A POTENTIAL NEW LOCUS OF WORKING MEMORY MODALITY EFFECTS

by

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In 5 experiments, subjects received and then followed the same navigation instructions presented in either words or arrows, which directed them to move in a 3-dimensional space represented as stacked, 2-dimensional matrices on a computer screen. When neither verbal nor spatial rehearsal was impeded by a dual task, and sufficient processing time was permitted, overall accuracy for implementing the move sequences with a computer mouse was equivalent for processing sequences of directional words and arrows. However, when verbal rehearsal was disrupted by a dual, articulatory suppression task, accuracy for words declined more than for arrows, and when spatial rehearsal was disrupted by a dual, pattern tapping task, only accuracy for arrows declined. Subjects' self-reported rehearsal strategies were significantly biased towards including the unimpeded modality in rehearsal. In this experimental series, the bias of the stimulus type (verbal for words and spatial for arrows) predicted how successful was rehearsal in the unimpeded modality. Importantly, the locus of the impact of pre-existing modality biases in long-term memory (LTM) on recall appears to be at rehearsal and not at encoding. It is possible that pre-existing asymmetries in modality biases in LTM may be incorporated into working memory representations such that they impact subsequent rehearsal of such representations.

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[1] Experiment 1 of this experimental series is not included in the thesis but is mentioned in the discussion of results for Experiment 4a.

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CHAPTER 1

Introduction

Much effort has been invested over the years into quantifying working memory (WM) limits for the amount of information that can be processed at a time. WM limits can provide insight into constraints of the working memory space for coordinating task acquisition, language, and complex reasoning. However, a conundrum for assessing exactly how much information can be processed at a time is that the infrastructure that is recruited into WM can impact measures of processing efficiency. Decades of research has shown that consciously instigated strategies such as (a) rehearsal, and (b) chunking of items, can significantly increase recall beyond the natural limit of three to five chunks (Cowan, Morey, Chen, Gilchrist, & Saults, 2008; Ericsson, Chase, & Faloon, 1980). Our research suggests that another possible candidate for influencing WM limits may be pre-existing modality biases in long-term memory (LTM) that are incorporated into WM representations. Once incorporated into WM representations, such modality biases can impact the efficiency with which such representations are subsequently processed if such processing is also modality-biased.

If a stimulus type has been processed in the same modality many times before, practiced mental representations and practiced responses for particular modalities can be strongly reinforced in long-term memory (LTM). In tests of the ability in procedural working memory to select the correct, instant response, modality-biased representations in LTM can decrease the time taken to respond correctly if the response is in the highly practiced modality for that stimulus type. In traditional tests of recall for declarative items, pre-existing asymmetries in modality biases in LTM do not appear to have been considered as a potential factor in recall performance. One likely reason is that the response for recalling items is delayed. It is not known whether modality biases associated with stimuli in LTM are incorporated into working memory representations generated from such stimuli. If modality biases are incorporated into WM representations, subsequent operations performed on those representations may be impacted when facilitated in particular modalities. We speculate that subsequent operations could include retrieving representations back into the WM space once they have been encoded during (a) rehearsal, or (b) recall. In our experiments, we examined the influence on rehearsal of WM representations generated from stimuli that are biased towards particular modalities in LTM.

Although we examine the impact on rehearsal of pre-existing modality biases in LTM, we also speculate that such biases may also impact recall itself. In tests of recall for declarative knowledge, pre-existing asymmetries in modality biases in LTM based on a lifetime of processing episodes are not taken into consideration. The reason that practice effects from responding to stimuli in the same way over many trials are not expected to influence recall of declarative items is that typically stimuli are not presented more than once (Oberauer, 2010). We suspect that even when stimuli are only presented once in an experiment, pre-existing asymmetries in modality biases for stimuli in LTM based on a lifetime of processing episodes can be incorporated into WM representations at encoding.

Research on the influence of modality-biased processing on recall of declarative items in WM has focused on the influence of pre-categorical, modality-biased sensory information. Saults and Cowan (2007) demonstrated how traces of raw sensory input from stimulus presentation can be used to increase recall of items being maintained in WM. In the experiment, the echoic trace for an acoustic array of digits and the iconic trace for a visual array of squares were masked with a bimodal mask inserted between presentation and the response. Consequently, the extra increase in recall predicted by the modality of stimulus presentation (and thus, modality of sensory input) disappeared from WM span. It is possible that in addition to the modality that a stimulus is presented in being important to recall of declarative items, the modality that a stimulus has been processed in many times before must also be taken into account. Conceivably, biases in the material from LTM that is used to construct WM representations could be adopted in such representations such that they impact the efficiency of subsequent processing of such representations.

Traditionally, the impact of modality biases in LTM on WM performance depending on the response modality is found in tests of procedural working memory for selecting the correct, instant response. For example, in choice-reaction time tasks, providing that the response modality matches the modality that is strongly mapped to the stimulus in LTM, accuracy improves and the time taken to instantly respond to stimuli decreases (Miles & Proctor, 2011). It is not necessary for modality bias from LTM to be incorporated into WM representations in such experiments because the response is instant. However, in tests of recall for declarative knowledge, the response is always delayed because multiple items must be retained in WM for later recall. It is unknown whether modality bias from LTM would be incorporated into WM representations such that recall might be improved if the modality of the response is the same as the modality that the stimuli are strongly mapped to in LTM.

In our experiments we are examining the degree to which pre-existing modality biases in LTM affect the utility of rehearsal for extending recall of rehearsed items. Thus, if pre-existing modality biases of stimuli in LTM predict recall, it will be attributable to the impact of such biases on the modalities of rehearsal and not the modality of the response. Rehearsal is modality-specialized and could benefit from a modality-specialized code in LTM that is strongly mapped to the same modality that rehearsal is conducted in due to many prior, processing episodes. For example, the stronger mapping of words than arrows to phonological code and vocal responses in LTM could render subsequent verbal rehearsal to be more efficient if WM representations are encoded from words than from arrows. Conversely, the stronger mapping of arrows than words to relative spatial coordinates and embodied movement in LTM could render subsequent spatial rehearsal to be more efficient if WM representations are encoded from arrows than from words.

If it is true that pre-existing biases from LTM can be incorporated into WM representations such that they impact the success of subsequent rehearsal of such representations, the effects should be at rehearsal and not at encoding. The priming of the response by modality-biased LTM is considered to be an important factor for increasing processing efficiency when instantly responding to a single stimulus (Lu & Proctor, 2001). To the extent that rehearsal is procedurally weighted towards representing items in responses of a particular modality it might be impacted by the strong response code associated in LTM with individually presented, modality-polarized stimuli.

However, if the effects are at encoding, then perhaps faster activation associated with modality-biased LTM increases the number of items that can be encoded in a limited time period. In a series of Stroop experiments, Lu and Proctor (2001) found that stimulus priming is asymmetrical in its time-course of activation depending on how strongly mapped stimuli are to modalities. A key-press response was made to either words or arrows that were superimposed onto each other. Either stimulus type could be the target or distractor. The distractor stimulus appeared anywhere from 500 ms prior to the stimulus to right at onset of the target stimulus. When bottom-up processing for the more strongly mapped arrow-to-key press response was task-irrelevant, synchronous onset of stimuli at 0 ms was optimal for maximal interference with the more weakly mapped word-to-key press response. The more weakly mapped word-to-key press response elicited no interference of processing at 0 ms stimulus onset asynchrony (SOA). However, it did elicit maximal interference at an SOA of 300 ms, indicating that more weakly mapped bottom-up processing takes longer to activate in time to influence controlled processing. Therefore conceivably, for fast-activating, strongly mapped LTM, more items could be encoded in a limited time period than for slow-activating, weakly mapped LTM. If so, improvement in the number of items recalled would not necessarily be due to modality biases from LTM being incorporated into WM representations. Rather, the number of items recalled would likely have been pre-determined at encoding and rehearsal would simply reinforce those items until it is time to make the response.

In order to encourage rehearsal, we chose a navigational paradigm that was originally developed by Barshi and Healy (e.g., Barshi & Healy, 2002, 2011; Schneider, Healy & Barshi, 2004; Schneider, Healy, Barshi, & Kole, 2011). Given that in this paradigm, subjects have difficulty recalling sequences of three moves or more, the requirement in our paradigm of recalling anywhere from one to six moves in the correct order necessitates systematic rehearsal. Subjects received the same navigation instructions presented in either words or arrows while viewing two-dimensional matrices on a computer screen. Two popular rehearsal strategies in this paradigm are subvocalizing the move sequence in verbal shorthand or visualizing movement through a pathway of relative coordinates on the ever-present matrices. Thus, the modality bias of words and arrows can be crossed with verbal and spatial rehearsal in analyses of move recall. For the response, subjects are instructed to click with a mouse the sequence of coordinates on the matrices that matches the directions encoded in the instructions.

