

ABSTRACT

SPATIAL UPDATING AND SET SIZE: EVIDENCE FOR LONG-TERM MEMORY RECONSTRUCTION

by Eric Hodgson

Four experiments required participants to keep track of the locations of (i.e., spatially update) 4, 6, 8, 10, or 15 target objects. Across all conditions, updating was unaffected by memory set size. Although traditional set size effects were observed (i.e., a linear increase of latency with memory load), these effects were independent of the updating process. The patterns of data and the participant strategies observed in this study were inconsistent with the traditional view of spatial updating as an online, automatic process. The current results are also inconsistent with an online, non-automatic updating process requiring working memory (WM) resources. Instead, it is concluded that participants formed enduring, but somewhat coarse, long-term memory (LTM) representations of the layouts at learning that were used to reconstruct spatial information about the layouts as needed. The current experiments support Amorim, Glasauer, Corpinot, and Berthoz's (1997) two-system model of spatial updating that includes updating through post-hoc reconstruction of spatial information from LTM.

SPATIAL UPDATING AND SET SIZE:
EVIDENCE FOR LONG-TERM MEMORY RECONSTRUCTION

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Introduction

As people move through the world, the spatial relationships between themselves and objects in the environment are constantly changing. For example, as you walk into your office, the doorway shifts from in front of you to immediately behind you, and after going to sit at your desk, the distance and direction to the doorway have changed again. The phenomenon of tracking the changing relations of oneself to locations in the environment is referred to as *spatial updating* (or often *egocentric updating*). Spatial updating is generally assumed to be either an online automatic process (Farrell & Robertson, 1998; Farrell & Thomson, 1998; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; May & Klatzky, 2000), or an online working memory (WM) process (Farrell & Thomson, 1999; Lindberg & Gärling, 1981; Rieser & Rider, 1991), but there is evidence that it can also involve long-term memory (LTM) processes (Amorim et al., 1997; Levine, Jankovic, & Palij, 1982). Determining the processes that underlie human spatial updating is of high theoretical interest, but can be somewhat difficult to examine.

In a recent experiment, Amorim, et al (1997; Exp. 2) demonstrated that spatial updating can be completed either online as one moves or, alternatively, in a post-hoc fashion at the end of one's motion. In their experiment, participants were asked to learn the position and orientation of a 3-dimensional capital letter 'F' and then update both its position and orientation while walking along a path. While they were walking, participants were required either to count the number of steps they had walked, or continuously report which side of the 'F' was closest to them. Amorim and his colleagues showed that updating could be carried out successfully by participants who focused only on the path they walked, and then later reconstructed spatial information about the target from LTM. According to this theory, changes in self-motion are monitored through a process of path-integration (Loomis, Klatzky, Golledge, & Philbeck, 1999). At the terminus of the movement, calculations of new self-to-object relationships are made based on a memory of the layout as viewed from the starting point. Amorim refers to this as an "updating-reconstruction-updating cycle" (Amorim, et al. 1997, p. 417), whereby people may only monitor a small subset of spatial information in the environment during movement, and then infer other spatial information as it becomes necessary. In its strongest form, an argument

could be made that if one had an enduring representation of the environment, such as a cognitive map, then it would only be necessary to remember one's starting position and heading, and the distance and direction of one's movement. From this, a person could calculate her new position in the environment and derive any egocentric self-to-object bearings and distances that were required. Thus, from an enduring memory of the local environment, people are able to derive the information that they need to successfully navigate to complete the task at hand, without having to have overloaded themselves by updating the locations of objects that are irrelevant to the current situation, are in a distal environment, or are simply beyond their capacity to actively monitor. In contrast to an online process, updating under these conditions is a post-hoc reconstruction process that utilizes enduring spatial information about the local environment.

Amorim and his colleagues reported that participants who used post-hoc updating sometimes committed gross errors (such as misjudging the orientation of the target object by 90°). These types of errors were not observed for participants who actively monitored the target as they walked. Additionally, these participants had significantly higher error than participants who were required to update online, suggesting that post-hoc updating is more prone to error than online updating due to a coarser representation and / or a noisy reconstruction process. Despite its somewhat higher error rates, however, LTM updating would be efficient in that online resources would not be taxed. Also, given the relatively limitless storage of LTM, a vast number of locations could be updated as long as they were adequately encoded, and updating accuracy should be relatively unaffected by the number of to-be-updated objects.

The dissociation between online updating and post-hoc updating has important implications for the study of spatial updating. Presumably, post-hoc updating would rely heavily on LTM representations, while online updating would be expected to utilize WM or be an automatic process. LTM, WM, and automatic systems are qualitatively different, and would be expected to be subject to different limitations. For example, as discussed above, it might be expected that online updating (whether automatic or WM) would be more precise than an LTM reconstruction process. Also, an online system would likely have a limited capacity, and would not be expected to update every known location in the world simultaneously, because this would likely exceed online processing capacity. More importantly, it would exceed functional necessity (e.g., you do not need to actively update the direction to the cereal isle unless you are

Table 1:

A Sample of the Diversity of Memory Set Size Across the Updating Literature

Study	Number of To-Be-Remembered Targets
Amorim, et al. (1997)	1
Reiser & Rider (1991)	1, 3, or 5
Klatzky et al. (1998)	3
Waller, Montello, Richardson, & Hegarty (2002)	4
Wang & Spelke (2000)	4, 6
Féry, Magnac, & Israël (2004)	5
Brou & Doane (2003)	6
Farrell & Robertson (2000)	7
Mou, McNamara, Valiquette, & Rump (2004)	9, 10
Wang & Brockmole (2003b)	11 (local & global combined)

in a grocery store). Conversely, an LTM system has access to relatively limitless storage, and might not be expected to exhibit capacity limitations.

Although Amorim, et al. (1997) have shown evidence for two distinct types of updating that occur as a result of explicit instructions, it is unclear which method is relied on in the absence of instructions. The following experiments seek to examine this issue by exploring the capacity limits of spatial updating. This should provide insight into which type of updating participants use by default in a typical updating task – making pointing estimates without vision before and after a rotation from the center of a surrounding layout of to-be-updated target locations (e.g., Brou & Doane, 2003; Farrell & Robertson, 1998, 2000; Féry et al., 2004; Holmes & Sholl, in press; Rieser, 1989; Wang, 1999; Wang & Brockmole, 2003a, 2003b; Wang & Spelke, 2000; Woodin & Allport, 1998; Wraga, 2003).

Additionally, if capacity limits are found, it will be informative to document the amount of spatial information that is updated as one moves. Across the updating literature, there is wide diversity in the number of target locations that participants are asked to update (see Table 1), ranging from a single target (e.g., Amorim et al., 1997; Rieser & Rider, 1991) to more than ten locations (e.g., Mou et al., 2004; Wang & Brockmole, 2003b). Despite this broad range, and the potentially important implications, little attention has been focused on the issue of capacity limits

of the spatial updating system. The importance of this issue can be seen by contrasting two recent results in the area of spatial updating.

In several experiments, Wang & Spelke (2000) had participants learn a layout of either four or six (separate experiments) target objects that surrounded a small booth, and then point to each object from within the booth while oriented and again after a disorientation procedure. The variability of subjects' responses was measured in the oriented (*eyes-closed*) phase and in the disoriented phase. Variable error was significantly higher after disorientation, which the authors interpreted as a disruption of an online, constantly updated, egocentric representation of the environment. These results were also interpreted as providing evidence against an enduring spatial representation such as a cognitive map.

Alternatively, Mou, McNamara, Valiquette, and Rump (2004) had participants stand and learn a layout of either nine or ten objects (separate experiments), then walk out into the center of the layout and turn to face a specified object. The participant then closed her eyes and was asked to make a judgment of relative direction (i.e., imagine that you are at the shoe facing the book, point to the jar). In this task, participants' performance was better for trials in which the imagined view was aligned with their original learning view than trials that were aligned with the direction they were currently facing (although performance on these trials was facilitated relative to the remaining imagined headings). The authors interpreted these results as support for an enduring representation of the spatial layout with a preferred viewpoint (i.e., the learning viewpoint).

While these two studies both confirm humans' ability to update self-to-object relationships during self-motion, they come to nearly opposite conclusions on the nature of spatial representations. One possible reason for this difference is that participants in Wang and Spelke's (2000) study never updated more than six targets, whereas those in Mou, et al's (2004) study never updated fewer than nine to complete their task. These represent very different memory loads, and participants in these studies may have been relying on different memory systems. If an updating system were subject to a capacity limit falling between six and nine locations, then these contrasting results might be expected. Mou, et al (2004) addressed this as a possibility, but no firm conclusions could be drawn as spatial updating capacity was not manipulated or tested.

