulting in significantly worse updating performance. If, however, that secondary task explicitly requires updating, performance is improved in comparison to offline updating (Amorim et al., 1997). From this perspective, the failure to find evidence of online updating in recent studies could just be due to the movement not providing sufficient time for opportunistic updating.

The early finding that irrelevant movements cannot be ignored (Farrell & Robertson, 1998; May & Klatzky, 2000) suggests a second alternative conceptualization of the updating process. Instead of differentiating online and offline updating in terms of when it is performed, we can separate them by their inputs. Presumably, both online and offline updating rely upon the same representations of external objects, however, the inputs driving those transformations are radically different. Online updating relies upon the relatively accurate movement record provided by proprioceptive and vestibular information. On the other hand, offline updating is driven by cognitively derived estimates of movement. In theory, the fidelity of that movement record (or estimation) would have ramifications on the accuracy and efficiency of the updating. If the encoding of movement in space is obligatory (as it would have to be if online updating were as well), the use of online or offline updating can be viewed in terms of input selection. In the absence of an accurate movement record, people would have to use the cognitively derived one. If the movement trace were available, people may be able to choose between using it or a cognitively derived one, opening the door towards individual differences in updating.

The issue of which form of updating is being observed is of critical importance to any investigation of working memory constraints. While early studies have found no effect of set size on updating (e.g. Linberg & Garling, 1981; Rieser & Rider, 1991), none of them attempted to differentiate between online and offline updating. Their results are entirely consistent with the current results and those of Hodgson & Waller (2006). To date, only Wang et al. (2006) has shown any effects of set size on error. What is interesting about their study is that they showed significant set size effects for both latency (i.e. offline updating) and error (i.e. online updating); perhaps this is evidence for the use of both online and offline updating? Unfortunately, their use of a target placement methodology makes direct comparisons to other studies impossible.

Until more studies explicitly consider and attempt to differentiate both online and offline updating, these issues are going to apply to any working memory investigations, regardless of the use of set size or dual-task manipulations.

7.0 FUTURE DIRECTIONS

All experimental investigations invariably result in more questions asked than answered, particularly when predictions fall short. At the very least, some evidence of online updating should have been found in experiment two. For a supposedly obligatory process, online updating is surprisingly difficult to find. Future work should try to reliably evoke online updating so that its working memory constraints can actually be assessed. The previous chapter also proposed the idea that online updating may actually be incremental and opportunistic offline updating performed during cognitive slack time. Work has already begun on a task similar to that of Amorim et al (1997) where subjects need to continuously report on tracked targets through a prolonged translation. Three alternative models of the task are currently being developed: offline, online, and incremental/opportunistic offline. It is hoped that these models might be able to better constrain and inform the actual methodology needed to tease these alternative accounts apart.

As a general spatial reasoning theory and architectural extension, ACT-R/S has shown some promise. However, it is still incomplete in terms of implementation and full vetting. As was mentioned in the implementation details (4.2.3, 5.0), the architecture does not currently provide error predictions. However, the dataset from experiment two has provided a starting point for the derivation of a functional form for error estimates. The coming months will see the previous models extended and fit to the available error data as well. The greatest test of any theory of spatial reasoning is to account for genuine spatial behavior, not just imagined perspective changes. ACT-R/S will soon be subjected to the ultimate vetting process as it is embedded into robotic systems, which rely upon psychologically plausible sensors. It is this endeavor that presents the greatest test of the assumptions within ACT-R/S.

8.0 CONCLUSIONS

Spatial updating is an incredibly complex set of processes, whether one views it as transforming egocentric representations (Wang, 1999) or anchoring the self within an allocentric map (King, Burgess et al., 2002; Mou et al., 2004; O'Keefe & Nadel, 1978). Both of these perspectives view the process as automatic, with the ability to perform it offline when movement information is not available. It should be possible to differentiate the major representational theories by looking at the working memory constraints of online updating. While no evidence of online updating was found in either experiment, the fact that some subjects showed the alignment effect reversal in experiment one is does support egocentric representational theories. As the modeling illustrated egocentric representations can account for both stable and reversible viewpoint dependencies (1a,d).

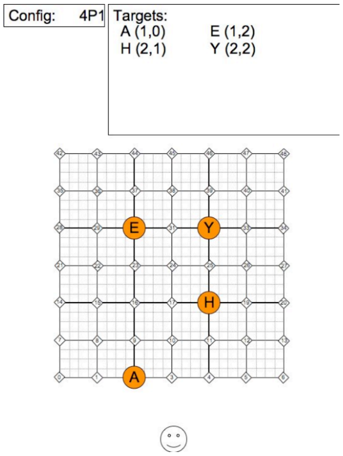
It is surprising that neither study showed any evidence of online updating. It might be time to move away from conceptualizing it as an obligatory process and consider that individuals may have strategic control over its use. If that is indeed the case, then methodologies need to be adapted to detect such control and the possibility that subjects might be utilizing both online and offline updating within any given trial. Regardless, this work and that of Hodgson & Waller (2006) clearly shows that blanket assumptions of online updating are unwarranted and further investigations of working memory constraints will require greater control over the form of spatial updating subjects engage in.

It is my personal hope that the ultimate publication of this work will nudge other spatial theorists towards more formal implementations of their theories. Most of the other accounts are simply too vague to make testable predictions at the level necessary to actually differentiate them. Personal conversations with some of these researchers provide me with hope, as all have acknowledged the need to do just that. While ACT-R/S is far from perfect, it is an important first step towards getting researchers, modelers, and models out of the box and into the world, whether that box be the computer screen or imagined perspectives in the mind.

APPENDIX A

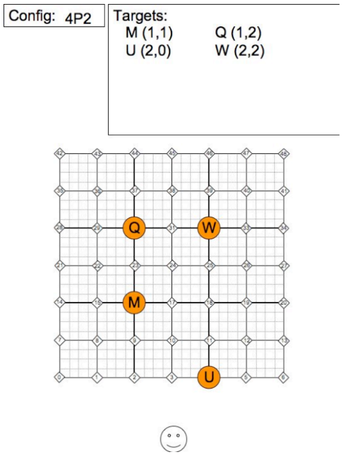
SPATIAL CONFIGURATIONS

A.1 EXPERIMENT ONE



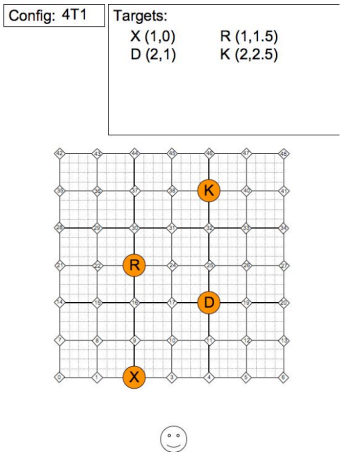
Config: 4P1

Targets:
A (1,0) E (1,2)
H (2,1) Y (2,2)