We chose directional words and arrows to manipulate modality bias of stimulus type because words are more strongly mapped to the verbal modality and arrows are more strongly mapped to the spatial modality in long-term memory (Baldo, Shimamura & Prinzmetal, 1998; Clark & Brownell, 1975; MacLeod, 1991; Miles & Proctor, 2011; O'Leary & Barber, 1993; Shimamura, 1987; Virzi & Egeth, 1985). In LTM, words tend to be more strongly associated than arrows with language related conceptual meaning and vocalizations Thus, verbal WM representations may be superior when encoded from words than from arrows. In LTM, arrows tend to be more strongly associated than words with spatial meaning and embodied movement. Thus, spatial WM representations may be superior when encoded from arrows than from words. Based on such evidence, we expect that word stimuli will facilitate more efficient verbal rehearsal than arrows, and arrows will facilitate more efficient spatial rehearsal than words. Our measure of processing efficiency of rehearsal is the proportion of trials for which the entire move sequence is correct.

To influence which modality of rehearsal is favored, either the verbal or spatial modality was impeded by a concurrently enacted dual task. It has been found (a) that articulatory suppression wherein the same word is subvocalized impedes verbal processing for a concurrent task, and (b) that tapping in a square pattern impedes spatial processing for a concurrent task (Repovs & Baddeley, 2006). However, tapping in the same location should not impede any modality of processing for a concurrently enacted task. Therefore, we adopted the first two dual tasks in our experiments to selectively impede verbal and spatial rehearsal respectively for the main navigational task. We adopted the third, simple foot tapping task to provide a control within which two tasks occur at the same time but no modality of rehearsal is impeded. We administered questionnaires to assess the modalities in which subjects rehearsed.

In terms of WM modality effects we predict the following. Given that arrows and words can be rehearsed in both modalities, most people will elect to include the unimpeded modality in rehearsal. However, if they only rehearse in the dual task-impeded modality, performance should decline. When rehearsing in the unimpeded modality, the modality bias of the stimuli should predict how successful rehearsal is for recall. Move recall should tend to be better for words than for arrows when complex foot tapping impedes spatial rehearsal. The reason for this prediction is that words map better onto the unimpeded verbal modality in LTM. Conversely, move recall should tend to be better for arrows than for words when verbal rehearsal is impeded by articulatory suppression. The reason for this prediction is that arrows map better onto the unimpeded spatial modality in LTM. We expect asymmetries in modality bias from LTM in WM representations to be influential only at higher item load when efficient rehearsal would be particularly important to move recall. Specifically, modality effects are expected to occur only for sequences of 3 to 6 moves and not for sequences of 1 to 2 moves, wherein performance will likely be at ceiling.

To ascertain whether the impact of modality biases in LTM is on encoding of items or on rehearsal of items that have incorporated such biases from LTM, we also manipulated the timing of the dual task. The dual task could occur: (a) at stimulus presentation, (b) during an added retention interval between stimulus presentation and the response, (c) during “both” stimulus presentation and the retention interval, or (d) not at all – “no dual task”. Encoding will only occur at stimulus presentation. If modality effects are localized to the conditions that include stimulus presentation, then the efficiency of encoding is likely being impacted by modality biases in LTM. Rehearsal should be weighted towards the retention interval. If modality effects are localized to conditions that include the retention interval, then modality biases in LTM are likely being incorporated into WM representations such that efficiency of subsequent rehearsal of the representations is impacted.

CHAPTER 2

General Method

Apparatus and Materials

iMAC computers and RealBasic computer software were used to depict the navigational instructions and to record the subjects’ manual movements of the mouse as they implemented moves on two-dimensional matrices depicted on the computer screen.

A three-dimensional model of the two-dimensional space that the subjects navigated on the computer screen was placed next to the computer monitor during training and test. The model consisted of four 4-by-4 matrices stacked to represent a four-storey building made of wooden pillars and grid-lined paper floors.

A metronome for timing of the dual tasks was placed on the table next to the computer monitor and was played during practice of the dual tasks in all experiments, and during experimental trials for Experiments 2 and 3. In Experiments 4a and 4b, the metronome beat was programmed into the software for experimental trials.

A gray board upon which the subjects tapped their foot for the two tapping dual tasks was placed under the desk out of the subjects' view. The board was 30.5 cm long by 30.5 cm wide by 5 cm deep, with four 8.75 cm long by 8.75 cm wide by 5 cm deep squares affixed to the top of each of the board's four corners.

A questionnaire regarding the rehearsal strategies utilized by each subject was administered in paper format after each of the experiments was completed.

Procedure (See Appendix A for a table of the research questions for each experiment)

Subjects first reviewed training materials tailored to their assigned condition. The subjects were directed to imagine themselves as a pilot who is reading and implementing navigational messages. A detailed explanation was given as to how to interpret and implement the messages on the matrices. Then subjects began training on the dual tasks while receiving feedback from the experimenter until the experimenter informally decided that they were proficient at conducting the dual tasks.

The four possible dual tasks that subjects could be required to perform to the beat of a metronome were (a) simple articulatory suppression, (b) complex articulatory suppression, (c) simple foot tapping, and (d) complex foot tapping. The simple articulatory suppression group repeated "Monday." The complex articulatory suppression group repeated the sequence "Tuesday, Friday, Thursday, Monday." They were told to speak clearly and not to whisper the words. In Experiments 2 and 3, subjects said the days of the week to every metronome beat. In Experiments 4a and 4b, subjects said "Mon" (i.e., the first syllable) on every first beat and "day" (i.e., the second syllable) on every second beat. For the foot tapping tasks, subjects chose which foot they would use, and each tap of the foot was timed to the beat of the metronome. The simple foot tapping group tapped with either the heel or toes in the center of the board. The complex foot tapping group tapped the foot in an anti-clockwise direction on the corners of the board.

After practicing the dual tasks, subjects began practicing the navigational task. In Experiments 2 and 3 subjects did not perform the dual tasks while learning how to do the navigational task. However, in Experiments 4a and 4b they did. During this time, the subjects received audible feedback from the computer regarding whether they followed the messages correctly, hearing "perfect" or "nice try." During the practice session, to the extent that the subjects were not following the navigation messages correctly, the experimenter communicated specific clarifications regarding the subjects' performance and answered the subjects' questions.

In the navigational task, subjects viewed messages comprised of moves to the right of the matrices, then used a mouse to implement the moves on the matrices. There were 72 trials constituting 72 navigational messages. Each trial (constituting a message) could be anywhere from one to six moves in length for Experiments 2 and 3, and was held constant at four moves for Experiments 4a and 4b. The matrices upon which the moves were to be implemented were vertically stacked and visibly present on the left of the computer screen throughout the entire trial.

During a trial, subjects viewed the moves one at a time, with each move staying on the screen until the last move in the sequence disappeared from the screen. The incrementally presented moves appeared at 1500 ms intervals for Experiments 2 and 3, 1250 ms intervals for Experiment 4a and 2500 ms intervals for Experiments 4b. Additionally, the timing of the dual tasks was 80 beats per min for Experiments 2 and 3, and increased to 96 beats per min for Experiments 4a and 4b.

The navigational moves across the 72 trials were identical for every subject, except that the moves could be in word or arrow format (stimulus type). One move amounted to an instruction to navigate either forward, back, left, or right within a matrix, or either up or down between matrices, for a distance of either one or two squares, or one or two levels. There was one representative move from each of the three dimensions (forward-back axis, left-right axis, up-down axis) in each set of three moves. The starting position was held constant[2] and was visibly marked by a red asterisk throughout the entire experiment, although the starting position was different from practice trials to experimental trials.

In Experiments 2 and 3, after the moves disappeared from the screen, a beep occurred, and subjects were immediately able to click the moves with the mouse on the stacked matrices on the left of the screen. In Experiments 4a and 4b, a retention interval was added between stimulus presentation and enactment of the response. For the response in all experiments, subjects clicked every square in the spatial path dictated by the moves, and they clicked the DONE CLICKING button when finished to initiate the next trial. See Appendix B for an example of the moves on the matrices. Then there was a 2-s pause before stimulus presentation started in the next trial. Subjects were instructed to defer clicking the button if they needed a break.

Subjects could forget to do the dual task or not perform the dual task properly due to focusing on the main navigational task. Consequently, the experimenter stayed in the room at all times and reminded subjects, when appropriate, about the protocol for performing the dual task.

Rehearsal strategies. Each questionnaire was coded independently by two researchers for

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[2] For practice trials, 3rd matrix, 2nd column, 3rd row. During experimental trials, 2nd matrix, 3rd column, 2nd row.

the modalities of processing included in a subject's rehearsal strategies. Use of verbal subvocalizations was coded as rehearsal strategies including a "verbal component." Use of spatial strategies was coded as rehearsal strategies including a "spatial component." Spatial strategies included tapping out relational moves with the hands or feet and visualizing the path and/or tracing the path on the adjacent matrices with a finger. Use of visual strategies that did not include visualizing the path, but instead comprised of (a) remembering the arrows or words as pictures, or (b) remembering the direction-encoded colors associated with the arrows, were coded as rehearsal strategies including a "visual component."

Analyses

A-priori accuracy measures (in results section)

Mixed factorial analyses of variance (ANOVAs) were conducted to assess whether stimulus type influences the impact of selective decrements in accuracy depending on whether verbal or spatial processing is impeded by a dual task. For accuracy of implementation of messages, each message (trial) scored a 1 when the entire message was accurately implemented and a 0 when the entire message was incorrectly implemented. Mean scores reflect the proportion of trials that were accurately implemented. The within-subjects variable of message length was examined for effects of cognitive load on performance.