To my knowledge, only one study has directly addressed the issue of updating capacity, although not as its primary focus (Rieser & Rider, 1991; but see also Wang et al., 2004). Rieser and Rider (1991) asked participants to view a layout of one, three, or five target objects.

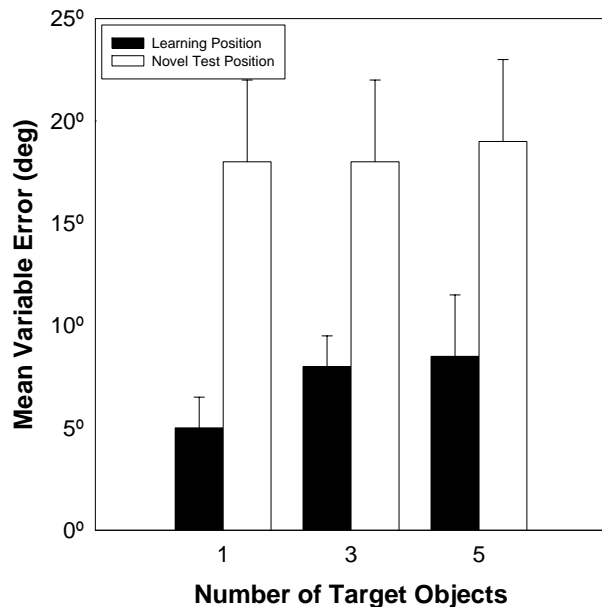


Figure 1: Approximate data for adult participants in Rieser & Rider (1991, Exp. 2). Pointing performance was not affected by the number of to-be-updated target objects, but did exhibit a significantly decrement after movement.

Blindfolded participants were prompted to point towards a single, random target, and then walked out into the layout. At the end of their path, participants were asked to make another pointing estimate to one of the targets. Participants had no prior knowledge of where the endpoint of their path would be, or which target’s bearing they would have to estimate.

There was an increase in variable error after movement, but this increase was statistically equivalent for each set size (see Fig. 1). The authors interpreted this as evidence that the environment is updated holistically as a person moves, not in reference to single objects. If this were the case, updating would not be subject to

capacity effects, because even complex layouts could be updated as a whole. In light of Amorim, et al.’s (1997) findings, however, these results could be interpreted as evidence for LTM reconstruction, as the updating process was somewhat noisy – yielding higher error after movement – and error rates were equivalent for all memory loads.

An alternative explanation, however, is that five targets is not a high enough memory load to exceed the capacity limits of spatial updating. Traditional measures of short-term memory storage across many areas have advocated a WM capacity of around seven items (Banks & Fariello, 1974; Burrows & Okada, 1975; Miller, 1956). Thus, a lack of capacity effects with five or fewer objects may not be surprising. In the following experiments, a higher range of set sizes spanning those commonly used in the updating literature (see Table 1) are used to extend the range of Rieser & Rider (1991) to provide better detection of any capacity limits.

In sum, there are several unanswered questions regarding spatial updating. What memory systems underlie the updating process in this type of task? If multiple systems are involved, what are the conditions under which each system is used? Are these processes subject to capacity limits? If so, what are those capacity limits? Given the importance of this issue for making claims relating to cognitive mapping, spatial representations, and the mechanisms of the updating process itself, the capacity limit of spatial updating necessitates further exploration.

The following experiments address these questions by manipulating the number of to-be-updated targets in a common updating paradigm. The dissociation between LTM updating and online updating is more directly explored in Experiments 3 and 4. Patterns of capacity effects across conditions should provide a good indication as to what systems are being utilized during a typical updating task and what, if any, the limitations of those systems are.

To preview, no indications of a capacity-limited updating process is found in any of the experiments (up to 15 target locations), and evidence is shown that suggests participants are relying on effortful post-hoc reconstruction of spatial information from LTM rather than an online updating process. The findings have important implications for current methodology in research on spatial updating as well as claims to the automaticity of spatial updating.

Experiment 1

Methods

Participants. Twenty-six participants (thirteen female) from Miami University's psychology subject pool participated in exchange for course credit. All participants were run individually in 45-minute sessions. Two participants were omitted for failing to follow directions (e.g., lifting up the blindfold to look at the layout of objects), leaving a sample of 24 participants (12 female).

Materials. During the experiment, each participant learned 4 different sets of target objects: one each of size 4, 6, 8, and 10. The sets were composed of different thematically related sets of objects (kitchen objects, office objects, stuffed animals, and sports equipment) to reduce any interference between sets. Different combinations of themes and set sizes were used for each participant so that each combination of a set size and theme occurred equally often.

For each participant, the locations of the targets were pseudo-randomized¹ from a set of 15 predetermined locations that surrounded the participant in a 5.94 x 3.43 meter space. The distance and orientation from the stool to each of the 15 locations was staggered to create an irregular array. No location was closer than 1.45 m or further than 3.28 m. The angle of separation between adjacent locations averaged 24°, and was never less than 18°.

Throughout the experiment, participants were seated on a rotating stool in the center of the layout. During testing, participants wore a V8 virtual headset (HMD) that obstructed any vision of the layout, and displayed simple text instructions (i.e., “Point to the Cup”) at 72 kHz. Responses were made with a gun-shaped pointing device (ACT Labs PC USB Light Gun) equipped with an Intersense InertiaCube² which provided online (180 kHz) measurement of the pointing direction (pitch, roll, and yaw) with a resolution of 0.01°, accurate to within 1°. Headphones mounted on the HMD played white noise that masked ambient noise during testing and prevented participants from hearing the experimenter removing objects and arranging the next layout. A Pentium IV using a script written in the Python programming language controlled all presentation and data collection.

Procedure. Following an informed consent procedure and a brief introduction to the experiment, participants were asked to sit on the stool in the center of the room (see Fig. 2). Each object in the first layout was pointed to and named, and participants were given as much time as they desired to learn the locations of the objects, with the foreknowledge that they would have to point to them while blindfolded. Participants were also instructed that at one point during each set, they would be required to rotate on the stool, and that they should try as best they could to keep track of all of the objects while rotating.

Instructions were given on the proper procedure for using the light gun. To start each trial, participants were required to lay the gun flat in their lap, which was enforced by the experiment script. The latency timer was stopped when the light gun was lifted from the participant’s lap (as measured by the roll of the inertial tracker). All participants were given a set of practice trials with the pointing procedure, and were corrected if they had any problems. Equal emphasis was given to speed and accuracy during the pointing instructions.

¹ Purely random arrangements were used in pilot testing, but occasionally led to unusual configurations (e.g. – with a set size of 4, all 4 objects might be placed right next to each other, 20° apart, directly behind the participant. This would not be a comparable task to learning a layout that was more dispersed. Thus, the layouts were randomly selected from subsets of configurations that were of roughly equal irregularity and dispersion to balance difficulty across participants.

For each trial, a message such as “Point to the Stapler” appeared in the center of the HMD display (or on a computer monitor during practice) and remained on the screen until the participant pointed to the target and clicked the trigger of the light. After the participant returned the light gun to the resting position, the next trial was begun following a 2 second delay. Each object was pointed to twice per phase, with the order of objects being randomized in two blocks (i.e., point to each of the objects once in a random order, and then a second time in a newly randomized order).

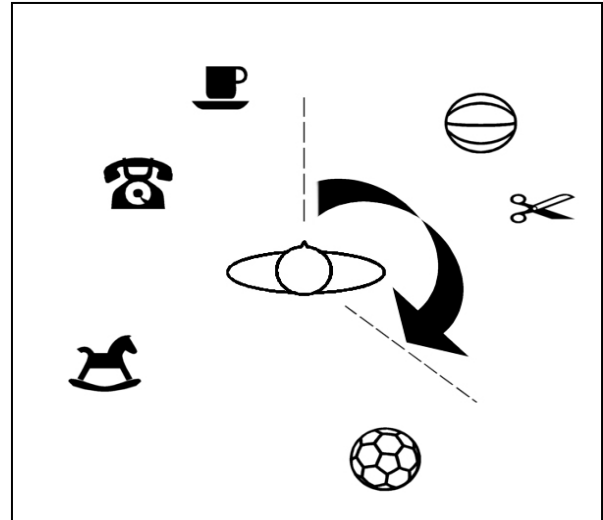


Figure 2: Hypothetical layout of six target objects around the participant. Sample heading before and after the rotation are indicated by dotted lines.

After studying the current layout, participants completed a practice phase with full vision, pointing to each target as prompted. This was followed by a blindfolded, pre-rotation test phase. Participants were then reminded to keep track of all of the objects in the set as best they could and prompted to rotate slowly either to the right or left (counterbalanced across sets for each participant) until the experimenter asked them to stop. All rotations were approximately 135°, and were followed by a final, post-rotation test phase. These procedures were repeated until the participant completed all four sets.