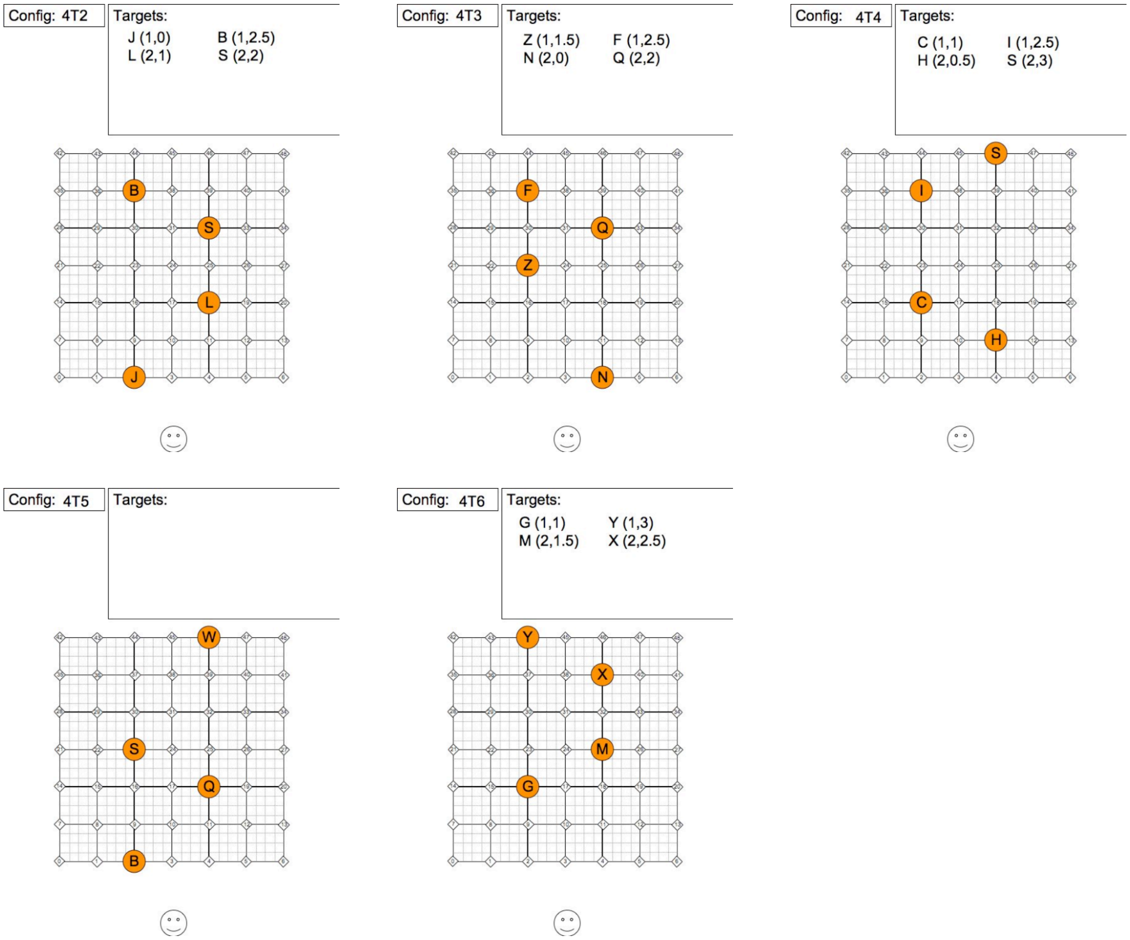
Config: 4P2

Targets:
M (1,1) Q (1,2)
U (2,0) W (2,2)



Config: 4T1

Targets:
X (1,0) R (1,1.5)
D (2,1) K (2,2.5)



Config: 4T2

Targets:
J (1,0) B (1,2.5)
L (2,1) S (2,2)

Config: 4T3

Targets:
Z (1,1.5) F (1,2.5)
N (2,0) Q (2,2)

Config: 4T4

Targets:
C (1,1) I (1,2.5)
H (2,0.5) S (2,3)

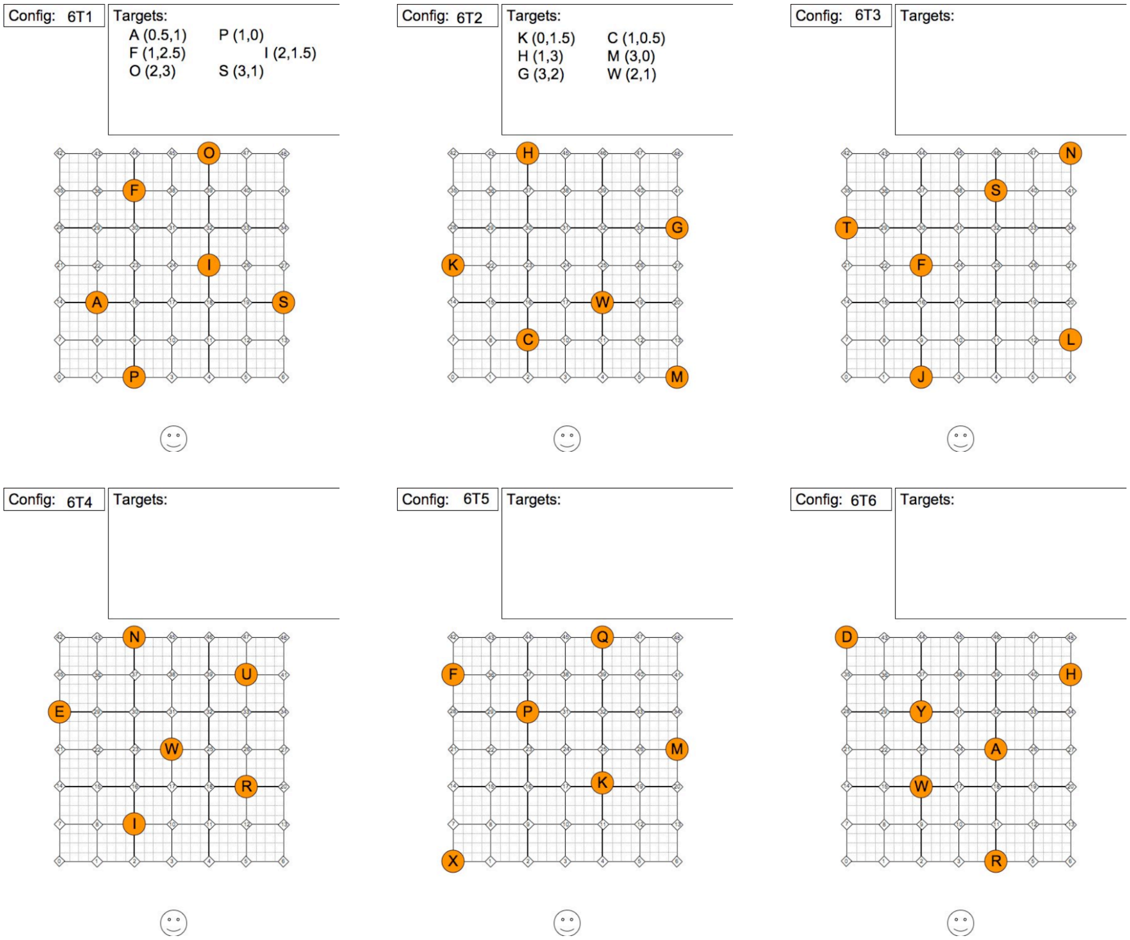
Config: 4T5

Targets:

Config: 4T6

Targets:
G (1,1) Y (1,3)
M (2,1.5) X (2,2.5)

Figure A.1 Experiment 1, training and set size 4 configurations



Config: 6T1

Targets:

A (0.5,1) P (1,0)
F (1,2.5) I (2,1.5)
O (2,3) S (3,1)

Config: 6T2

Targets:

K (0,1.5) C (1,0.5)
H (1,3) M (3,0)
G (3,2) W (2,1)

Config: 6T3

Targets:

Config: 6T4

Targets:

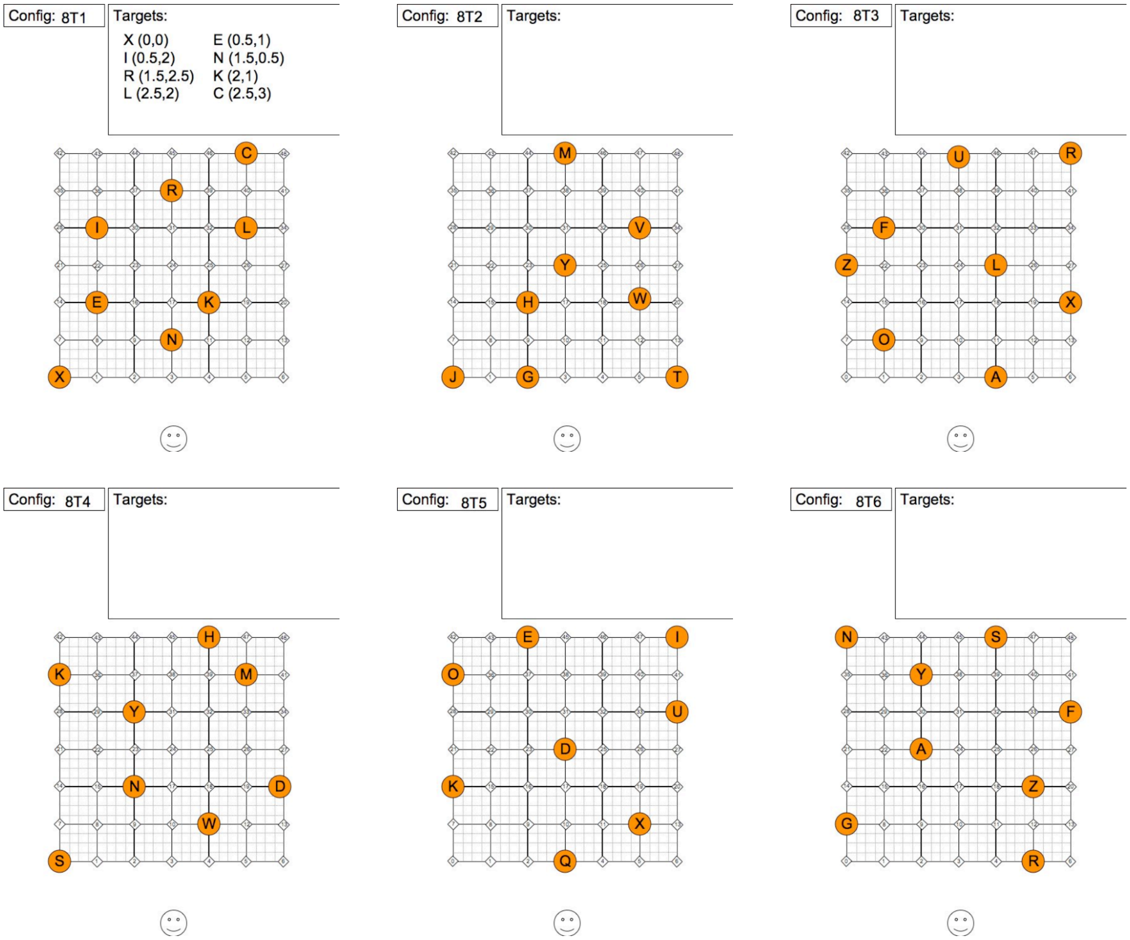
Config: 6T5

Targets:

Config: 6T6

Targets:

Figure A.2 Experiment 1, set size 6



Config: 8T1

Targets:

X (0,0) E (0.5,1)
I (0.5,2) N (1.5,0.5)
R (1.5,2.5) K (2,1)
L (2.5,2) C (2.5,3)

Config: 8T2

Targets:

Config: 8T3

Targets:

Config: 8T4

Targets:

Config: 8T5

Targets:

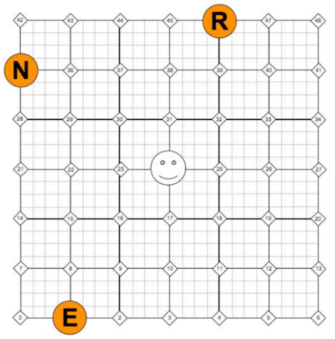
Config: 8T6

Targets:

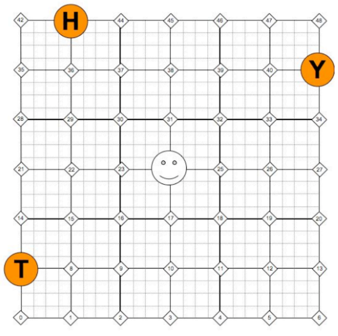
Figure A.3 Experiment 1, set size 8

A.2 EXPERIMENT TWO

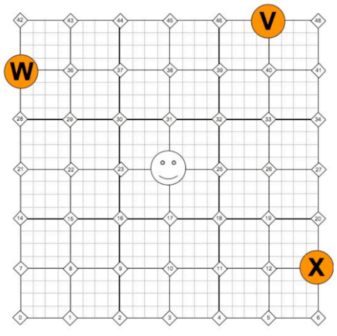
Config: 3P1



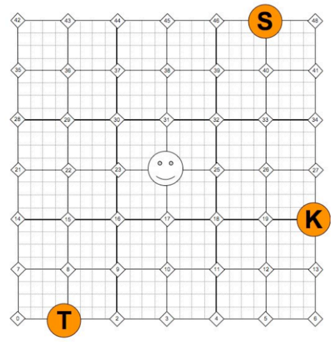
Config: 3P2



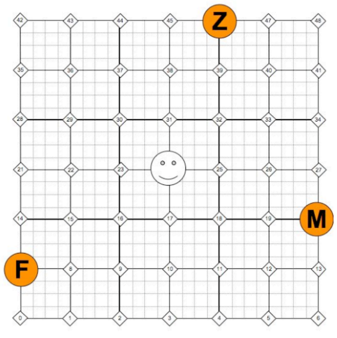
Config: 3T1



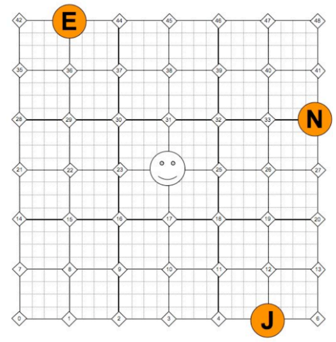
Config: 3T2



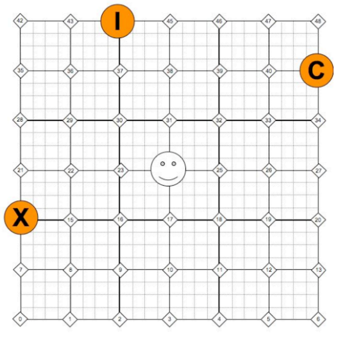
Config: 3T3



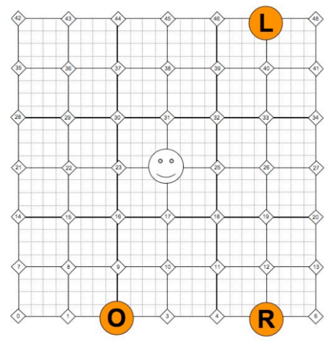
Config: 3T4



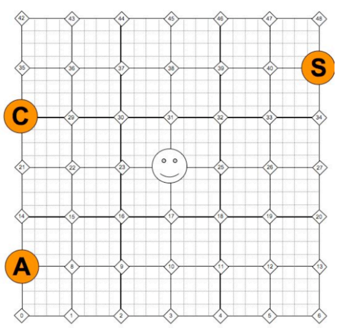
Config: 3T5



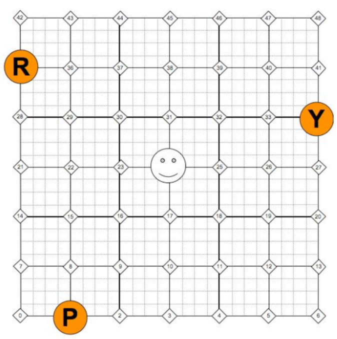
Config: 3T6



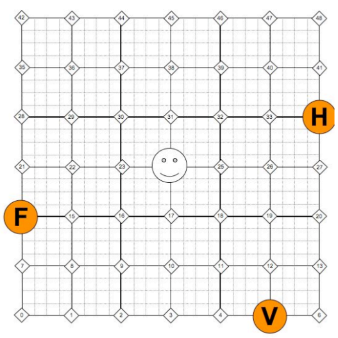
Config: 3T7



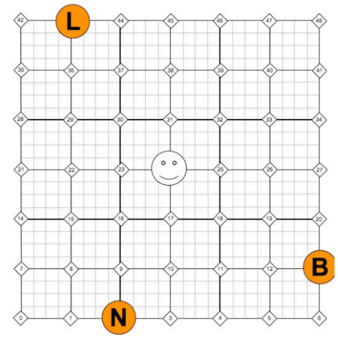
Config: 3T8



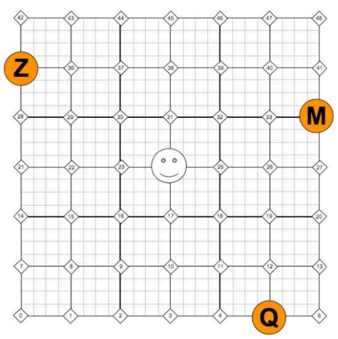
Config: 3T9



Config: 3T10



Config: 3T11



Config: 3T12

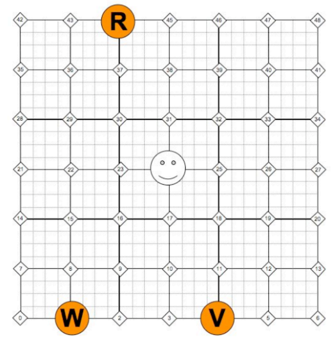


Figure A.4 Experiment 2, training and test configurations

APPENDIX B

EXPERIMENT QUESTIONNAIRES

Table B.1 Basic demographic questions

01sex	Sex	○ Male	○ Female	
02age	Age			
03education	Highest Education Level	○ High school	○ Undergraduate	○ Graduate
04verbal	SAT/GRE Verbal			
05math	SAT/GRE Math			

Table B.2 Experiment one debriefing questionnaire*

01wholistic When asked to visualize a single target location, I imagined not only the target but the ones near it as well

○ Never ○ ○ ○ ○ Always

02piecemeal When asked to visualize a target location, I "saw" only the target

○ Never ○ ○ ○ ○ Always

03map I would describe my mental images of the targets as map-like, as if I were seeing them from above

○ Never ○ ○ ○ ○ Always

04ego I would describe my mental images of the targets as egocentric, as if I were seeing them from my current or previous viewing location

○ Never ○ ○ ○ ○ Always

05update When I turned to face a new position I actively tried to imagine the locations of the targets relative to myself

○ Never ○ ○ ○ ○ Always

06mnemonic I would try to make sentences, acronyms, or stories out of the target letters to better remember them

○ Never ○ ○ ○ ○ Always

07serial When trying to remember a specific target, I'd often have to remember previous targets first. e.g. To remember "Q", I had to go through "M" and "W" first.

○ Never ○ ○ ○ ○ Always

08geometry While studying the locations I'd try to group targets into geometric clusters.

○ Never ○ ○ ○ ○ Always

09pegging When trying to figure out where a specific target was, I'd first figure out where an easier location was and then figure out where the target was relative to the easier location.

○ Never ○ ○ ○ ○ Always

10confidence Overall, I was fairly confident about the accuracy of my responses.

○ Unsure ○ ○ ○ ○ Confident

11difficulty How difficult was this task

○ Very Easy ○ ○ ○ ○ Very Hard

12rotateDiff I found that judgments were more difficult after I had turned around

○ Strongly Disagree ○ ○ ○ ○ Strongly Agree

13studyTime Do you feel there was enough time to study the configurations

○ Not enough time ○ ○ ○ ○ Plenty of time

14pointingTime Do you feel there was enough time to make each judgment

○ Not enough time ○ ○ ○ ○ Plenty of time

* Question ordering and scale directionality were randomized.

Table B.3 Experiment two debriefing questionnaire*

01wholistic	When asked to visualize a single target location, I imagined not only the target but the ones near it as well ○ Never ○ ○ ○ ○ Always
02piecemeal	When asked to visualize a target location, I "saw" only the target ○ Never ○ ○ ○ ○ Always
03map	I would describe my mental images of the targets as map-like, as if I were seeing them from above ○ Never ○ ○ ○ ○ Always
04ego	I would describe my mental images of the targets as egocentric, as if I were seeing them from my current or previous viewing location ○ Never ○ ○ ○ ○ Always
05update	When I turned to face a new position I actively tried to imagine the locations of the targets relative to myself ○ Never ○ ○ ○ ○ Always
06mnemonic	I would try to make sentences, acronyms, or stories out of the target letters to better remember them ○ Never ○ ○ ○ ○ Always
07serial	When trying to remember a specific target, I'd often have to remember previous targets first. Ex. To remember "Q", I had to go through "M" and "W" first.

○ Never ○ ○ ○ ○ Always

08geometry While studying the locations I'd try to group targets into geometric clusters.