Post-hoc analyses of modalities of processing (in appendices)

Rehearsal strategies. Multinomial logistic regressions, binomial logistic regressions, and generalized estimating equations were conducted to analyze the relationship between stimulus modalities, dual task-impeded modalities, and subjects' choice of rehearsal strategy – the categorical dependent variable. Rehearsal strategies were examined as a between-subjects variable (use of verbal, spatial, or both modalities in rehearsal), or a within-subjects variable (rehearsal strategies with a verbal component, spatial component). Subjects were assigned with equal *n* to all of the a-priori, counterbalanced variables, except for the post-hoc rehearsal variables, the group assignments for which were determined by subjects' own self-reports.

Systematic Errors. Post-hoc between-subjects ANOVAs were conducted to examine whether a signature error type as the dependent measure can objectively confirm subjects' self-reported rehearsal strategies (verbal, spatial, or both modalities) – the independent variable. Group assignments for rehearsal strategies were determined by subjects' own self-reports, resulting in an unequal *n* between groups.

The error type was proportion of incorrect trials for which, after the first error, the rest of the moves were correct but the rest of the coordinates were not correct. Only message lengths 2 to 6 were examined because for message length 1 there were no more moves to be made after the first error. The rationale for this error type is that when an error is made, the wrong coordinate will be clicked. Without the aid of a visualized pathway on the matrices, the error will not be as apparent. If the rest of the verbally subvocalized moves are correctly implemented, in spite of the clicked squares being incorrect, the subject is likely using a pure verbal rehearsal strategy. See Appendix C for a graphic demonstration of the error type.

CHAPTER 3

Experiment 2 Method

Participants

Forty-eight University of Colorado undergraduates participated in return for credit in an introductory psychology course. All participants were native English speakers and were not color blind. Twelve subjects were randomly assigned with fixed rotation to each of the four conditions, which were combinations of two crossed variables: stimulus type (words versus arrows) and dual task type (articulatory suppression versus foot tapping).

Design and Procedure. See Appendix D for a diagram of the design.

Within-subjects variables. The within-subjects variable of message length consisted of 1 to 6 moves. The different length trials (or messages) were presented in a pseudorandom order, such that every block of 12 trials included two trials of each of the six different message lengths, and, apart from moves of one, no two trials contained the same sequence of moves.

Between-subjects variables. As in all experiments**,** a between-subjects variable was stimulus type (arrows versus words). Formatting of stimuli varied between experiments. See the stimuli for this experiment in Appendix E. The between-subjects variable of dual task type consisted of (a) simple articulatory suppression wherein subjects repeated “Monday,” which was intended to impede verbal processing, and (b) simple foot tapping, wherein subjects tapped in the center of the board, which was intended to recruit only a-modal processing.

Trial stages. In addition to the trial design described in the General Methods section, the navigation message was presented twice in a row in immediate succession prior to when subjects enacted the response. Moreover, each subject performed the dual tasks continuously throughout each trial from encoding until they had completed their response. Although the metronome was timed at 80 beats per min, it was neither programmed into the software nor synchronized with events during the trial (such as stimulus presentation).

Experiment 2 Results

A-priori Accuracy Measures

Overall ANOVA. The overall ANOVA included the between-subjects variables of stimulus type (words, arrows) and dual task type (simple articulatory suppression, simple foot tapping) and the within-subjects variable of message length (1 to 6 moves).

Verbal modality effect. (See Table 1, for the statistics.)

Table 1
Experiment 2: Overall ANOVA statistics.

Variables	*df*	MSE	*F*	*p*	*Partial Eta Squared*
Stimulus Type	1(43)	.353	16.412	<.001*	.272
Dual Task Type	1(43)	.353	6.309	.016*	.125
Stimulus Type X Dual Task Type	1(43)	.353	8.746	.005*	.166
Message Length	5(215)	.090	304.978	<.001*	.874
Message Length X Stimulus Type	5(215)	.090	6.480	<.001*	.128
Message Length X Dual Task Type	5(215)	.090	5.015	<.001*	.102
Message Length X Stimulus Type X Dual Task Type	5(215)	.090	2.405	.038*	.052

* $p<.05$

There was a main effect of stimulus type, $F(1,43) = 16.412$, MSE=.353, $p < .001$, $\eta_p^2 = .272$, relating to the fact that overall performance was better for arrows ($M = .73$) than words ($M = .61$). Performance was more accurate for the simple foot tapping control ($M = .70$) than when verbal processing was impeded by the articulatory suppression task ($M = .63$), $F(1,43) = 6.309$, MSE=.353, $p = .016$, $\eta_p^2 = .125$. The reason for superior performance for arrows over words is revealed in the interaction of stimulus type and dual task type, $F(1,43) = 8.746$, MSE = .353, $p = .005$, $\eta_p^2 = .166$. See Figure 1. When verbal processing was impeded by articulatory suppression, accuracy of implementing the moves was negatively impacted for words but not for arrows compared to the simple foot tapping control.

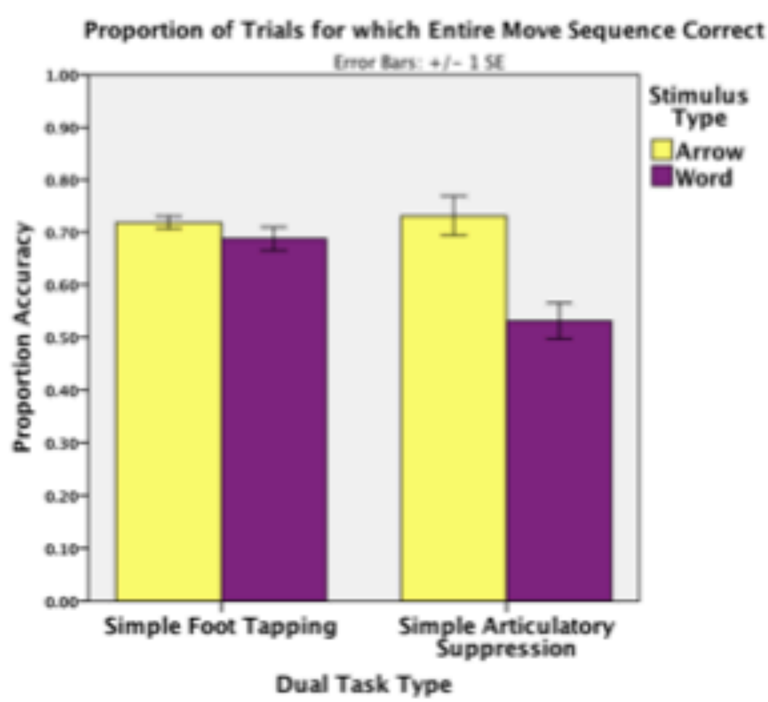

Figure 1. Experiment 2: verbal modality effect. Proportion correct as a function of stimulus type, and dual task type.

Verbal modality effect and cognitive load. Performance decreased monotonically as working memory was taxed for rehearsing more moves per message length, $F(5,215) = 304.978$ MSE = .090, $p < .001$, $\eta_p^2 = .874$. Additionally, cognitive load stemming from the number of moves to be memorized was only detrimental to performance for longer message lengths of 3 to 6 moves. Performance was at ceiling for moves of 1, and was almost at ceiling for moves of 2. The interaction of stimulus type and message length revealed that at higher cognitive load of message lengths 3 through 6, performance was worse for words than arrows, $F(5,215) = 6.480$, MSE = .090, $p = <.001$, $\eta_p^2 = .128$. Per the interaction of dual task type by message length, at higher cognitive load of 3 to 6 moves performance was worse when verbal processing was impeded by articulatory suppression than when modalities were unimpeded, $F(5,215) = 5.015$, MSE = .09, $p < .001$, $\eta_p^2 =.102$. However, the disadvantage for impeding verbal processing with articulatory suppression was not as evident for moves of 1 or 2. The significant three-way interaction of stimulus type by dual task type by message length revealed that losing the benefits of verbal processing due to articulatory suppression was more detrimental for words than arrows at higher item load, $F(5,215) = 2.405$, MSE=.090, $p =.038$, $\eta_p^2 = .052$. See Figure 2.

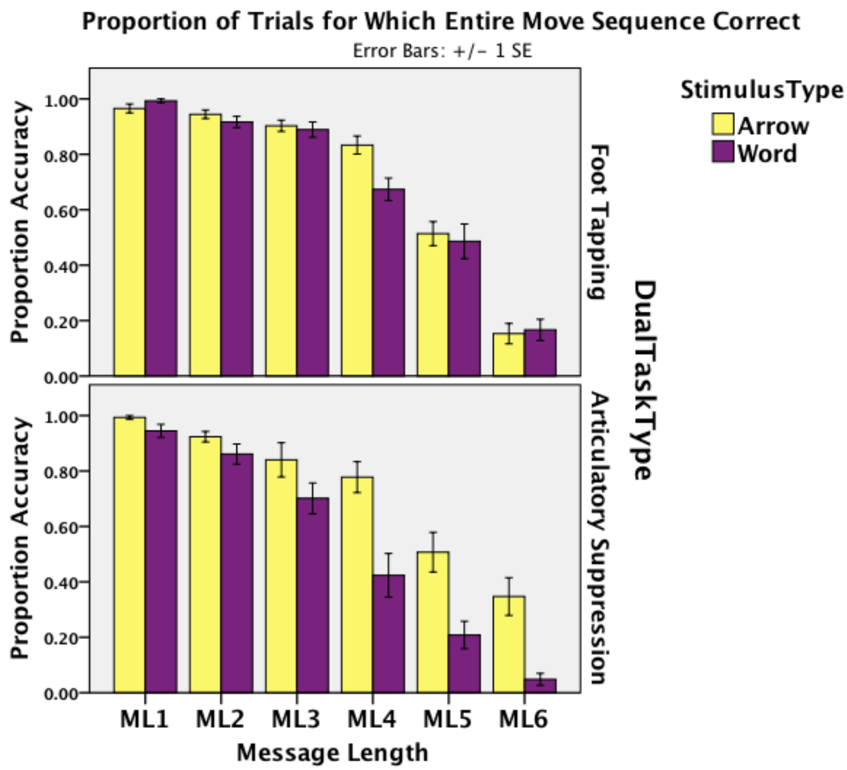

Figure 2. Experiment 2: verbal modality effect and cognitive load. Proportion correct as a function of stimulus type, dual task type, and message length.