It was assumed that participants could not correctly update an object’s location after self-rotation if they did not know its position in the layout. Therefore, a learning criterion was imposed on the pre-rotation phase to ensure that participants had adequately learned the layout. In order to proceed to the post-rotated phase, participants had to point to each object in the layout within 45° of absolute angular error and maintain a mean absolute error below 25° for the entire phase. This criterion successfully eliminated unwanted noise from the data, as I was interested in failures in updating, and not failures in encoding². If a participant failed to meet the criterion,

² A pilot experiment was run without this criterion. Forgetting a single object’s location, or mixing up two objects would yield a small number of trials with abnormally high error (frequently over 100°) that skewed otherwise accurate performance. Such a pattern was frequently observed. While these types of errors may be interesting, they are not the phenomenon of interest in the present study, as the forgetting takes place prior to (and independent of) updating. The overall pattern of results found in piloting was not changed by imposing this criterion in the final experiment.

she reviewed the layout and repeated the practice and pre-rotation phases until she was able to pass successfully. The cutoff values for the criterion were determined in pilot testing to be reasonably passable, while still catching major errors (i.e., mixing up two objects or general sloppiness in pointing) prior to updating.

At the conclusion of the experiment, informal exit interviews were conducted and participants were debriefed about the purpose of the experiment. Participants were given the opportunity to specify how they approached the task and what, if any, strategies they employed.

Analyses. Responses were measured in terms of both latency and error. For each trial, pointing error was measured as the signed difference between the orientation of the light gun (yaw) when the trigger was clicked and the actual bearing (yaw) from the center of the stool to the location of the target. Latency was measured as the time between the onset of instructions (i.e., point to the stapler) in the HMD and the time at which the participant moved the light gun beyond a threshold (described above), thus eliminating noise caused by different amounts of movement required to point to different locations. Three dependent measures were analyzed in the following experiments: mean absolute updating error (updating error), adjusted mean absolute updating error (adjusted updating error), and mean latency.

Of primary interest for this research is updating error. This variable is a measure of the absolute difference in signed errors of pointing to a target before and after rotation, indicating how well participants have kept track of the location at which they remember the target being (regardless of the physical accuracy of that location). For example, if a participant missed the stapler by -10° before rotating and $+15^\circ$ after rotating, her updating error for that object would be 25° . In a perfectly accurate updating system, updating error should be zero degrees, reflecting the fact that pre- and post-rotation estimates did not differ.

Updating error, as defined above, can come from two sources. First, the participant can misperceive the magnitude of rotation. It is known that under conditions in which people have limited or no visual information, perception of the magnitude of one's own movement can be error-prone (Foo, Warren, Duchon, & Tarr, 2005; Loomis et al., 1999; May & Klatzky, 2000; Montello, Richardson, Hegarty, & Provenza, 1999). Thus, some updating error could be attributed to a change in bias in participant's pointing responses. For example, if a participant was unbiased prior to rotation, but underestimated the rotation by 20° and pointed accordingly, a mean updating error of 20° would be expected. Second, updating error may be introduced by

cognitive limitations, such as a capacity limitation (an inability to track all targets) or by any reconstruction of the layout from a coarse LTM representation (Amorim et al., 1997). This source of error is independent of the perception of one's movement, and represents a cognitive limitation on how the perceived movement is applied to one's knowledge of the environment.

To examine this second source of error, updating error was adjusted by removing the mean change in bias that occurred by participants' misperceiving the magnitude of their rotation. The mean change in bias was calculated for each participant and for each set of targets by taking the absolute difference between mean signed error before and after rotation. The absolute change in bias was then subtracted from the updating error for that participant in that set to form an adjusted updating error score. If a participant is perfectly able to monitor the magnitude of their rotation, then her change in bias would be 0° , and the adjusted updating error will be equal to the unadjusted updating error. Conversely, if the participant misperceived the amount of rotation but had no error in applying that knowledge in making her pointing responses, all of the updating error would be accounted for by the change in bias, yielding an adjusted updating error of 0° . Thus, adjusted updating error is bounded by a minimum of 0° and a maximum equal to the unadjusted updating error. As an example, if a participant had a mean updating error of 25° with six target objects, and was found to have underestimated her rotation by an average of 10° , her adjusted updating error would be 15° .

Latency was measured as the time between stimulus onset and the beginning of the participant's response (described above). This represents a measure of 'thinking time' and excludes the amount of time it takes the participant to move her arm to the desired bearing and depress the response button. Thus, latency is not affected by the amount of movement required to provide a pointing estimate, (e.g., targets in front of the participant might be pointed to faster than targets behind the participant because of the amount of movement required).

Gender of the participant was included as a factor in all initial analyses, and it occasionally exhibited a main effect or higher-order interaction. However, these effects were unsystematic and were not of primary interest to the current research. Thus, gender was dropped from the final analyses reported below. All significant main effects of gender are reported in footnotes for the interested reader.

Results

Updating Error. Updating error in Experiment 1 averaged 20.87° (95% CI $\pm 2.72^\circ$) across layouts (see Fig 3), and, manipulating the number of to-be-remembered targets (4, 6, 8, 10) had no appreciable effect. A repeated-measures ANOVA indicated no significant effect of set size ($F(3,68) < 1$).

Adjusted Updating Error. Updating error was adjusted for each participant and each set size (as described above) to eliminate any change in bias from misperceiving the amount of rotation. After this adjustment, there were still no significant differences among set sizes ($F(3,58) < 1$). The mean adjusted updating error collapsed across set sizes was 3.48° (95% CI $\pm 0.92^\circ$).

*Latency*³. The latency results for Experiment 1 are presented in Figure 4. Thinking time (as defined above) increased linearly with the number of target objects, yielding a significant linear trend ($F(1,23)=27.41, p<.001, f=1.09$). This linear increase was the same before and after the rotation, and did not interact with the test phase (before or after rotation). However, response times were significantly slower after rotation (mean increase = 151ms; $F(1,23)=20.77, p<.001, f=0.95$).

Discussion

Of primary interest in Experiment 1 was the finding that no differences in updating performance were observed as the number of target objects was increased; both updating errors and adjusted updating errors were equivalent for four, six, eight, and ten targets (see Fig 3). If updating had occurred online and was sensitive to capacity, then one of two patterns would have been expected. First, updating error might be expected to increase linearly as the number of targets was increased, reflecting the increased memory load. Alternatively, a sizable increase in

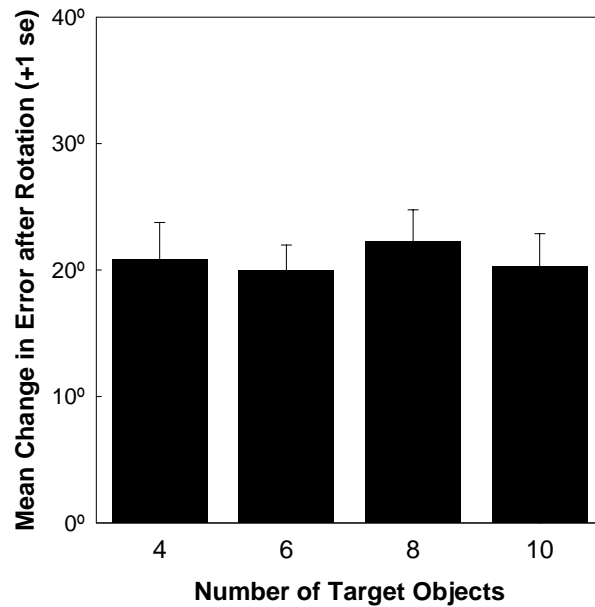


Figure 3: Updating error (in degrees) for Exp. 1. No indication of a capacity effect was observed.

³ The main effect of gender was significant ($F(1,22)=4.49, p=.046, f=0.45$), with females in this experiment responding slightly faster than males (mean latencies of 1.39s and 1.68s, respectively).

updating error could be expected at the point that participants' memory capacity was exceeded. The absence of either of these trends casts doubt on the use of a capacity-limited online updating process in the current experiment.

It could be argued that updating is sufficiently automatic and efficient to be unaffected by increases in memory load (at least up to ten items). However, one aspect of the experiment casts doubt on this interpretation. Specifically, participants were frequently observed forming and using elaborate mnemonic techniques to memorize the layout of objects at learning. Some participants, for example, reported making up a sentence with the first letter of each object, or verbally repeating the order of targets around the room until they felt confident. During testing, pointing responses for these participants could be made by counting the correct number of places down the list, rather than simply and automatically knowing the correct bearing. Those who used this type of strategy were often observed making counting motions during pointing responses (i.e., pointing to each object in order and iterating through the list until the appropriate target was reached).