○ Never ○ ○ ○ ○ Always

09pegging When trying to figure out where a specific target was, I'd first figure out where an easier location was and then figure out where the target was relative to the easier location.

○ Never ○ ○ ○ ○ Always

10confidence Overall, I was fairly confident about the accuracy of my responses

○ Unsure ○ ○ ○ ○ Confident

11preDiff How difficult was the pointing task before rotating

○ Very Easy ○ ○ ○ ○ Very Hard

12postDiff How difficult was the pointing task after rotating

○ Very Easy ○ ○ ○ ○ Very Hard

13offline Instead of updating the locations as I rotated, I waited until I'd stopped moving to figure out where the targets were

○ Never ○ ○ ○ ○ Always

14studyTime Do you feel there was enough time to study the configurations

○ Not enough time ○ ○ ○ ○ Plenty of time

15pointingTime Do you feel there was enough time to make each judgment

○ Not enough time ○ ○ ○ ○ Plenty of time

16preNDiff How difficult was the 1back task before rotating

○ Very Easy ○ ○ ○ ○ Very Hard

17postNDiff How difficult was the 1back task while rotating

○ Very Easy ○ ○ ○ ○ Very Hard

18updateNDiff How difficult was it to track the locations of the targets while doing the 1back task

○ Very Easy ○ ○ ○ ○ Very Hard

19updateDiff How difficult was it to track the locations of the targets when you WERENT doing the 1back task

○ Very Easy ○ ○ ○ ○ Very Hard

20confusion During the 1back, how frequently did you accidentally remember the number of the cue instead of the location

○ Never ○ ○ ○ ○ Always

*21verbalSpace*** To help me remember the location of the cue, I'd repeat the name of the direction it came from (i.e. "Right" or "Left").

○ Never ○ ○ ○ ○ Always

*22spatialSpace*** To help me remember the location of the cue, I'd visualize the location instead of using the name of the direction.

○ Never ○ ○ ○ ○ Always

23nbackTime Do you feel there was enough time to respond during the 1back

○ Not enough time ○ ○ ○ ○ Plenty of time

* Question ordering and scale directionality were randomized.

** Spatial condition only.

APPENDIX C

1-BACK DEVELOPMENT

The purpose of the secondary task in experiment two was to introduce modality specific processing that would interfere with the working memory resources required to engage in spatial updating. To aid in analysis, the task needed to be able to support isomorphs that would engage different working memory resources. The n-back task provided a natural fit, particularly considering that it has been used to assess both verbal and spatial working memories (Baddley, 2003). Because of the physical constraints of the experiment, all stimuli had to be presented auditorily. Similarly, the time constraints would not permit the traditional probing for response methodology (e.g. McElree, 2001; Awh et al., 1996). Instead, a continuous response version was utilized (Gevins et al., 1990).

During the n-back task, participants would hear a continuous stream of audio cues. For each cue, the participant would verbally respond with either a “yes” or a “no” depending on whether or not a specific feature of the cue was the same as the Nth previous. Two different versions of the n-back were developed, each with the exact same stimuli, but participants were to attend to different features of the cues. The stimuli used were stereo recordings of three numbers (0, 2 and 7) read from three different locations (left, center and right). For the verbal n-back, participants attended and matched only to the number, regardless of where they heard it. The spatial n-back had participants attend to the location, regardless of the number heard (figure C.1).

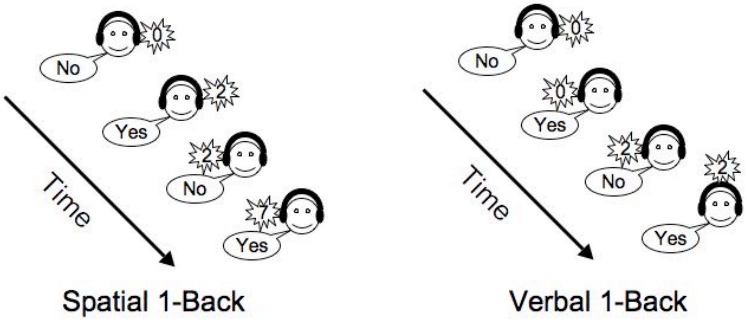


Figure C.1 Spatial and verbal N-back for N=1.

Average performance on both versions was roughly equivalent for N's of 1-4. However, the correlations of the spatial and verbal scores undermine the possibility that both are taping into a common working memory store (figure C.2).

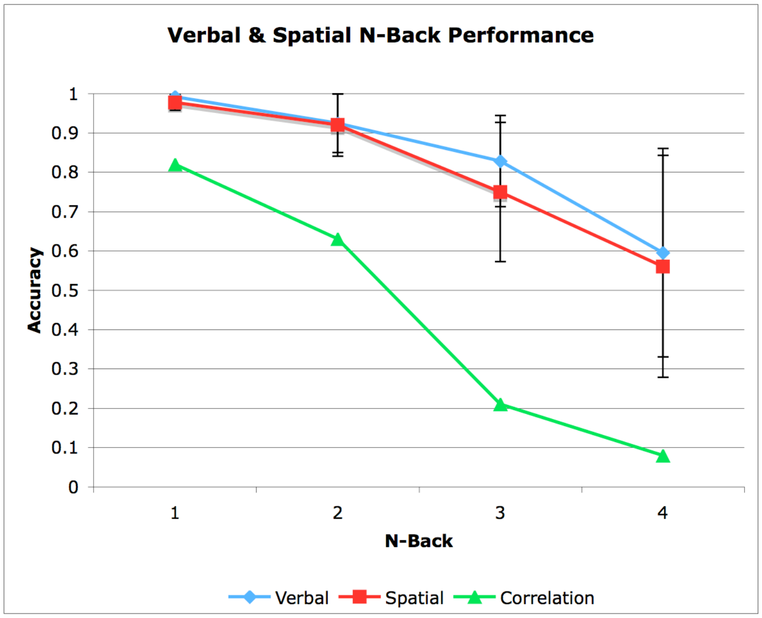


Figure C.2 Verbal & spatial N-Back accuracy & correlation.

With the viability of the two n-backs established, the difficulty of performing them in a dual-task environment had to be assessed. A handful of pilot subjects were asked to engage in the various n-backs while tracking targets during a simple rotation. All of the participants aborted shortly after attempting the spatial 2-back block, reporting that it was "simply impossible." As such, only the 1-back versions of the task were used in the final study.

Unfortunately, the early versions of the N-back task did not record the full subject response set and merely reported per-trial accuracies. As such neither D-prime nor error distribution analyses were conducted on the pilot data.

APPENDIX D

MODEL PARAMETER ESTIMATION

Because ACT-R/S representations a theoretical extension to the ACT-R cognitive architecture, initial models were fit using the default values for the core parameters (*:bll* 0.5, *:lf* 0.5, *:w* 1). The fitting of the models in these experiments was based solely on two parameters controlling the spatial updating.