Experiment 2 Discussion

Directional word and arrow stimuli can be rehearsed verbally and spatially. As such, when a modality of rehearsal is impeded by a dual task, efficiency of processing in the unimpeded modality becomes important for recall. Crucially, words are verbally-biased and arrows are spatially-biased in LTM. Therefore, we expected worse move recall when the stimulus type is not as well mapped in LTM to the unimpeded modality utilized in rehearsal. Accordingly, performance was worse for words than for arrows under articulatory suppression of verbal rehearsal compared to the simple foot tapping control. Spatial rehearsal was likely less successful for words than for arrows. See Figure 1.

Across all task manipulations, recall declined monotonically as the number of moves to-be-recalled increased, confirming the veracity of item load for examining working memory limits. Importantly, as the number of moves to-be-recalled increased, more efficient rehearsal would have become crucial to successful recall. Accordingly, we found that differences in performance occurred at the longer sequences of 3 to 6 moves and to be minimal at shorter sequences of 1 to 2 moves. See Figure 2.

Experiment 3 Method

Participants

Ninety-six University of Colorado undergraduates participated for credit in an introductory psychology course. All participants were native English speakers and were not color blind. Twelve subjects were assigned with fixed rotation to each of the eight conditions, which were combinations of three crossed variables: stimulus type (words versus arrows), dual task type (foot tapping tasks versus articulatory suppression tasks), and dual task complexity (simple versus complex).

Design and Procedure See Appendix D for a diagram of the design.

This experiment is identical to Experiment 2 except for two changes:

1. Two dual tasks were added resulting in four dual tasks: (a) simple articulatory suppression, and (b) complex articulatory suppression, which were both intended to impede verbal processing, (c) simple foot tapping, which was intended to recruit only a-modal processing, and (d) complex foot tapping, which was intended to impede spatial processing. Dual tasks were analyzed as dual task type (foot tapping versus articulatory suppression tasks) crossed with dual task complexity (simple versus complex).

2. Instead of performing the dual tasks during both the encoding and response phase as in Experiment 2, subjects only performed the dual tasks during the encoding phase when the stimuli were being presented.

Experiment 3 Results

A-priori Accuracy Measures

Overall ANOVA. The overall ANOVA included the between-subjects variables of stimulus type (words, arrows), dual task type (articulatory suppression, foot tapping), and dual task complexity (simple, complex)[3], and the within-subjects variable of message length (1 to 6 moves).

Verbal and spatial modality effects. (See Table 2, for the statistics.)

[3] For simple articulatory suppression, "Monday" was repeated, and for complex articulatory suppression, "Tuesday, Friday, Thursday, Monday," was repeated. For the simple foot tapping control, the center of a board was tapped, and for complex foot tapping, a pattern was tapped on the corners of a board.

Table 2
Experiment 3: Overall ANOVA statistics.

Variables	*df*	MSE	*F*	*p*	η_p^2
Stimulus Type	1(87)	.076	.841	.362	.009
Dual Task Type	1(87)	.076	41.519	<.001*	.321
Dual Task Complexity	1(87)	.076	3.226	.076	.035
Stimulus Type X Dual Task Type	1(87)	.076	30.962	<.001*	.260
Stimulus Type X Dual Task Complexity	1(87)	.076	8.419	.005	.087
Dual Task Type X Dual Task Complexity	1(87)	.076	11.587	.001	.116
Stimulus type X Dual Task Type X Dual Task Complexity	1(87)	.076	4.400	.039	.048
Message Length	5(440)	.016	563.619	<.001*	.865
Message Length X Stimulus Type	5(440)	.016	3.570	.004	.128
Message Length X Dual Task Type	5(440)	.016	19.754	<.001*	.183
Message Length X Dual Task Complexity	5(440)	.016	.473	.797	.005
Message Length X Stimulus Type X Dual Task Type	5(440)	.016	5.545	<.001*	.059
Message Length X Stimulus Type X Dual Task Complexity	5(440)	.016	2.082	.067	.023
Message Length X Dual Task Type X Dual Task	5(440)	.016	2.148	.059	.024

Complexity					
Message Length X Stimulus type X Dual Task Type X Dual Task Complexity	5(440)	.016	2.705	.020	.030

* $p < .05$

The significant interaction of stimulus type, dual task type, and dual task complexity revealed complementary verbal and spatial modality effects, $F(1,87) = 4.400$, MSE = .076, $p = .039$, η_p^2 = 048. For the verbal modality effect, performance was worse for the combined articulatory suppression tasks (M = .52), wherein verbal processing was impeded, than for the simple foot tapping control (M = .73). Importantly, the decline in performance was worse for words (M_{diff} =.28) than for arrows (M_{diff} = .14). For the spatial modality effect, performance was worse for complex foot tapping (M = .61), wherein spatial processing was impeded, than for the simple foot tapping control (M = .73). Importantly, the decline in performance only occurred for arrows (M_{diff} = .24), and not for words (M_{diff} = -.02). See Figure 3.

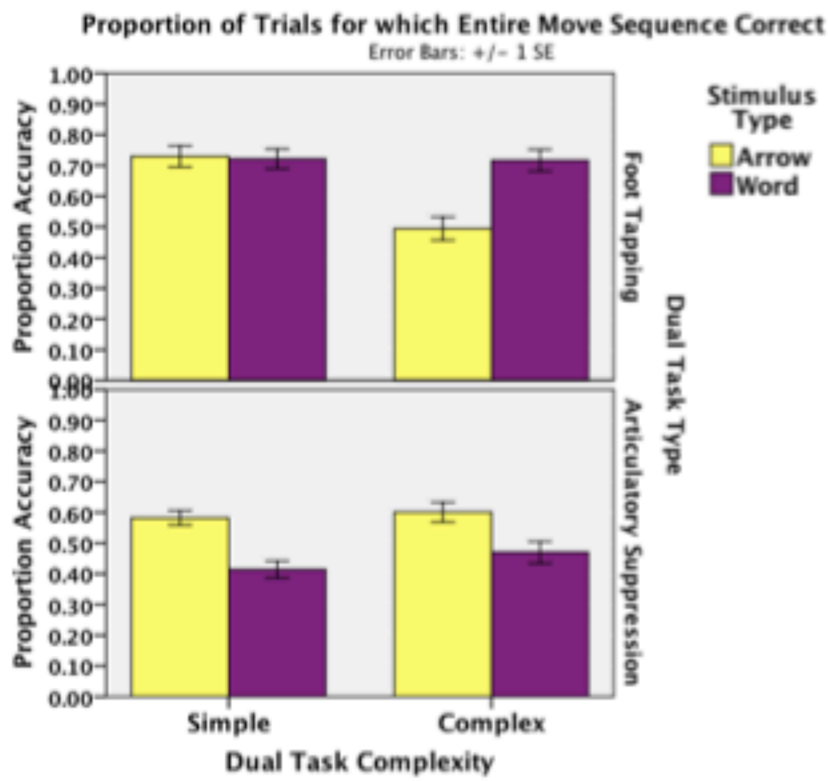

Figure 3. Experiment 3: verbal and spatial modality effects. Proportion correct as a function of stimulus type, dual task type, and dual task complexity.

Verbal and spatial modality effects and cognitive load. Performance decreased monotonically as working memory was taxed for rehearsing more moves per message length, $F(5,440) = 563.619$, MSE = .016, $p < .001$, $\eta_p^2 = .865$. Performance only declined for moves of 3 to 6. A four-way interaction of stimulus type, dual task type, dual task complexity, and message length replicated Experiment 2, in that the locus of the modality effects was at longer message lengths wherein cognitive load was increasingly taxed, $F(5,440) = 2.705$, MSE = .016, $p < .020$, $\eta_p^2 = .030$. At higher cognitive load of message lengths 3 to 6, performance was negatively impacted for words more than for arrows for articulatory suppression tasks. Conversely, performance was negatively impacted for arrows but not words for complex foot tapping. However, for the simple foot tapping control, performance for arrows and words was comparable for longer message lengths. Such disadvantages depending on stimulus type and dual task combination were not evident at message lengths of 1 and 2 wherein cognitive load was negligibly taxed. See Figure 4.