Exit interviews confirmed the prevalent use of these types of strategies. In the entire experiment, there was only one participant who did not offer a precise, verbalizable strategy for

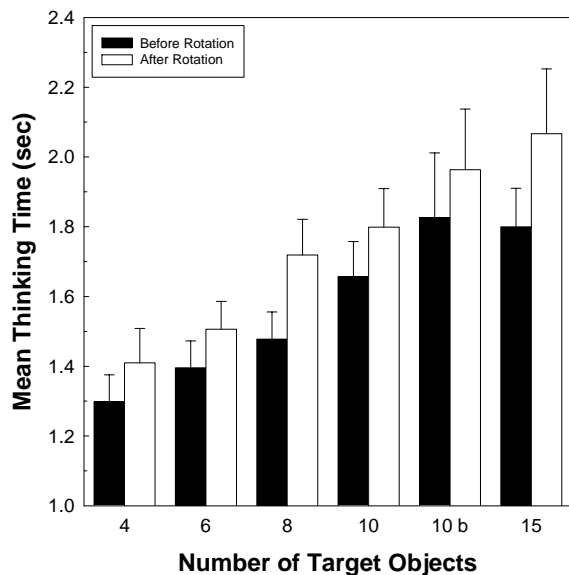


Figure 4: Thinking time (in seconds) from Exp. 1 (set sizes 4-10) and Exp. 2 (set sizes 10b & 15). A typical list-length effect is evident in the linear increase of latency with the number of to-be-remembered items. However, this effect is independent of updating. Participants were consistently slower after rotation.

completing the task. Of the remaining participants, nine reported trying to memorize the order of targets; six participants reported trying to memorize and track certain anchor points, such as the object immediately in front of them or the objects closest to cardinal directions. Only five participants reported trying to visualize the layout or trying to map the layout onto a clock-face, which incorporates both the order and the relative angle to each target. Such strategies imply an explicit attempt to encode the layout into long-term memory and then retrieve and / or reconstruct the information as needed; these strategies are not consistent with the view of updating as an online, automatic

process.

Another aspect of the data that argues against an automatic updating process is the sizable increase in error after rotation. In terms of participants' memory of the layout, the non-zero updating error and adjusted updating error show that participants were unable to maintain a perfectly stable representation of even four targets through a 135° rotation. Such inaccuracy is consistent with Amorim, et al.'s (1997) finding of higher error for LTM updating. Also, the adjusted updating measure effectively eliminates error associated with tracking the magnitude of rotation, leaving 3.48° of error that was the result of participants' failure to accurately infer their relationship to the environment. If updating were online, one would expect that any error in updating should be accumulated by the end of one's movement, contributing only to the change in bias. That error exists independent of any misperception of the magnitude of rotation does not support the hypothesis that participants are updating all self-to-object relations online.

Instead, it seems that participants were able to maintain an immediate awareness of the environment prior to rotation, yielding relatively accurate performance. After rotation, however, participants likely used a coarser long-term store of the layout and reconstruct the bearing to each object from their new facing direction.

The only indications of a capacity-limitation in Experiment 1 come from the analyses of thinking times. While there was a linear increase in reaction times as the number of targets was increased, the increase was unmediated by the updating process, and did not differ before or after rotation. This type of effect is consistent with traditional list-length effects (Atkinson, Holmgren, & Juola, 1969; Banks & Fariello, 1974; Flexser, 1978; Holmgren, Juola, & Atkinson, 1974), in which response time increases with the number of to-be-remembered items. This effect is also consistent with the observation that many participants were treating the layouts as a simple list, memorizing the target objects in a particular sequence at learning and then iterating through the list of targets at test.

In summary, the results of Experiment 1 warrant two conclusions. First, there was no evidence of a capacity limit for updating between four and ten targets. Second, the pattern of results observed and the strategies that were reported in Experiment 1 are more consistent with updating through LTM reconstruction than any form of online updating.

Experiment 2

One of the original intentions of this research was to extend the range tested by Rieser & Rider (1991), on the premise that five items may not have exceeded humans' updating capacity. Similarly, it may be the case that humans have a high capacity for spatial information, which was not exceeded by ten locations. Experiment 2 extends the current paradigm to test people's ability to update as many as 15 targets.

Methods

Participants. Twelve participants (six female) from Miami University's psychology subject pool participated in exchange for course credit. All participants were run individually in 45-minute sessions. None of the participants had participated in Experiment 1.

Materials and Procedure. Materials and procedures were the same as those used in Experiments 1, with the exception that the four object sets were consolidated into two larger groups. Office and kitchen supplies were combined to form a 'household objects' set. Sports equipment and stuffed animals comprised a set of 'toys.' Using these larger sets of target objects, each participant was asked to learn and update two layouts – comprised of 10 and 15 targets. Set size order and theme were counterbalanced across participants.

Results

Updating Error. The results for updating error in Experiment 2 are presented in Figure 5. As in Experiment 1, the manipulation of set size had no significant effect on updating error ($t(11)=0.24, p>.80$). Collapsed across set sizes, the overall magnitude of updating error was 24.26° (95% CI $\pm 4.06^\circ$), which is comparable to Experiment 1.

Adjusted Updating Error. Updating error was adjusted for a change in pointing bias to eliminate any influences of perceptual error (i.e., misjudging the amount of the turn). As in Experiment 1, there was no significant difference in adjusted updating error between set sizes ($t(11)=0.46, p>.65$). Collapsed across set sizes, adjusted updating error was 4.92° (95% CI $\pm 2.71^\circ$).

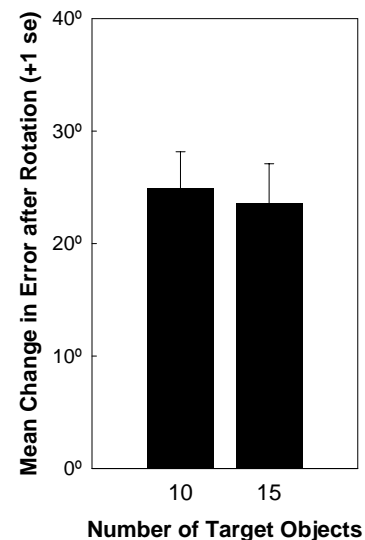


Figure 5: Updating error (in degrees) for Experiment 2. Again, no indication of a capacity effect was observed.

Latency. Latency results were analyzed using a 2 (set size) x 2 (phase: before or after rotation) repeated-measures ANOVA. The linear increase in thinking time observed in Experiment 1 was not significant in Experiment 2 ($F(1,11) < 1, p > .65$), due largely to comparably slower responses with 10 targets in this experiment (mean increase from Exp. 1 = 167ms). As in the previous experiment, participants were significantly slower after rotation (mean increase = 185ms; $F(1,11)=11.32, p < .01, f=1.01$), and set size did not interact with phase ($p > .25$).

Discussion

The results of Experiment 2 closely parallel those of Experiment 1. There was no indication of a set size effect between 10 and 15 targets, and both error and latency levels were roughly equivalent to those in Experiment 1. The list length effect observed in the latency measure of Experiment 1 was not significant in Experiment 2, but the lack of effect can be attributed to somewhat slower response times with 10 targets in Experiment 2 compared to those in Experiment 1. Across experiments, the linear increase in response times – both before and after rotation – is consistent between 4 and 15 targets (see Fig. 4).

Updating error was again rather large (24.26°), and could not be totally accounted for by errors in perceiving the magnitude of rotation. Adjusted updating error across set sizes was 4.92° , again supporting the idea that extra error is introduced independent of the perceptual processes (i.e., a reconstruction process using a coarser, LTM representation of the layout).

The elaborate strategies observed in Experiment 1 were also prevalent in Experiment 2. In exit interviews, seven of the 12 participants reported that they approached the task by trying to memorize the order of target objects around the room. Five participants reported trying to keep track of particular anchor points. Only two participants reported trying to form a “mental map” of the layout, or trying to visualize the layout. As in Experiment 1, all but one participant reported some explicit, verbalizable strategy.

One obvious strategy that was underrepresented was a chunking strategy. Because the larger sets used in Experiment 2 were combinations of the smaller sets used in Experiment 1, it would have been plausible for participants to group objects together into these categories. This was not a novel strategy, as groupings based on colors or other properties would have also been possible and were available in all experiments. However, a chunking strategy may have been more salient in Experiment 2. Despite the availability and obvious utility of chunking strategies

in reducing memory load (Bower, 1969; Bower, Clark, Lesgold, & Winzenz, 1969; Tulving, 1962), only 1 participant reported trying to group objects together in Experiment 2.