D.1 INITIAL ESTIMATION

All initial parameter estimates were derived from a random subset of data from the set size four, egocentric visualizer group. The spatial updating parameters, mental translation and rotation rates, were derived by examining the difference in the number of transformations necessary to complete aligned and contra-aligned judgments. Specifically:

$\Delta t_s = 3/MT + 180/MR$

$\Delta t_r = 3/MT - 180/MR$

Where Δt_s is the latency difference between stay-contra and stay-aligned (1.7s), Δt_r is the latency difference between rotate-contra and rotate-aligned (-0.96s). MT and MR are the mental translation and rotation rates. The average distance between aligned and contra-aligned positions is 1.5m, and each judgment requires two translations (when capacity is less than 3). Combining the two equations yields a mental rotation rate of 138°/s and a mental translation rate of 7.8m/s.

D.1.1 Ecological validity of updating

As with all parameter estimates, one has to ask how reasonable the values are. Even though most evaluations of parametric ranges evolve as a given architecture ages, we can look towards other empirical studies for clues. While the number of studies providing sufficient information to extrapolate these values are limited, they paint a picture that is consistent with the current estimates (table D.1).

Table D.1 Parameter estimates derived from published sources

Study	Translation Rate	Rotation Rate
Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998	7-10 m/s	90-180°/s
Easton & Sholl, 1995	2.5 – 25 m/s	135°/s
Waller, Montello, Richardson, & Hegarty, 2002	7-10 m/s	125-225°/s

APPENDIX E

MODELING DETAILS

ACT-R/S and all of the models presented here are implemented with jACT-R, a Java^{tm} implementation of ACT-R. While at the time of press, jACT-R is not feature complete, all of the architectural elements the models depend upon have been validated. The software can be downloaded from http://jactr.org/. In anticipation of future software changes, a complete operating environment is available at http://anthonymharrison.com/dissertation/.

E.1 SPECIFIC MODELS

Because of the size of the models, they are not included directly. Rather URLs are provided to each model. All of the models linked here are in the jACT-R format, as opposed to the traditional ACT-R Lisp structure.

- Model 1a : Offline (http://anthonymharrison.com/dissertation/models/1a/model/)
- Model 1b : Online (http://anthonymharrison.com/dissertation/models/1b/model/)
- Model 1c : Transient (http://anthonymharrison.com/dissertation/models/1c/model/)
- Model 1d : Allo (http://anthonymharrison.com/dissertation/models/1d/model/)

- Model 2 : Dual (http://anthonymharrison.com/dissertation/models/2/model/)

E.2 PARAMETER SPACE EXPLORATIONS

Because of the scope and scale of the parameter space explorations, the output of them are not included here. For each model referenced, a brief outline of the space searched and the findings are presented along with a URL to view the actual searches. All simulation were of at least 1000 runs with *ActivationNoise* (*:ans*) set to 0.1.

E.2.1 Model 1a : Offline

Initial searches were focused on mental transformation rate parameters (*MentalTranslationRate* & *MentalRotationRate*), examining the general effect on the qualitative model fits. Across the range of values tested, the majority exhibited the qualitative pattern (i.e. alignment effect and its reversal), and most yielded strong correlations (RMSE were heavily affected). Subsequent searches verified that both default retrieval time (*LatencyFactor* or *:lf*) and decay rate (*BaseLevelLearning* or *:bll*) merely adjusted latencies up or down, with little interaction. Details: http://anthonymharrison.com/dissertation/models/1a/search

E.2.2 Model 1b : Online

Massive space searches were performed again looking at the transformation rates and retrieval parameters. Additional dimensions examined the influence of capacity (*ChunkCapacity*) and the number of rehearsals. Generally speaking, increases to capacity show the greatest effect from two to three. Beyond that, because of the nature of the model, there is no additional benefit. Online updating, itself, provides little additional benefit since the task permits so much slack time for offline updating and rehearsal. The number of rehearsals only served to slightly reduce retrieval times. Details: http://anthonymharrison.com/dissertation/models/1b/search

E.2.3 Model 1c : Transient

To test Wang's (1999) assertion that updating is entirely transient, ACT-R/S was slightly modified to introduce a new parameter (*EncodeUpdatedRepresentations*). The searches from 1a were repeated with encoding turned off and compared to those from 1a. Across the board, when updating is transient, JRDs after rotation take 2-3s longer to complete, often hitting the time-limit in the task. For the majority of the sampled spaces, the standard alignment effect dominated. Details: http://anthonymharrison.com/dissertation/models/1c/search

E.2.4 Model 1d : Allo-surrogate

Parameters for this model were taken directly from 1a, and no further searches were conducted.

E.2.5 Model 2 : Dual-task

Parameters for this model were taken directly from 1a. While the SOA could have been explored, it was not the primary focus and was not explored.

REFERENCES

Amorim, M., Glasauer, S., Corpinot, K., & Berthoz, A. (1997). Updating an object's orientation and location during nonvisual navigation: A comparison between two processing modes. *Perception & psychophysics, 59*, 404-418.

Anderson, J. R. (2007). *How can the human mind occur in the physical universe?* New York, NY: Oxford University Press.

Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of the mind. *Psychological Review, 111*(4), 1036-1060.

Atkinson, R. C., Holmgren, J. E., & Juola, J. F. (1969). Processing time as influenced by the number of elements in the visual display. *Perception & psychophysics, 6*, 321-326.

Awh, E., Jonides, J., Smith, E. E., Schumacher, E. H., Koeppe, R. A., & Katz, S. (1996). Dissociation of storage and rehearsal in verbal working memory: Evidence from positron emission tomography. *Psychological science, 7*, 25-31.

Baddley, A. (2003). Working memory: looking back and looking forward. *Nature reviews neuroscience, 4*(10), 829-839.

Banks, W. P., & Fariello, G. R. (1974). Memory load and latency in recognition of pictures. *Memory & Cognition, 2*, 144-148.

Book, A., & Garling, T. (1981). Maintenance of orientation during locomotion in unfamiliar environments. *Journal of experimental psychology: human perception and performance, 7*, 995-1006.

Burgess, N., Donnett, J. G., Jeffery, K. J., & O'Keefe, J. (1999). Robotic and neuronal simulation of the hippocampus and rat navigation. In N. Burgess, K. J. Jeffery & J. O'Keefe (Eds.), *The hippocampal and parietal foundations of spatial cognition* (pp. 149-165): Oxford University Press.

Burgess, N., Jackson, A., Hartley, T., & O'Keefe, J. (2000). Predictions derived from modelling the hippocampal role in navigation. *Biological cybernetics, 83*, 301-312.

Burgess, N., Maguire, E. A., & O'Keefe, J. (2002). The human hippocampus and spatial and episodic memory. *Neuron, 35*, 625-641.

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

Byrne, M. D., Becker, S., & Burgess, N. (2007). Remembering the past and imagining the future: a neural model of spatial memory and imagery.

Byrne, P., & Becker, S. (2004). Modeling mental navigation in scenes with multiple objects. *Neural computation, 16*, 1851-1872.

Cohen, J. (1988). *Statistical power analysis for the behavioral sicences* (2 ed.). Hillsdale, NJ: Erlbaum.

Cohen, N. J., & Eichenbaum, H. (1991). The theory that wouldn't die: A critical look at the spatial mapping theory of hippocampal function. *Hippocampus, 1*(3), 265-268.