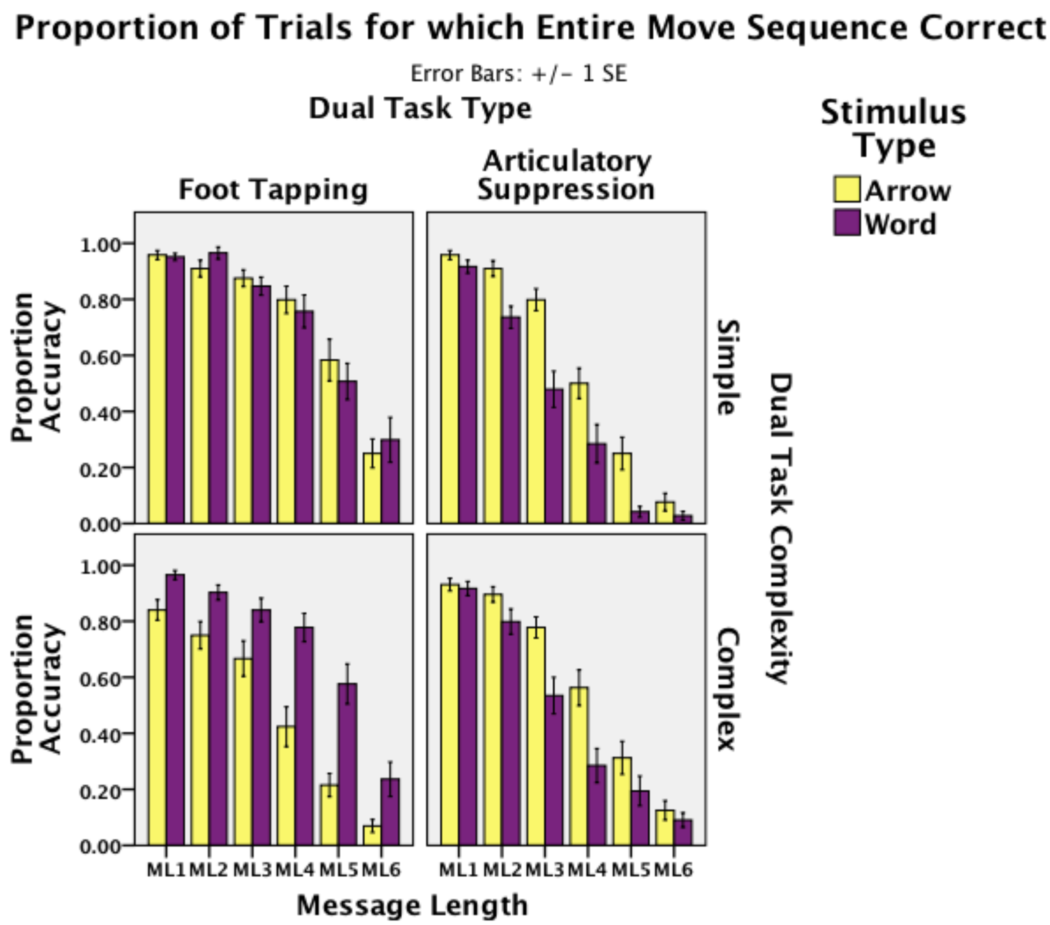

Figure 4. Experiment 3: modality effects and cognitive load. Proportion correct as a function of stimulus type, dual task type, dual task complexity, and message length.

Experiment 3 Discussion

As mentioned in the Experiment 2 Discussion, directional word and arrow stimuli can be rehearsed verbally and spatially. As such, when a modality of rehearsal is impeded by a dual task, efficiency of processing in the unimpeded modality becomes important for recall. Crucially, words are verbally-biased and arrows are spatially-biased in LTM. Therefore, we expected worse move recall when the stimulus type is not as well mapped in LTM to the unimpeded modality utilized in rehearsal. Accordingly, replicating Experiment 2, performance was worse for words than for arrows under articulatory suppression of verbal rehearsal compared to the simple foot tapping control. Spatial rehearsal was likely less successful for words than for arrows. Conversely for the new manipulation of impeding spatial rehearsal with complex foot tapping, performance was worse for arrows than for words compared to the simple foot tapping control. Verbal rehearsal was likely less successful for arrows than for words. See Figure 3.

As in Experiment 2, across all task manipulations, recall declined monotonically as the number of moves to-be-recalled increased, again confirming the veracity of item load for examining working memory limits. Importantly, as the number of moves to-be-recalled increased, more efficient rehearsal would have become crucial to successful recall. Accordingly, we found that differences in performance tended to occur at the longer sequences of 3 to 6 moves and to be minimal at shorter sequences of 1 to 2 moves. See Figure 4.

Experiment 4a Method

Participants. Forty-eight University of Colorado undergraduates participated in return for credit in an introductory psychology course. All participants were native English speakers. Two subjects were randomly assigned with fixed rotation to each of the 24 combinations of the three variables: stimulus type, dual task timing, and dual task order.

Design and procedure. See Appendix D for a diagram of the design.

Between-subjects variables. As in all experiments**,** a between-subjects variable was stimulus type (arrows versus words). Formatting of stimuli varied between experiments. See the stimuli for this experiment in Appendix F. Color coding of arrow stimuli for direction was removed to equate the now black and white arrow and word stimuli along the color dimension. The formatting of word stimuli was changed to make arrow and word stimuli more similar in terms of number of units (for each arrow there is a corresponding word), and in terms of being equally subject to transformations to internal mental representations of the moves. For example, "left left" is more similar in number of units than "left two squares" to "⬅".

There were four levels to the dual task timing variable: (a) presentation: conducted the dual tasks when stimuli were present on the computer screen, (b) retention interval: conducted the dual tasks during the retention interval, which was inserted between the presentation and the response phases as a measure of rehearsal, (c) both: conducted the dual tasks during the presentation and retention intervals, and (d) neither: did not conduct a dual task.

For the dual task order variable, the order of presentation of the within-subjects variable dual task type was counterbalanced across subjects using a Latin Square design.

Within-subjects variables. For the dual task type variable, subjects who performed the dual tasks performed three dual tasks (one dual task every block of 24 trials): (a) simple articulatory suppression, which was intended to impede verbal processing; (b) complex foot tapping, which was intended to impede spatial processing; and (c) simple foot tapping, which was intended to recruit only a-modal processing. Unlike Experiments 2 and 3, message length was not a variable and was held constant at four moves. Block (3 blocks of 24 trials each) was also examined separate to dual task type to assess training effects across blocks, regardless of the dual task type that took place in counterbalanced order in each of the blocks.

Practice. Per usual, practice consisted of six trials. Instead of practicing six different message lengths as was done in Experiments 2 and 3, subjects practiced messages of four moves. Additionally, subjects who performed a dual task practiced the main task while performing two consecutive trials of each of the dual task types. The order of the dual tasks in practice was the same as that of the experimental trials assigned to each subject.

Trial stages. In addition to the trial design described in the General Methods section, the following changes were made to Experiment 4a: The navigation message was only presented once, versus double presentation of messages that took place in Experiments 2 and 3.

Trial stages were coded such that if the screen was green and a metronome sound was heard, subjects were to enact the dual task to the beat. Conversely, if the screen was red and no metronome sound was heard, subjects were not to perform the dual task. The timing of the dual task metronome was increased from every 750 ms to every 625 ms. Thus, during the presentation phase, the dual task was enacted at the start of stimulus presentation on every first beat and half way through stimulus presentation on every second beat.

The presentation phase within which stimuli were presented was programmed to be 5 s, and the retention interval was also programmed to be 5 s. During the retention interval the matrices were in full view but a response could not be enacted, and subjects were free to rehearse moves until it was time to execute the response.

Due to dual task type being examined within-subjects, after subjects had made the moves on the matrices and had pressed DONE CLICKING to initiate the next trial, prior to the first, twenty-fifth and forty-ninth trial, instructions appeared on a blank background before trial initiation. For subjects in the no dual task condition, the instruction was “Click on CONTINUE when you are ready to proceed.” For subjects in the dual task conditions, the instructions before a given critical trial (Trial 1, 25, or 49) were either “While the screen is green repeat MONDAY to the beat of the metronome,” “While the screen is green, tap your foot to the beat of the metronome ON THE CORNERS OF THE BOARD in an anti-clockwise direction,” or “While the screen is green, tap your foot to the beat of the metronome IN THE CENTER OF THE BOARD."

Experiment 4a Results

A-priori Accuracy Measures

Overall ANOVAs. An initial overall ANOVA excluding subjects with no dual task examined the effect of dual task type on accuracy. The ANOVA included the between-subjects variables of stimulus type (words, arrows), dual task timing (presentation, retention interval, both), and dual task order (ABC, BCA, CAB), and the within-subjects variable of dual task type (articulatory suppression, complex foot tapping, simple foot tapping).

A second overall ANOVA examined the effect of performing two tasks at the same time on accuracy across blocks. The ANOVA included the between-subjects variables of stimulus type (words, arrows) and dual task presence (dual task/n=36, no dual task/n=12) and the within-subjects variable of block (Block 1, Block 2, Block 3).

Effect of dual task type on accuracy. (See Table 3, for the statistics.)

Table 3
Experiment 4a: Initial overall ANOVA statistics.