In summary, the results of Experiment 2 mirror and extend those of Experiment 1. No effects of capacity limitations were apparent. Also, the non-zero adjusted updating error, presence of elaborate mnemonic strategies, and list length effects in latencies (extending from Exp. 1) supported the hypotheses of updating via a post-hoc LTM reconstruction process and is inconsistent with online updating (automatic or otherwise). Taken together, the results of Experiments 1 and 2 extend the findings of Rieser & Rider (1991), and give no indications of capacity-limited updating between one and fifteen target locations.

Experiment 3

Experiment 3 attempted to further dissociate LTM and WM updating by introducing an interference task during updating. Experiments 1 and 2 showed that LTM is involved in spatial updating for this type of task, but they do not necessarily show that WM is not also involved. Experiment 3 will address this more directly by exploring the degree to which updating across set sizes is affected by an interference task. If an online updating process that utilizes WM is being employed, then the interference task should degrade updating performance by competing for cognitive resources, and may be impaired to a greater extent with higher memory loads. If, however, updating is carried out exclusively through an LTM reconstruction process, then the interference tasks should have no appreciable effects, particularly on adjusted updating error.

The type of interference task to be used is also an important consideration. Some investigations of spatial updating (e.g., Bök & Gärling, 1981; Lindberg & Gärling 1981) have used tasks such as backwards counting and found small impairments of updating. However, because backwards counting is a verbal task, it might not be expected to interfere specifically with spatial processing. Therefore, Experiment 3 examined the type of interference task by contrasting verbal interference (backwards counting) with spatial interference (mental rotation).

Methods

Participants. Twenty-five participants (twelve female) from Miami University's psychology subject pool participated in exchange for course credit. One female was replaced for failing to follow directions and becoming disoriented. All participants were run individually in 20-minute sessions, and none had participated in the previous experiments.

Materials and Procedure. Materials and procedure were the same as those used in Experiments 1 and 2 with the addition of an interference task during rotation, which was either verbal or spatial in nature. Type of interference was manipulated between participants.

The verbal interference task was a traditional backwards counting task that has been used in other investigations of automaticity and spatial updating (Böök & Gärling, 1981; Lindberg & Gärling, 1981).

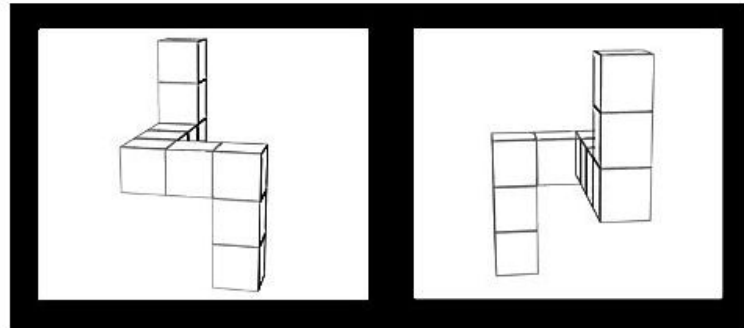


Figure 6: A sample pair of Shepard mental-rotation stimuli (Shepard & Metzler, 1971) used in the spatial dual-task of Exp. 3.

After the completion of the pre-rotation phase, participants were presented with a random 3-digit number, and asked to count backwards rapidly by threes out loud. After counting several steps backwards (e.g., 807... 804... 801... 798...) they were asked to slowly turn either to the right or left (counterbalanced across participants) until asked to stop. Participants were instructed that while they were turning, they were to continue counting, and also keep track of all of the target objects as best they could.

The spatial interference task was a Shepard mental rotation task (Shepard & Metzler, 1971). After the completion of the pre-rotation phase, the experimenter hit a button to display a pair of three-dimensional block patterns in the HMD display (see Fig 6) and concurrently instructed participants to rotate. At the end of the turn, the participant was asked to stop, and the figures were replaced by a blank screen. At this point, the participant had to decide whether the two blocks represented the same block shown from different viewpoints, or rather two different blocks. This task was assumed to involve an attempt to mentally rotate one of the block patterns into spatial alignment with the other (Shepard & Metzler, 1971), requiring visuo-spatial WM resources.

Results

Updating Error. Across all set sizes, participants in the spatial-interference condition were somewhat less accurate (mean updating error = 27.41°) than participants in the verbal interference task (mean updating error = 20.38°), but this difference was not significant. Comparable to Experiments 1 and 2, the mean updating error across conditions was 25.20 (95% CI \pm 4.3°).

To ascertain if the presence (and type) of a dual task had any appreciable effects on updating performance, the data from Experiment 1 was used as a ‘no-interference’ control group in a 4 (set size) x 3 (interference: verbal, spatial, none) mixed-model ANOVA. Despite

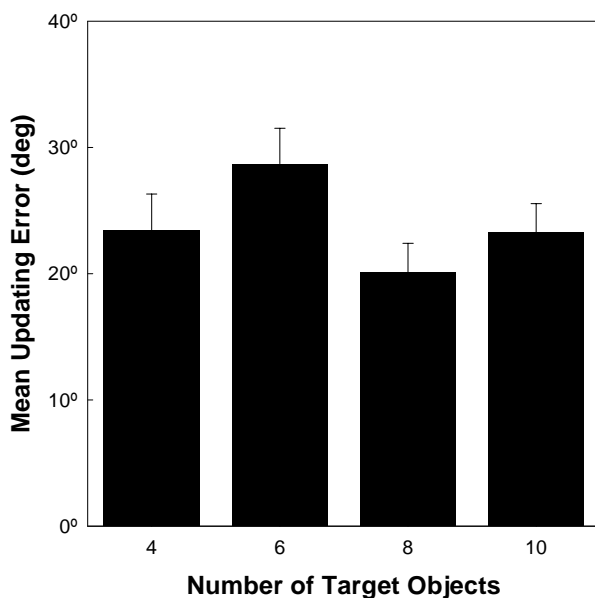


Figure 7: Updating error (in degrees) for Exp. 3, collapsed across interference type. A slight increase in updating error was observed with 6 targets, but no conclusive indications of capacity were found. Participants in the verbal-interference group had slightly less error at each set size, but the overall pattern was the same for both groups.

Adjusted Updating Error. Adjusted updating error was calculated as before for the data from Experiment 3 to eliminate any error of misperceiving the rotation. A one-way repeated-measures ANOVA showed no significant differences among set sizes ($F(3,57) < 1$), and that the cubic trend was no longer significant ($F(1,23)=1.87, p>.15$). Collapsed across set sizes and interference types, adjusted updating error was 4.17° (95% CI \pm 1.7°).

participants in the spatial interference task performing slightly worse (mean difference = 7.03°), interference was found to have no significant effect ($F(2,45)=2.39, p>.10$), and did not interact with set size ($F(6,128)=1.52, p>.15$). Therefore, it was dropped from further analyses of error measurements.

Updating error results collapsed across interference types are shown in Figure 7. The main effect of set size for the combined data set was non-significant ($F(3,128)=1.52, p>.21$). However, when the data from Experiment 3 were analyzed alone, there was a significant cubic trend across set sizes ($F(1,23)=10.15, p<.01, f=0.66$), driven by a small spike in updating error with 6 target objects (see Fig. 7).

Latency. A 4 (set size) x 2 (phase: before or after rotation) x 2 (interference type: verbal, spatial) mixed-model ANOVA was used to analyze the latency results. Thinking time increased linearly with the number of to-be-remembered targets ($F(1,22)=17.79, p<.001, f=0.90$) both before and after rotation, and did not interact with set size ($F(3,58) < 1$). Participants were again significantly slower after rotation (mean increase = 120ms; $F(1,22)=12.65, p<.01, f=0.76$). The type-of-interference manipulation had no appreciable effect on reaction times ($F(1,22)=1.23, p>.25$), and did not interact with any other factors (F 's $< 1.04, p$'s $> .35$). After collapsing across interference type, latency results were nearly identical to those found in Experiment 1 (see Fig. 4), both in magnitude and overall pattern.

Discussion

Experiment 3 addressed the idea that an online updating process using WM resources would be impeded by a dual task during rotation, amplifying any capacity effects. Additionally, it was predicted that a spatial (mental rotation) task should interfere more with spatial updating than a verbal (backwards counting) task. However, the presence and type of interference had no significant effect on updating performance, and did not interact with the number of targets being updated. With the exception of the slight rise in error with 6 objects (discussed below), the pattern and magnitude of the results in all dependent measures mirrored those of Experiment 1.

That the results were unchanged by a dual-task during rotation suggests that WM resources were not being taxed or exceeded by the updating process. The lack of any effect of set size or an interference type by set size interaction indicates that updating ability was not overloaded by concurrent spatial or verbal processing. Spatial-interference participants did perform slightly worse in Experiment 3 in all set sizes, showing that participants were not immune to the interference tasks. However, this effect was non-significant, and was eliminated completely by adjusting for a change in bias. Thus, the spatial-interference task may have slightly impeded participants' ability to gauge the magnitude of their rotation, but it did not alter the way in which subsequent information about the layout was recalled.