Creem, S. H., Wraga, M., & Proffitt, D. R. (2001). Imagining physically impossible self-rotations: geometry is more important than gravity. *Cognition, 81*, 41-64.

Diwadkar, V. A., & McNamara, T. P. (1997). Viewpoint dependence in scene recognition. *Psychological science, 8*(4), 302-307.

Easton, R. D., & Sholl, M. J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. *Journal of experimental psychology, 21*(2), 483-503.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological review, 102*(2), 211-245.

Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and the automatic updating of body-centered spatial relationships. *Journal of experimental psychology: learning, memory, and cognition, 24*(1), 227-233.

Farrell, M. J., & Thomson, J. A. (1998). Automatic spatial updating during locomotion without vision. *Quarterly journal of experimental psychology, 51A*, 637-654.

Farrell, M. J., & Thomson, J. A. (1999). On-line updating of spatial information during locomotion without vision. *Journal of motor behavior, 31*, 39-53.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3:A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods, 39*, 175-191.

Flexser, A. J. (1978). Long-term recognition latencies under rehearsal-controlled conditions: Do list-length effects depend on active memory? *Journal of experimental psychology: Learning, memory and cognition, 4*, 47-54.

Franklin, N., & Tversky, B. (1990). Searching imagined environments. *Journal of experimental psychology: general, 119*(1), 63-76.

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

Gevins, A. S., Bressler, S., Cutillo, B., Illes, J., Miller, J., Stern, J., et al. (1990). Effects of prolonged mental work on functional brain topography. *Electroenceph Clinical Neurophysiology, 76*, 339-350.

Gugerty, L., & Rodes, W. (2007). A cognitive model of strategies for cardinal direction judgments. *Spatial cognition and computation*.

Gunzelmann, G. (2006). *Representing human spatial competence in ACT-R.* Paper presented at the ACT-R Workshop, Pittsburgh, PA.

Gunzelmann, G., Anderson, J. R., & Douglass, S. (2004). Orientation tasks with multiple views of space: Strategies and performance. *Spatial cognition and computation, 4*(3 207-253).

Harrison, A. M., & Schunn, C. D. (2003). ACT-R/S: Look Ma, No "cognitive-map"! *Fifth International conference on cognitive modeling*.

Hartley, T., Tinkler, I., & Burgess, N. (2004). Geometric determinants of human spatial memory. *Cognition, 94*, 39-75.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence, 32*, 175-191.

Hodgson, E., & Waller, D. (2006). Lack of set size effects in spatial updating: evidence for offline updating. *Journal of experimental psychology: learning, memory and cognition, 32*(4), 854-866.

Holmgren, J. E., Juola, J. F., & Atkinson, R. C. (1974). Response latency in visual search with redundancy in the visual display. *Perception & psychophysics, 16*, 123-128.

Holmes, M. C., & Sholl, M. J. (2005). Allocentric coding of object-to-object relations in overlearned and novel environments. *Journal of experimental psychology: Learning, memory and cognition, 31*(5), 1069-1087.

Hupbach, A., Hardt, O., Nadel, L., & Bohbot, V. D. (2007). Spatial reorientation: Effects of verbal and spatial shadowing. *Spatial cognition and computation, 7*(2), 213-226.

Jola, C., & Mast, F. W. (2005). Mental object rotation and egocentric body transformation: two dissociable processes? *Spatial cognition and computation, 5*(2&3), 217-237.

Jones, R., Zaientz, J., Wessling, J., Stensrud, B., Lisse, S., & Ray, D. (2006). *Spatial and temporal reasoning (SPAT-R).* Paper presented at the 26th Annual SOAR Workshop.

Just, M. A., Carpenter, P. A., & Varma, S. (1999). Computational modeling of high-level cognition and brain function. *Human brain mapping, 8*, 128-136.

Kelly, J. W., Avraamides, M. N., & Loomis, J. M. (in press). Sensorimotor alignment effects in the learning environment and in novel environments. *Journal of experimental psychology: Learning, memory and cognition*.

Kieras, D., & Meyer, D. E. (1997). An overview of the EPIC architecture for cognition and performance with application to human-computer interaction. *Human-computer interaction, 12*, 391-438.

King, J. A., Burgess, N., Hartley, T., Vargha-Khadem, F., & O'Keefe, J. (2002). The human hippocampus and viewpoint dependence in spatial memory. *Hippocampus, 12*, 811-820.

King, J. A., Trinkler, I., Hartley, T., Vargha-Khadem, F., & Burgess, N. (2004). The hippocampal role in spatial memory and the familiarity-recollection distinction: a case study. *Neuropsychology, 18*(3), 405-417.

Klatzky, R. L., Loomis, J. M., Beall, A. C., Chance, S. S., & Golledge, R. G. (1998). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological science, 9*(4), 293-298.

Klauer, C. K., & Zhao, Z. (2004). Double dissociations in visual and spatial short-term memory. *Journal of experimental psychology: general, 133*, 355-381.

Laird, J., Newell, A., & Rosenbloom, P. (1987). Soar: An architecture for general intelligence. *Artificial intelligence, 33*, 1-64.

Linberg, E., & Garling, T. (1981). Acquisition of locational information about reference points during locomotion with and without a concurrent task: effects of number of reference points. *Scandinavian journal of psychology, 22*, 109-115.

Linberg, E., & Garling, T. (1983). Acquisition of different types of locational information in cognitive maps: Automatic or effortful processing? *Psychological research, 45*, 19-38.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., Philbeck, J. W., & Golledge, R. G. (Eds.). (1991). *Human navigation by path integration*. Baltimore: Johns Hopkins University Press.

Lyon, D. R., Gunzelmann, G., & Gluck, K. A. (2004). Emulating a visuospatial memory field using ACT-R. *Proceedings of the sixth international conference on cognitive modeling*, 368-369.

Mast, F. W., Kosslyn, S. M., & Berthoz, A. (1999). Visual mental imagery interferes with allocentric orientation judgments. *Neuroreport, 10*(17), 3549-3553.

May, M. (2004). Imaginal perspective switches in remembered environments: Transformation versus interference accounts. *Cognitive psychology, 48*, 163-206.

May, M., & Klatzky, R. L. (2000). Path integration while ignoring irrelevant movement. *Journal of experimental psychology: learning, memory, and cognition, 26*(1), 169-186.

McElree, B. (2001). Working memory and focal attention. Journal of experimental psychology: Learning, memory & cognition, 27, 817-835.

McNamara, T. P. (2003). How are the locations of objects in the environment represented in memory? In C. Freksa, W. Brauer, C. Habel & K. F. Wender (Eds.), *Spatial Cognition 3* (pp. 174-191). Berlin: Springer-Verlag.

Meilinger, T., Knauff, M., & Bulthoff, H. H. (submitted). Working memory in wayfinding - a dual task experiment in a virtual city.

Mittelstaedt, M. L., & Mittelstaedt, H. (1980). Homing by path integration in a mammal. *Naturwissenschaften, 67*, 566-567.

Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of experimental psychology: learning, memory, and cognition, 28*(1), 162-170.

Mou, W., McNamara, T. P., Rump, B., & Xiao, C. (2006). Roles of egocentric and allocentric spatial representations in locomotion and reorientation. *Journal of experimental psychology: Learning, memory and cognition, 32*(6), 1274-1290.

Mou, W., McNamara, T. P., Valiquette, C. M., & Rump, B. (2004). Allocentric and egocentric updating of spatial memories. *Journal of experimental psychology: learning, memory, and cognition, 30*, 142-157.

Newell, A. (1973). You can't play 20 questions with nature and win.

Nori, R., Iachini, T., & Giusberti, F. (2004). Object localisation and frames of reference. *Cognitive process, 5*, 45-53.

O'Keefe, J. (1993). Kant and the sea-horse. In N. Eilan, B. Brewer & R. McCarthy (Eds.), *Spatial reprsentation: problems in philosophy and psychology* (pp. 43-64). Blackwell: Oxford.

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

Presson, C. C., DeLange, N., & Hazelrigg, M. D. (1989). Orientation specificity in spatial memory: What makes a path different from a map of the path? *Journal of experimental psychology: learning, memory and cognition, 15*(5), 887-897.

Presson, C. C., & Hazelrigg, M. D. (1984). Building spatial representations through primary and secondary learning. *Journal of experimental psychology: learning, memory and cognition, 10*(4), 716-722.

Presson, C. C., & Montello, D. (1994). Updating after rotational and translational body movements: coordinate structure of perspective space. *Perception 23*, 1447-1455.

Ratliff, K. R., & Newcombe, N. S. (2005). *Human spatial reorientation using dual task paradigms*. Paper presented at the 27th annual cognitive science society.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of experimental psychology: learning, memory, and cognition, 15*(6), 1157-1165.

Rieser, J. J., & Rider, E. A. (1991). Young children's spatial orientation with respect to multiple targets when walking without vision. *Developmental psychology, 27*(1), 97-107.

Roskos-Ewoldsen, B., McNamara, T. P., Shelton, A. L., & Carr, W. (1998). Mental representations of large and small spatial layouts are orientation dependent. *Journal of experimental psychology: learning, memory and cognition, 24*(1), 215-226.

Salvucci, D. D., & Taatgen, N. A. (in press). Threaded cognition: An integrated theory of concurrent multitasking. *Psychological Review*.

Schneider, W., & Chein, J. M. (2003). Controlled & automatic processing: behavior, theory, and biological mechanisms. *Cognitive science, 27*, 525-559.

Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive psychology, 43*, 274-310.

Shelton, A. L., & McNamara, T. P. (2004). Orientation and perspective dependence in route and survey learning. *Journal of experimental psychology: learning, memory, and cognition, 30*(1), 158-170.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*, 701-703.

Sholl, M. J. (1999). Egocentric frames of reference used for the retrieval of survey knowledge learned by map and navigation. *Spatial cognition and computation, 1*, 475-494.

Sholl, M. J. (2001). The role of a self-reference system in spatial navigation. In D. R. Montello (Ed.), *Spatial information theory: foundations of geographic information science* (pp. 217-231). Berlin: Springer.

Sholl, M. J., & Bartels, G. P. (2002). The role of self-to-object updating in orientation-free performance on spatial-memory tasks. *Journal of experimental psychology: learning, memory, and cognition, 28*(3), 422-436.

Sholl, M. J., Fraone, S. K., & Allen, G. (Eds.). (2004). *Visuospatial working memory for different scales of space*. Mahwah, NJ: Erlbaum.

Sholl, M. J., & Kenny, R. J. (2005). Sources of interference in spatial long-term memory retrieval. *Spatial cognition and computation, 5*(2&3), 187-215.

Sholl, M. J., & Nolin, T. L. (1997). Orientation specificity in representations of place. *Journal of experimental psychology: learning, memory and cognition, 23*(6), 1494-1507.

Simons, D. J., & Wang, R. F. (1998). Perceiving real-world viewpoint changes. *Psychological science, 9*(4), 315-320.

Valiquette, C. M., McNamara, T. P., & Labrecque, J. S. (2007). Biased representations of the spatial structure of navigable environments. *Psychological research, 71*, 288-297.

Waller, D., & Hodgson, E. (2006). Transient and enduring spatial representations under disorientation and self-rotation. *Journal of experimental psychology: learning, memory, and cognition, 32*(4), 867-882.

Waller, D., Loomis, J. M., Golledge, R. G., & Beall, A. C. (2000). Place learning in humans: the role of distance and direction information. *Spatial cognition and computation, 2*, 333-354.

Waller, D., Montello, D., Richardson, A. E., & Hegarty, M. (2002). Orientation specificity and spatial updating of memories for layouts. *Journal of experimental psychology: learning, memory and cognition, 28*(6), 1051-1063.

Wang, R. F. (1999). Representing a stable environment by egocentric updating and invariant representations. *Spatial cognition and computation, 1*, 431-445.

Wang, R. F. (2004). Between reality and imagination: when is spatial updating automatic? *Perception & psychophysics, 66*(1), 68-76.

Wang, R. F. (2007). Spatial processing and view-dependent representations. In F. W. Mast & L. Jancke (Eds.), *Spatial Processing in Navigation, Imagery, and Perception*: Springer Science & Business Media, Inc.

Wang, R. F., & Brockmole, J. R. (2003). Human navigation in nested environments. *Journal of experimental psychology: learning, memory, and cognition, 29*(3), 398-404.

Wang, R. F., & Brockmole, J. R. (2003). Simultaneous spatial updating in nested environments. *Psychonomic bulletin & review, 10*(4), 981-986.

Wang, R. F., Crowell, J. A., Simons, D. J., Irwin, D. E., Kramer, A. F., Ambinder, M. S., et al. (2006). Spatial updating relies on an egocentric representation of space: Effects of the number of objects. *Psychonomic bulletin & review, 13*, 281-286.

Wang, R. F., Hermer, L., & Spelke, E. S. (1999). Mechanisms of reorientation and object localization by children: a comparison with rats. *Behavioral neuroscience, 113*(3), 475-485.

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

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

Woodin, M. E., & Allport, A. (1998). Independent reference frames in human spatial memory: body-centered and environment-centered coding in near and far space. *Memory & Cognition, 26*(6), 1109-1116.

Wraga, M. (2003). Thinking outside the body: an advantage for spatial updating during imagined versus physical self-rotation. *Journal of experimental psychology: learning, memory and cognition, 29*(5), 993-1005.

Wraga, M., Creem, S. H., & Proffitt, D. R. (1999). The influence of spatial reference frames on imagined object- and viewer rotations. *Acta Psychologica, 102*, 247-264.

Wraga, M., Creem, S. H., & Proffitt, D. R. (2000). Updating displays after imagined object and viewer rotations. *Journal of experimental psychology: learning, memory and cognition, 26*(1), 151-168.

Wraga, M., Creem-Regehr, S. H., & Proffitt, D. R. (2004). Spatial updating of virtual displays during self- and display rotation. *Memory & Cognition, 32*(3), 399-415.