Variables	*df*	MSE	*F*	*p*	η_p^2
Stimulus Type	1(17)	.027	99.703	<.001*	.847
Dual Task Timing	2(17)	.027	7.851	.004*	.466
Dual Task Order	2(17)	.027	1.673	.216	.157
Stimulus Type*Dual Task Timing	2(17)	.027	2.154	.145	.193
Stimulus Type*Dual Task Order	2(17)	.027	8.050	.003*	.472
Dual Task Timing*Dual Task Order	2(17)	.027	4.155	.015*	.480
Stimulus Type*Dual Task Timing*Dual Task Order	2(17)	.027	1.974	.142	.305
Dual Task Type	2(36)	.009	46.981	<.001*	.723
Dual Task Type*Stimulus Type	2(36)	.009	4.127	.024	.187
Dual Task Type*Dual Task Timing	4(36)	.009	3.653	.013*	.289
Dual Task Type*Dual Task Order	4(36)	.009	7.046	<.001*	.439
Dual Task Type*Stimulus Type*Dual Task Timing	4(36)	.009	2.637	.050	.227
Dual Task Type*Stimulus Type*Dual Task Order	4(36)	.009	.530	.714	.056

Dual Task Type*Dual Task Timing*Dual Task Order	8(36)	.009	1.351	.251	.231
Dual Task Type*Stimulus Type*Dual Task Timing*Dual Task Order	8(36)	.009	1.877	.095	.294

* $p < .05$

Poor performance of arrows. The low-level performance of arrows (M = .36) compared to words (M = .68) indicates that subjects were experiencing difficulty with arrow stimuli, $F(1,17) = 99.703$, MSE = .027, $p < .001$, $\eta_p^2 = .847$.

Verbal modality effect but no spatial modality effect. Only a verbal modality effect was found, wherein performance was depressed for articulatory suppression (M = .39) compared to complex foot tapping (M = .58) and simple foot tapping (M = .58), $F(2,36) = 46.981$, MSE = .009, $p < .001$, $\eta_p^2 = .723$. Accuracy for complex and simple foot tapping tasks was comparable, thus no spatial modality effect occurred. The negative impact of impeding verbal processing, as measured by the difference between articulatory suppression and simple foot tapping, was more for words (M_{diff} = .23) than for arrows (M_{diff} = .15), $F(2,36) = 4.127$, MSE = .009, p = 024, $\eta_p^2 = .187$. See Figure 5.

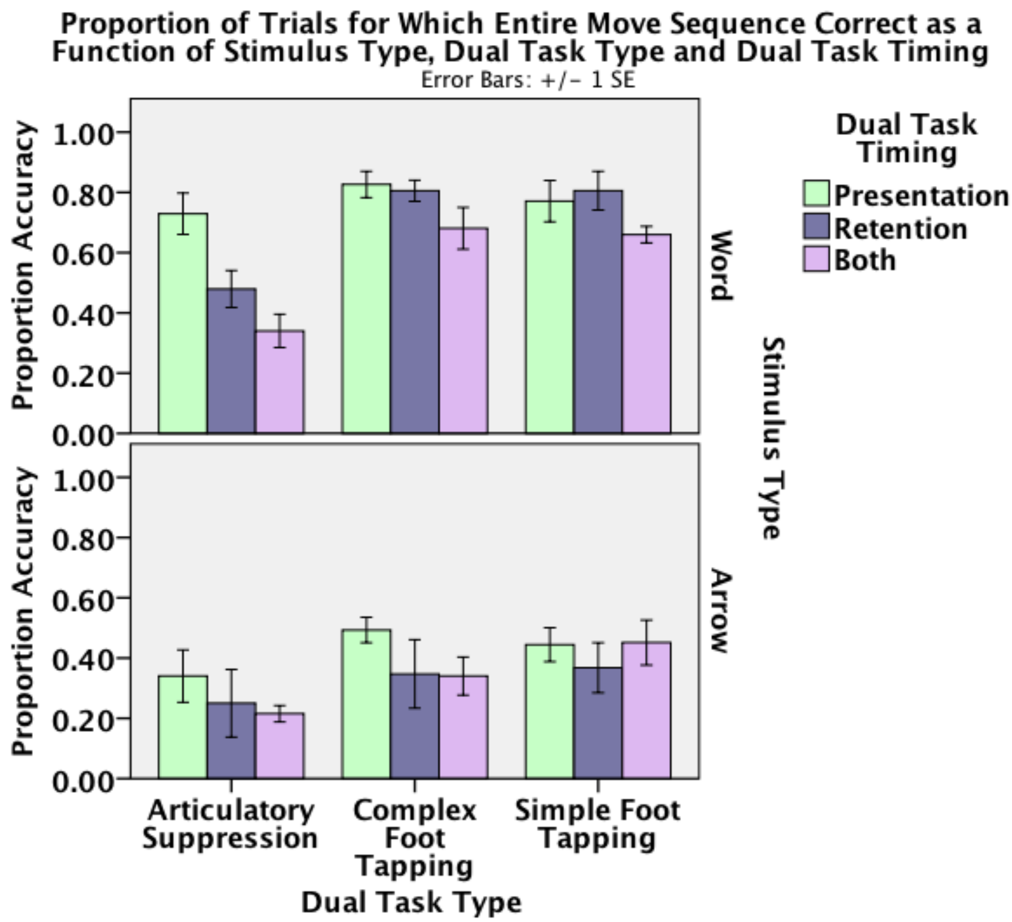

Figure 5. Experiment 4a: verbal modality effect. Proportion correct as a function of stimulus type, dual task type, and dual task timing.

The significant interaction of dual task type and dual task order, wherein performance was worse when the dual task was performed in the first block (e.g., complex foot tapping), suggests that the spatial effect for words was due in part to a general training effect, $F(4,36) = 7.046$, MSE = .009, $p < .001$, $\eta_p^2 = .439$. See Figure 6.

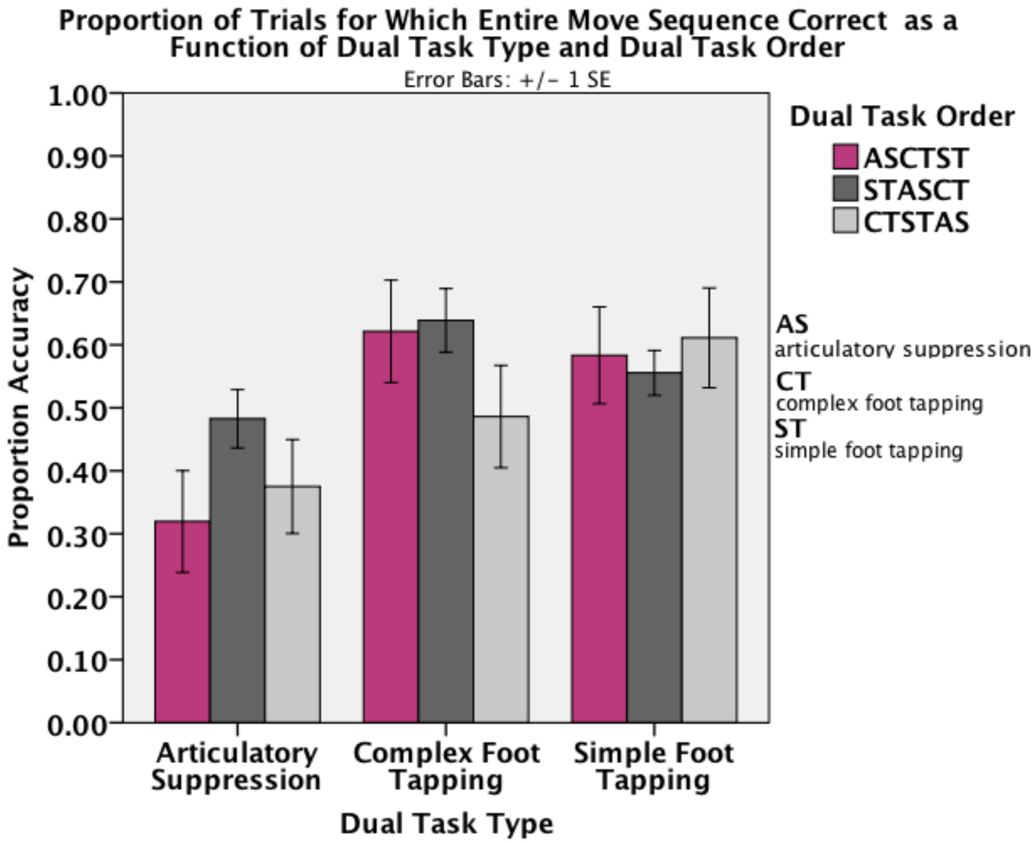

Figure 6. Experiment 4a: verbal modality effect. Proportion correct as a function of dual task type, and dual task order.

Locus of verbal modality effect. The interaction of dual task type and dual task timing revealed that the verbal modality effect was limited to the retention interval and both conditions for dual task timing, $F(4,36) = 3.653$, MSE = .009, $p = .013$, $\eta_p^2 = .289$. Rehearsal, but not encoding, is common to the dual task timing conditions wherein the verbal modality effect was found. The marginally significant interaction of stimulus type, dual task type, and dual task timing suggests that this pattern was more clearly delineated for words than for arrows for which performance was depressed, $F(4,36) = 2.637$, MSE = .009, $p = .050$, $\eta_p^2 = .227$. See Figure 5.