While misperceiving the magnitude of the turn does represent a failure to update accurately, it is independent of deriving one's spatial relation to objects in the environment. Tracking the magnitude of one's movement can be carried out via path-integration by monitoring one's changing relation to the origin of movement (Loomis et al., 1999), and would not require that all self-to-object relations were calculated in real time. Because participants were asked to

rotate until prompted to stop, monitoring one's own movement in this task is a necessarily online process. That this process was differentially susceptible to spatial versus verbal interference suggests that even this component of updating is not wholly automatic, and may require WM resources. However, this process does seem unaffected by changes in the number of target objects, and only slightly degraded by a spatial dual task.

The increase in error and reaction times with six targets is a new and potentially interesting effect, with several potential explanations. It may be the case that this spike in error may represent the point of a strategy shift to cope with the higher memory load. Participants using a simpler strategy with only four targets may have tried to utilize the same strategy with six targets, and found it insufficient, switching to a more effective strategy for the larger set sizes. This seems unlikely, however, as no such pattern was observed in Experiments 1 and 2. Thus, it seems likely that this effect represents a type I error, resulting from a cluster of uncharacteristic performance in a few participants.

In sum, there were no indications that capacity had been exceeded by the addition of a dual task in Experiment 3, using between four and ten targets. In fact, the addition of a dual task during rotation did not lead to slower or significantly less accurate responses. Further extending the results of previous experiments, exit interviews again confirmed the use (and prevalence) of explicit, verbalizable LTM encoding strategies. These findings provide converging evidence that the updating process used by participants in this type of paradigm is more consistent with an LTM reconstruction process, and not an online updating process.

Experiment 4

In Experiments 1-3, participants seemed to rely heavily on a post-hoc reconstructive process for spatial updating. In Experiment 4, I examined whether this tendency was due to the explicit and deliberate nature of the learning task, or whether post-hoc reconstruction is the default updating system used by participants in this type of updating task, independent of the degree to which learning is deliberate and moderated by elaborate strategies. To this end, Experiment 4 introduces an incidental-learning paradigm designed to prevent elaborate LTM encoding techniques (i.e., using a mnemonic to memorize the order of the targets around the room) and to allow for more natural interaction and updating of target locations. If online updating is observed in this type of task, then the long-term memory updating observed in

Experiment 1 may be attributed to task-specific demands, and an attempt of the participants to forgo normal processes and strategies in an attempt to maximize accuracy at testing.

Methods

Participants. 70 participants from Miami University's psychology subject pool participated in exchange for course credit. A high number (14) of participants had to be replaced in Experiment 4, for various reasons related to the incidental paradigm.

There was some concern that participants who had participated in other experiments in our lab might guess the true nature of the experiment and make deliberate attempts to encode the target locations if they had knowledge that they were to be tested on their spatial abilities. Participants were questioned about this during the post-experiment debriefing, and one participant was removed for this reason.

Four participants were replaced because, after being asked to rotate 90° during the experiment, they spontaneously rotated back to their original facing direction before proceeding with the final phase of the experiment.

Finally, a total of nine participants were replaced for failing to learn the object locations adequately (i.e., exhibiting accuracy levels greater than 2/3 of chance prior to rotation). Because I was interested in measuring updating performance, it is important that participants knew where the target objects were located before the rotation.

In the end, 56 participants (28 female) were included in the final analysis. All participants were run individually in 20-minute sessions. None had participated in any of the previous experiments.

Materials. Materials were the same as those used in Experiments 1 and 2 with the following exception. Because the number of targets was manipulated between participants in this experiment, only one set of target objects was required. Thus, all targets were drawn from the set of office supplies. Participants interacted with and updated either 4, 6, 8, or 10 targets.

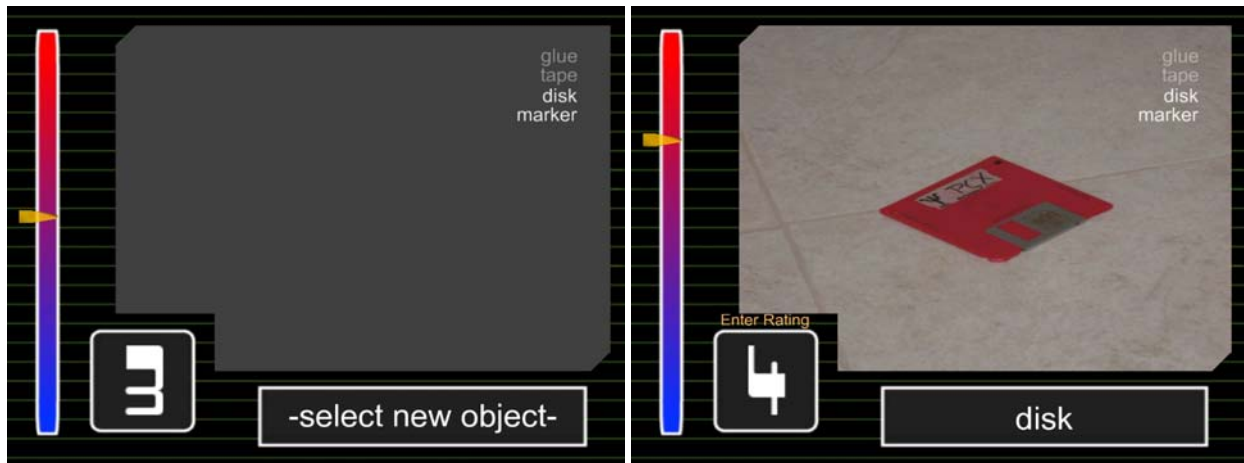


Figure 8: The interface that participants interacted with in Experiment 4 under the pretense of gathering product ratings. Left Panel: Participants pointed to and ‘selected’ each object in the list (upper right corner of display). Right Panel: Once an object was selected, participants entered their rating (slider and number on the left side of the display) by adjusting the pitch of the pointing device, which caused a pointer to move along the slider.

Procedure. As in the other experiments, the layout was arranged on the floor of the lab room in a different configuration for each participant, and the participant was seated on a rotating stool in the center of the layout. All references to spatial cognition were omitted from the introduction and informed-consent procedures. Instead, the experiment was introduced as user-testing for a product-rating interface. The interface (see Fig. 8) allowed participants to examine a randomized list of ‘products’ and rate them on dimensions such as usability, aesthetics, and appropriateness for all age-groups. Each to-be-rated object was pointed to and named by the experimenter, but participants were not given time to study the layout deliberately.

Prior to each phase, participants received instructions about the dimension they were to rate objects on, as well as the scale anchors (e.g., 1 = not visually appealing, 5 = very visually appealing). Participants used the light gun to point to and ‘select’ each object on a list. Ratings were given by tilting the gun up or down, which moved a pointer along a scale in the corresponding direction on the interface. An integer between one and five was visible on the interface, showing the current scale value. After moving the pointer to the desired rating, participants depressed the trigger of the light gun to enter their rating and were prompted to select the next object on the list.

Three rounds of ratings were conducted in the following order: perceived usability, aesthetics, and appropriateness for all age ranges. The first round of ratings was conducted by having participants interact with the interface on the computer screen. Thus, the first phase

represented an incidental learning phase in which participants could interact with the layout and the object locations with full vision, but with no intention of learning or memorizing the targets' locations.

The final two rounds of ratings were conducted by having the participants interact with the interface in the HMD, under the pretence of comparing the usability of the interface on a desktop computer versus using VR equipment. The HMD effectively blindfolded participants so that they no longer had vision of the room or the layout. Participants were instructed not to remove the HMD for the duration of the experiment, and were told that if they forgot exactly where one of the objects was located, that they should give their best estimate.

Between the second and third rounds of ratings, parts of the interface suddenly disappeared, and a message was presented telling the participants that the position tracker had failed. The experimenter feigned surprise, and asked the participant to rotate either to the right or to the left (counter-balanced across participants) so that he could straighten out the wires and reset the tracker. During pilot testing, it was discovered that participants would not rotate 135° without excessive prompting, so – unlike the previous experiments – participants were stopped after a 90° rotation. The experimenter “reset” the tracker so that the experiment could continue, and asked the participants to finish the last round of ratings from their current facing direction.

As with the previous experiments, exit interviews were conducted at the conclusion of the experiment. Participants were given an opportunity to specify what, if any, strategies they had used to complete the task. Participants were also fully debriefed as to the true nature of the experiment and asked not to discuss the experiment with any of their classmates.

Pointing estimates were recorded when the participant pointed to each object and depressed the trigger of the light gun to ‘select’ it. No instructions were given to emphasize high accuracy or speeded responses, but participants were told that if real product evaluations were being done, it would be important that people rated the correct object. As such, they were told that if they accidentally selected the wrong object, they would be prompted to try again. A “Try Again” message was displayed any time the participant’s pointing direction differed from the actual bearing to the target by more than 30° while pointing with vision. No other limitations or criterion for accuracy was imposed.

Results

Updating Error. The results for updating error in Experiment 4 are presented in Figure 9. Like the previous experiments, the manipulation of set size had no significant effect on updating error, but updating error did appear to increase slightly as number of targets was increased in Experiment 4. However, a one-way ANOVA indicated that there was no main effect of set size ($F(3,52)=1.17, p>.30$), and that the linear increase was also non-significant ($F(1,55)=2.59, p>.11$). Collapsing across set size, mean updating error was 25.02° (95% CI $\pm 3.43^\circ$), which was comparable to Experiments 1-3.

Adjusted Updating Error. Adjusted updating error was calculated as before to eliminate any error from misperceiving the amount of rotation. A one-way ANOVA showed no significant differences among set sizes for adjusted updating error ($F(3,52) < 1$). Collapsed across set sizes, the mean adjusted updating error was 10.88° (95% CI $\pm 3.24^\circ$).

Cross-experiment Analyses. As a manipulation check to ascertain the differences between incidental and explicit learning, data from all participants in the Experiments 1-4 were entered into a one-way ANOVA, using experiment number as a between-participant variable. Mean updating error and mean adjusted updating error (collapsed across set

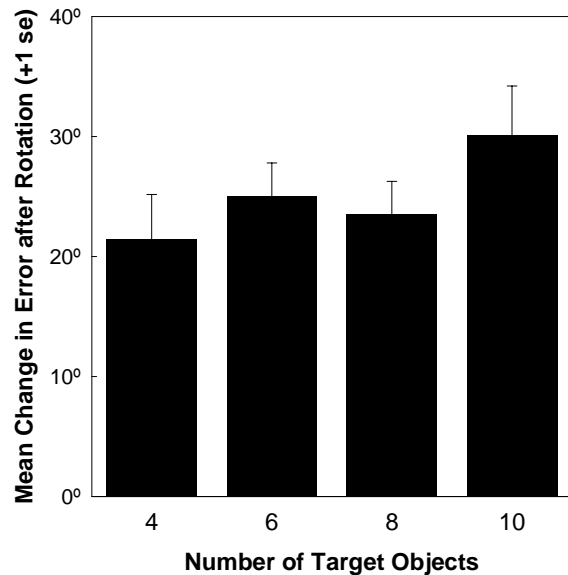


Figure 9: Updating error (in degrees) for Exp. 4. As in the previous experiments, no indication of a capacity limit was observed.

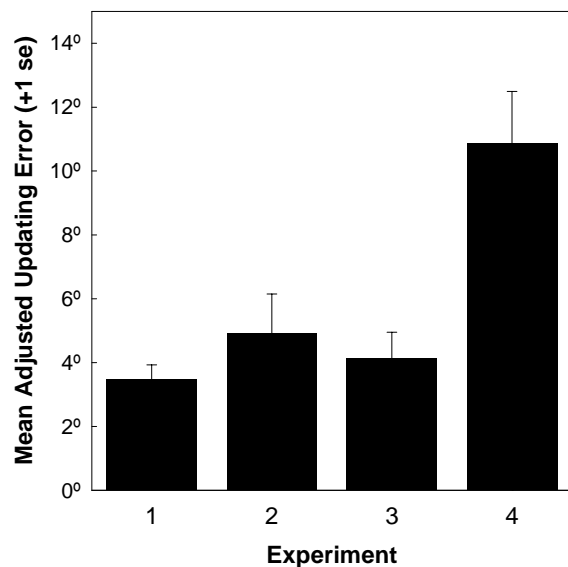


Figure 10: Mean adjusted updating error (in degrees) across experiments. Adjusted updating error was much higher ($F(1,115)=15.87, p<.001$) in the incidental-learning paradigm (Exp. 4) than for the explicit-learning paradigm (Exp.'s 1-3).

size) were analyzed to explore changes in accuracy as a result of the type of learning (explicit, incidental). For updating error, there was no significant difference in accuracy across experiments ($F(3,112) < 1$), indicating that the magnitude of updating error was equivalent across the 4 experiments. For adjusted updating error, however, accuracy levels did differ across experiments (see Fig. 10; $F(3,112)=5.90, p<.001, f=0.40$) and were best described by a 1 1 1 -3 contrast (explicit learning versus incidental learning:

$F(1,115)=15.87, p<.001$).

*Latency*⁴. Unlike the previous experiments, participants were not instructed to respond quickly, and the previous method of measuring thinking times was not available. Thus, the responses latencies reported in Experiment 4 (see Fig. 11) represent the total response time (including movement).

The linear increase in reaction times seen in the previous experiments was not present in Experiment 4 ($p>.40$), and set size did not exhibit a main effect ($p>.08$). Also differing from the previous findings, participants in Experiment 4 were significantly faster after rotating (mean decrease = 532ms; $F(1,52)=9.46, p<.01, f = 0.43$). As before, set size and phase did not interact ($p>.60$).

Discussion

Experiment 4 was designed to examine updating behavior under incidental-learning conditions, when participants would be unable to employ mnemonic techniques and other LTM encoding strategies at learning. Note, however, that this did not prevent LTM encoding that may occur from natural interaction with the environment. It is only designed to prevent explicit LTM

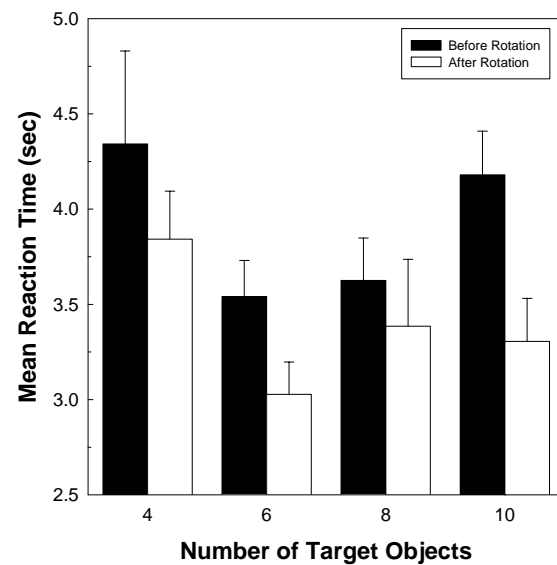


Figure 11: Thinking time (in seconds) for Exp. 4. Unlike the previous experiments, no list-length effect was observed, and participants were faster after the rotation.

⁴ The main effect of gender ($F(1,48)=8.25, p<.01, f = 0.42$) was significant in experiment 4. Like experiment 1, it was driven by a tendency for females to answer slightly faster (619ms) than males.

strategies (i.e., mnemonics) that are unrepresentative of spatial updating in day-to-day life, such as making up a sentence with the first letter of each landmark's name.

First, the magnitude of updating error in Experiment 4 (25°) was no different than that of Experiments 1-3 (21°, 24°, & 24°, respectively), and again was unmediated by the number of target objects. Thus, at first glance, the additional error induced by the updating process did not appear to change as a result of the type of learning (explicit or incidental) or as a function of increasing memory load.

However, the analyses of adjusted updating error provide additional insights. While the overall level of updating error did not increase relative to Experiments 1-3, the average magnitude of adjusted updating error across set sizes (10.88°) was more than double that of the previous experiments (3.48°, 4.92°, & 4.17°, respectively; see Fig. 11). This indicates that the relative amount of error attributable to misperceiving the magnitude of rotation was much less in Experiment 4, and that the error attributable to calculating / reconstructing spatial relations was significantly higher.

The decrease in misperception might be expected, given that participants were asked to rotate 90° in Experiment 4, and 135° in the previous experiment. The finding that higher error results from tracking one's movement through a larger rotation fits well with literature suggesting that the difficulty of imagined spatial transformation are a linear function of the magnitude of rotation (Evans & Pezdek, 1980; Rieser, 1989; Shepard & Metzler, 1971) and that some facilitation is often found at angles orthogonal to the learning heading (Mou & McNamara, 2002; Mou et al., 2004; Rieser, 1989; Shelton & McNamara, 1997).

It is also not surprising that the adjusted updating error is higher with incidental learning, given that participants in the explicit learning paradigm were given an unlimited amount of study time in which to purposefully encode the layout. This may have allowed for focused attention at learning, repetitions of each object, and the formation of elaborate strategies. Participants in the incidental-learning paradigm, however, were not given free study time, did not have the use of elaborate strategies, and were led to shift their attention to the objects' attributes instead of their locations. These differences could lead to a more accurate memory of the layout and better updating performance for participants who learned the layouts explicitly, particularly if one accepts the hypothesis that participants are updating via LTM reconstruction. Reconstruction from LTM should introduce less additional error (as measured by adjusted updating error) for

explicit-learning participants than for incidental-learning participants because the memory representation is stronger for the former. This was the pattern of results observed across the experiments in this paper.