Effect of performing two tasks at the same time on accuracy across blocks. Accuracy was significantly higher for words ($M = .74$) than arrows ($M = .51$), $F(1,43) = 21.599$, MSE = .066, $p < .001$, $\eta_p^2 = .329$. As an index of cognitive load, performance was significantly higher for subjects who had no dual tasks ($M = .74$) than for subjects who conducted two tasks at the same time ($M = .52$), $F(1,43) = 19.571$, MSE = .066, $p < .001$, $\eta_p^2 = .308$. Additionally, the interaction of stimulus type and dual task presence was marginally significant, $F(1,43) = 3.159$, MSE = .066, $p = .082$, $\eta_p^2 = .067$. The numerical trend was that the drop in performance when two tasks took place at the same time was more for arrows ($M_{diff} = .31$) than for words (M_{diff} = .13.) There was a main effect of block, wherein learning of the tasks appeared to occur in the first block ($M = .57$), which was significantly lower in accuracy compared to Block 2 ($M = .66$) and Block 3 ($M = .65$), which were comparable in performance, $F(2,88) = 4.653$, MSE = .022, $p = .012$, $\eta_p^2 = .096$. The lower accuracy in the first 24 trials for Block 1 was robust in that the increase in performance from Block 1 to Block 2 occurred independent of what stimulus type was trained, $F(2,88) = .099$, MSE = .022, $p = .906$, $\eta_p^2 = .002$, or whether or not a dual task was present, $F(2,88) = .354$, MSE = .022, $p = .703$, $\eta_p^2 = .008$. See Figure 7.

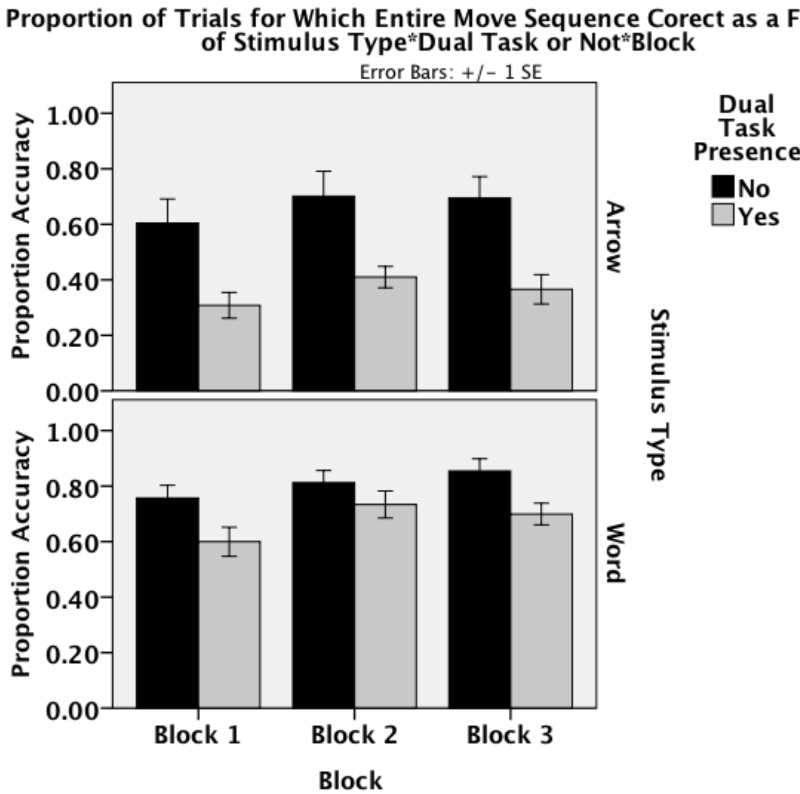

Figure 7. Experiment 4a: effect of performing two tasks at the same time. Proportion correct as a function of stimulus type, dual task presence, and block. Only the main effects of stimulus type, dual task presence, and block were significant.

Experiment 4a Discussion

There were five changes in this experiment that may have increased the difficulty of acquisition of the novel arrow stimuli . One, in Experiment 1 which is referred to but not included in this thesis, performance was worse for arrows than for words when move sequences were presented once-in-a-row instead of twice in-a-row at stimulus presentation (McCormick, 2010). See Figure 8.

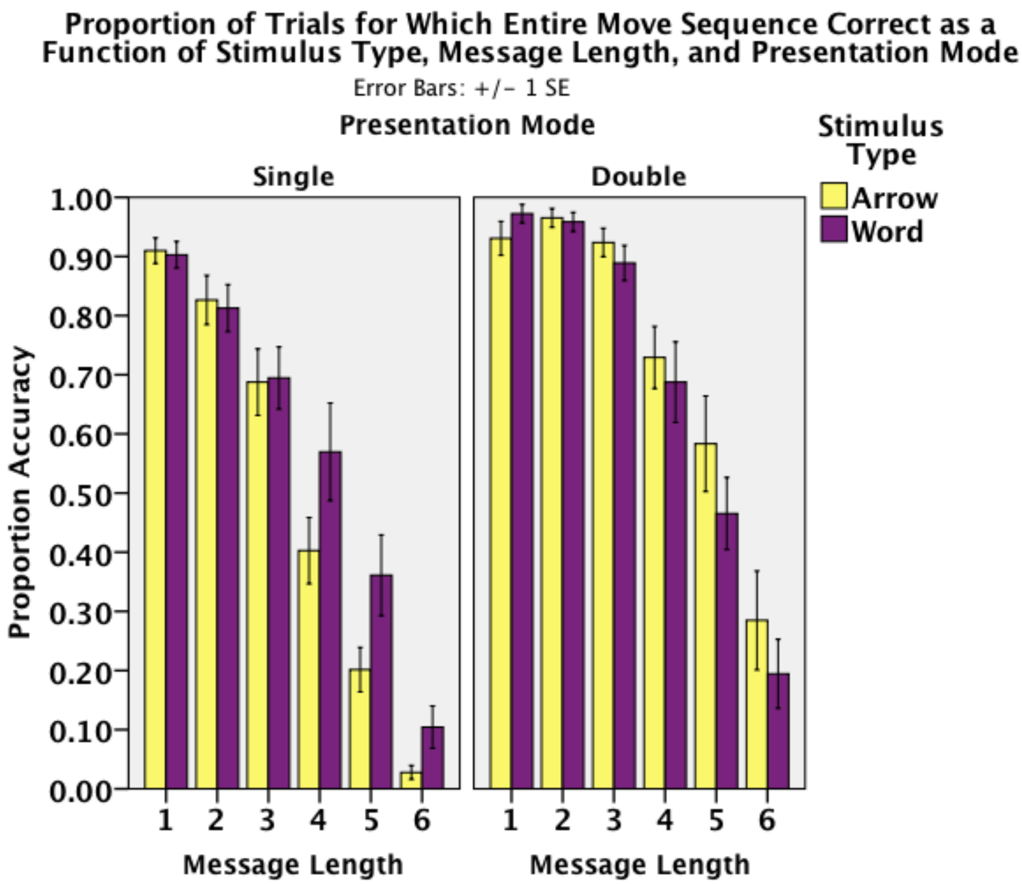

Figure 8. Experiment 1: effect of double versus single presentation of stimuli in a given trial. Proportion correct as a function of stimulus type, message length, and single versus double presentation of stimuli.

Thus, more time is needed to acquire the more novel arrow stimuli than the highly familiar word stimuli. Therefore, in Experiments 2 and 3 move sequences were presented twice-in-a-row. However, in this experiment, move sequences were presented once-in-a-row to prevent the rehearsal associated with a second round of stimulus presentation, which would have confounded the encoding versus rehearsal comparison for the dual task timing variable. Two, the number of to-be-recalled moves was changed to 4 moves instead of 1 to 6 moves in order to keep stimulus presentation and the newly added retention interval constant at 5 s. Given that in this paradigm, recall markedly declines at three moves (Barshi & Healy, 2002), cognitive load was sustained at a relatively high level. Three, arrows were changed from being color coded to being black and white, which might have made the novel arrow stimuli harder to translate into moves. Four, word stimuli were changed from harder (e.g., "up two levels") to easier (e.g., "up up") unitized format, which may have made it easier to translate words into moves. Five, subjects were trained on the navigational task while conducting the dual tasks for the 6 practice trials, instead of separately as was done in Experiments 2 and 3. The intention was for subjects to learn when to stop and start the dual tasks mid-trial. The unintended consequence was that task acquisition was additionally handicapped.

As a consequence of the unintended reduction in processing resources for acquisition of novel stimuli, accuracy for arrows was lower than for words (M_{diff} = .32). When no dual task occurred such that more processing resources were available for the main task, accuracy for arrows increased more than accuracy for words.[4] This finding suggests that acquisition of novel arrow stimuli was more sensitive to the availability of processing resources than the acquisition of the more familiar word stimuli was. See Figure 7.