Reaction time results in Experiment 4 also showed a distinct change from those in the explicit learning paradigm. Previously, reaction times had exhibited a linear increase as the number of target items was increased, and reaction times were always significantly slower after rotation, presumably reflecting the additional processing time of a reconstruction process. However, the reaction times in Experiment 4 did not exhibit either of these trends.

The lack of a linear increase suggests that participants in Experiment 4 were not treating targets in the layout like items in a to-be-remembered list. Naturally updating a local environment, visualizing a spatial arrangement, and / or reconstructing spatial information from LTM are qualitatively different processes than a serial, exhaustive search of a list and would not necessarily be expected to show traditional list-length effects. For example, if participants are oriented to their environment and have an immediate awareness of where objects are in the local environment, the correct bearing to a target can be accessed directly, rather than performing a serial, exhaustive search of a list of objects, selecting the requested target, and pointing to the correct position around the circle.

Additionally, while there was a significant main effect of phase (pre-, post-rotation) for the reaction time measure in Experiment 4, the effect was in the opposite direction as previous experiments, reflecting slower reaction times *before* rotation. Given that participants had no prior knowledge that they would need to remember the locations of the objects, it could be expected that some spatial information would need to be recovered once vision of the layout was occluded, and participants realized that they now needed to point to objects that were not visible. Exit interviews indicated that many of the participants, on donning the HMD, realized that they would need to remember where the objects were located in order to ‘select’ them. It is thus possible that there was a certain amount of reconstruction from LTM (i.e., remembering where one pointed to select the glue bottle during the first round of ratings) that occurred prior to rotation, and that once an initial reconstruction had been made, later reconstructions may have been facilitated.

Strategies. To address the issue of strategy use and to ensure that participants in the incidental-learning paradigm were not explicitly attending to and / or forming strategies to

remember the spatial locations of the objects, exit interviews similar to those in the previous experiments were conducted. As mentioned above, only one participant reported that they had realized the true nature of the experiment and made explicit attempts to encode the spatial layout; he was subsequently dropped from the experiment and replaced. Of the 56 participants used in the final analyses, only 13 (6 female) reported using any type of strategy. Additionally, the types of strategies employed by participants in the incidental learning paradigm were, for the most part, qualitatively different from those reported previously. While remembering the order was a primary strategy in Experiments 1-3, no participant reported attempting to memorize the order of objects around the room in Experiment 4. Most of the strategies reported amounted to an attempt to visualize the layout or recall motor movements from the initial phase. Five participants reported trying to keep track of a small number of anchor objects that they remembered well (e.g., the object most directly in front of them at learning) and “figuring everything else out from there.” Only three of the 56 participants reported using what could be considered an explicit strategy. All three of these participants reported grouping or associating subsets of objects together, and recalling the subsets. For example, one female reported that found it easy to remember that “all of the sticky stuff was on the left” (i.e., the glue and the tape). This represents a major shift from previous experiments in which nearly all participants reported using some type of strategy, and indicates that the incidental-learning paradigm was effective in eliminating explicit strategy use.

General Discussion

The results of these four experiments have several implications for better understanding the phenomenon of human spatial updating and for understanding how to investigate it. While it is often assumed in the literature that spatial updating is an online process (Farrell & Robertson, 1998; Farrell & Thomson, 1998; May & Klatzky, 2000), the current results are highly incompatible with any form of online updating of multiple targets (although it is compatible with online monitoring of the magnitude one has rotated). Patterns of results across the four experiments imply that participants did not update the object layouts online as they rotated, but instead reconstructed them from LTM representations that were somewhat coarse, introducing additional error and processing time.

In addition to casting doubt on the online nature of spatial updating (at least in this type of updating task), the assumption that spatial updating is automatic seems unwarranted given the present data. First, recent research suggests that giving explicit attention to an otherwise automatic process can actually hinder performance (Beilock, Berthenthal, McCoy, & Carr, 2004; Beilock, Carr, MacMahon, & Starkes, 2002). Experimenter observations and exit interviews showed that, with fore-knowledge that they would be tested on the spatial locations of targets, participants exerted much more than a minimal effort, employing elaborate encoding strategies and mnemonics to aid updating performance. Instead of hindering automatic performance, participants in these experiments who explicitly and effortfully encoded the layouts were less error-prone (as measured by adjusted updating error) when encoding was explicit than when it was incidental. Second, the processes of tracking one's motion was mildly affected by interference in the present research, suggesting that even this part of updating may not be wholly automatic.

It may be argued that online (possibly automatic) updating does exist, and that the experiments reported here simply did not tap that system. In fact, it seems highly plausible that there are separate mechanisms for the online updating and post-hoc updating systems proposed by Amorim, et al. (1997). However, this raises an important issue with the methodology that is prevalent in the spatial updating literature. The paradigms used in Experiments 1-3 represent a commonly-used task in the spatial updating literature (Brou & Doane, 2003; Farrell & Robertson, 1998, 2000; Féry et al., 2004; Holmes & Sholl, In Press; Rieser, 1989; Wang, 1999; Wang & Brockmole, 2003a, 2003b; Wang & Spelke, 2000; Woodin & Allport, 1998; Wraga, 2003). Studies using this paradigm are usually assumed to be testing an online updating system, but the current research shows that participants in this type of task may likely be using post-hoc reconstruction to recover self-to-object relations rather than updating those objects in real time. If one is intending to study online updating, care must be taken to ensure that the system being used by participants is, in fact, an online updating system and not a post-hoc reconstruction system.

As such, an important line of future research will be to outline the conditions under which updating is governed by online processes, and under which conditions updating is governed by an LTM reconstruction process. Experiment 4 provides the beginnings of some separation between the two processes, in that an implicit-learning paradigm was necessary to prevent

elaborate strategies that would likely foster LTM representations. However, even under these conditions, updating through reconstruction was observed.

Amorim's (1997) work provides some insight into conditions that may elicit online updating, showing that participants did update a target object online when they were required to continuously report on the changing self-to-object relation as they moved (although it should be noted that participants walked notably slower in this condition, indicating effortful updating; it is possible that this effortful updating may have been multiple LTM reconstructions). Additionally, Farrell and Thomson (1999) showed that participants adjusted their stride-length as they approached a target location while walking without vision, suggesting that their participants were updating the self-to-target distance online.

Conversely, research on nested environments (Wang & Brockmole, 2003a, 2003b) shows that people fragment the global environment into smaller units, and while they do not actively update distal environments unless specifically instructed to do so, they can make roughly accurate estimates to distal landmarks if asked, and are able to recover accurate spatial information about an environment, presumably from an enduring representation, upon re-entering it. For example, participants in Wang & Brockmole's studies often showed moderately high rates of error at estimating bearings to campus buildings that were not visible from within the local laboratory environment, but presumably these participants were able to accurately return to their dormitories after exiting the psychology building by reconstructing spatial knowledge of the campus environment from LTM and re-calibrating their orientation to campus landmarks to allow for accurate navigation. Research distinguishing online and LTM updating processes, and the conditions which give rise to each, will be essential in understanding spatial updating, navigation, and the nature of spatial representations.

The other major motivation of the present research was to explore and define any applicable capacity limitations of human spatial updating. It was assumed that targets in excess of updating capacity would yield high error, leading to an increase of updating error with set size (i.e., a linear trend). However, as no main effect or linear trend of set size was found in any of the experiments, the null effect raises the question of the power of the experiments to detect an effect of set size. To address this, the data from Experiments 1 and 3 (collapsed across interference type, as no significant effect was found) were combined to provide a data set with 48 participants who each updated sets of 4, 6, 8, and 10 target objects. A one-way repeated-

measures ANOVA indicated no significant effect of set size ($F(3,131)=1.52, p>.20$), and no linear trend ($F(1,47) < 1$). A power analysis was conducted using the covariance matrix obtained from the combined data to find the power of the above test to detect a main effect of set size (the less powerful of the two tests). The power to detect a medium-sized main effect of set size was found to be .91.

In conclusion, these experiments provide compelling evidence that spatial updating via LTM reconstruction is not limited by capacity, at least up to 15 items. Given the vast storage of LTM, and the ability to recall roughly accurate spatial information from other, distal environments when needed (Wang & Brockmole, 2003a, 2003b), it is unlikely that any appreciable capacity limitations would be observed with larger sets. However, it remains an open and important question as to whether an online updating system is capacity limited, and under what conditions people rely on an online versus LTM updating process.

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