Given the suppressed recall for arrows compared to words, no modality effects were found for arrows. That is, performance was comparably low when verbal and spatial processing were impeded by articulatory suppression and complex foot tapping as when they were not impeded for the simple foot tapping control. Conversely, the verbal modality effect replicated for words. Performance declined under articulatory suppression of verbal rehearsal compared to the

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[4] Marginal interaction of stimulus type*dual task presence, p = .08.

simple foot tapping control. Our interpretation of this result is that words were weakly mapped to the unimpeded spatial modality in LTM such that rehearsal was less successful for words than when verbal rehearsal could be utilized for the simple foot tapping control. See Figure 5.

Unlike Experiments 2 and 3, there appeared to be some impact of complex foot tapping impeding spatial rehearsal for words, which we would not predict because words map well onto the unimpeded verbal modality in LTM. However, this slight drop in performance can be explained by the interaction of dual task type and dual task order. Because the relatively smaller decline in performance for words for complex foot tapping only occurred in the first block, it was most likely due to a general training effect wherein verbal rehearsal was being improved upon in the first block. Because the drop in performance for words for articulatory suppression occurred across all blocks, it was likely due to the relative ineffectiveness of spatial rehearsal compared to verbal rehearsal across all blocks regardless of practice. See Figure 6.

A dual task timing variable was added to Experiment 4a to assess whether the locus of the influence of modality biases in LTM on recall is at encoding or at rehearsal of moves. The verbal modality effect occurred exclusively for the retention interval and both conditions, wherein most systematic rehearsal took place. Therefore, the locus appears to be at rehearsal for the retention interval and both conditions. See Figure 5.[5] It is important to note that the locus of the verbal modality effect was not at encoding. If the locus of the effect was at encoding, the effect should have occurred for the presentation and both conditions. This finding suggests that pre-existing modality bias in LTM for words and arrows was incorporated into WM

[5] Marginal interaction of stimulus type*dual task type*dual task timing, $p = .05$.

representations, such that subsequent rehearsal of those representations in particular modalities was impacted by such modality-bias.

Experiment 4b Method

Participants. Forty-eight University of Colorado undergraduates participated in return for credit in an introductory psychology course. All participants were native English speakers. Two subjects were randomly assigned with fixed rotation to each of the 24 combinations of the three variables: stimulus type, dual task timing, and dual task order.

Design and procedure. See Appendix D for a diagram of the design.

This experiment is identical to Experiment 4a except that the duration of stimulus presentation was doubled from 1250 ms to 2500 ms. The timing of each metronome beat for enactment of the dual tasks remained 625 ms, such that during the presentation phase, the dual task was enacted four times per stimulus instead of two times per stimulus. Consequently the duration of the presentation phase doubled from 5 s to 10 s and the duration of the retention interval doubled from 5 s to 10 s.

Experiment 4b Results

A-priori Accuracy Measures

Overall ANOVAs. An initial overall ANOVA excluding subjects with no dual task examined the effect of dual task type on accuracy. The ANOVA included the between-subjects variables of stimulus type (words, arrows), dual task timing (presentation, retention interval, both), and dual task order (ABC, BCA, CAB), and the within-subjects variable of dual task type (articulatory suppression, complex foot tapping, simple foot tapping.)

A second overall ANOVA examined the effect of performing two tasks at the same time on accuracy across blocks. The ANOVA included the between-subjects variables of stimulus type (words, arrows) and dual task presence (dual task/*n*=36, no dual task/*n*=12), and the within-subjects variable of block (Block 1, Block 2, Block 3.)

Effect of dual task type on accuracy. (See Table 4, for the statistics.)

Table 4 *Experiment 4b: Initial overall ANOVA statistics.*

Variables	*df*	MSE	*F*	*p*	η_p^2
Stimulus Type	1(17)	.114	11.485	.003*	.390
Dual Task Timing	2(17)	.114	.323	.728	.035
Dual Task Order	2(17)	.114	.418	.665	.044
Stimulus Type*Dual Task Timing	2(17)	.114	.090	.914	.010
Stimulus Type*Dual Task Order	2(17)	.114	.120	.888	.013
Dual Task Timing*Dual Task Order	2(17)	.114	.438	.780	.089
Stimulus Type*Dual Task Timing*Dual Task Order	2(17)	.114	.364	.831	.075
Dual Task Type	2(36)	.011	20.590	<.001*	.534
Dual Task Type*Stimulus Type	2(36)	.011	7.001	.003*	.280
Dual Task Type*Dual Task Timing	4(36)	.011	1.627	.189	.153
Dual Task Type*Dual Task Order	4(36)	.011	3.667	.013*	.290
Dual Task Type*Stimulus Type*Dual Task Timing	4(36)	.011	.875	.488	.089
Dual Task Type*Stimulus Type*Dual Task Order	4(36)	.011	.722	.583	.074
Dual Task Type*Dual Task Timing*Dual Task Order	8(36)	.011	1.577	.166	.260

* $p<.05$

Poor performance of arrows. Proportion accuracy was .22 worse for arrows ($M = .56$) than for words ($M = .78$), $F(1,17) = 11.485$, MSE = .114, $p = .003$, $\eta_p^2 = .390$.

Robust verbal modality effect and apparent-spatial modality effect. A verbal modality effect and spatial modality effect were found for dual task type, $F(2,36) = 20.590$, MSE = .011, $p < .001$, $\eta_p^2 = .534$. For the verbal modality effect, performance was depressed for articulatory suppression ($M = .58$) compared to the simple foot tapping control ($M = .75$). For the spatial modality effect, performance was depressed for complex foot tapping ($M = .66$) compared to the simple foot tapping control ($M = .75$.) However, the significant stimulus type by dual task type interaction indicates that the differences in accuracy depending on dual task type were larger for words than for arrows, $F(2,36) = 7.001$, MSE = .011, $p = .003$, $\eta_p^2 = .280$. See Figure 9.

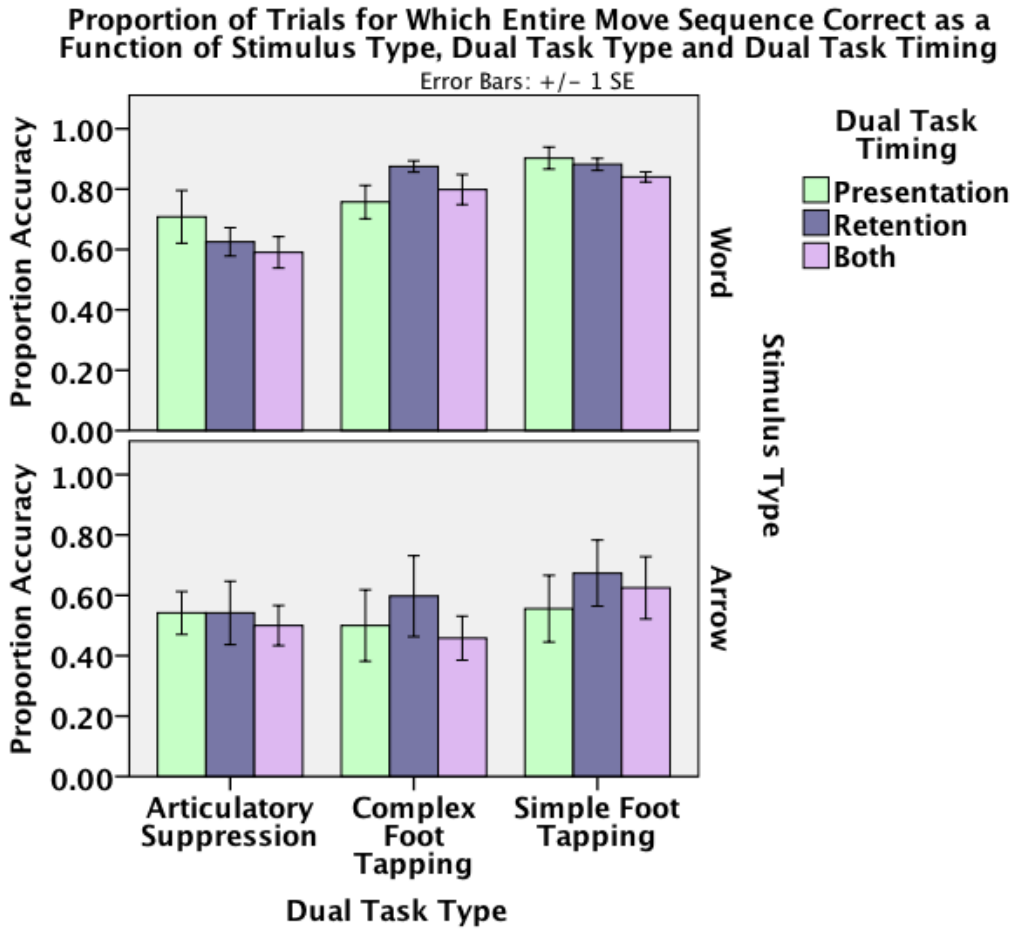

Figure 9. Experiment 4b: indication of verbal modality effect for word. Proportion correct as a stimulus type, dual task type, and dual task timing.

The interaction of dual task type and dual task order, wherein performance was worse when the dual task was performed in the first block (e.g., complex foot tapping), suggests that the spatial effect for words was due in part to a general training effect, $F(4,36) = 3.667$, MSE = .011, $p = .013$, $\eta_p^2 = .290$. See Figure 10. For the robust verbal modality effect, performance decrements occurred for articulatory suppression regardless of whether articulatory suppression occurred in the first, second, or third block of 24 trials.

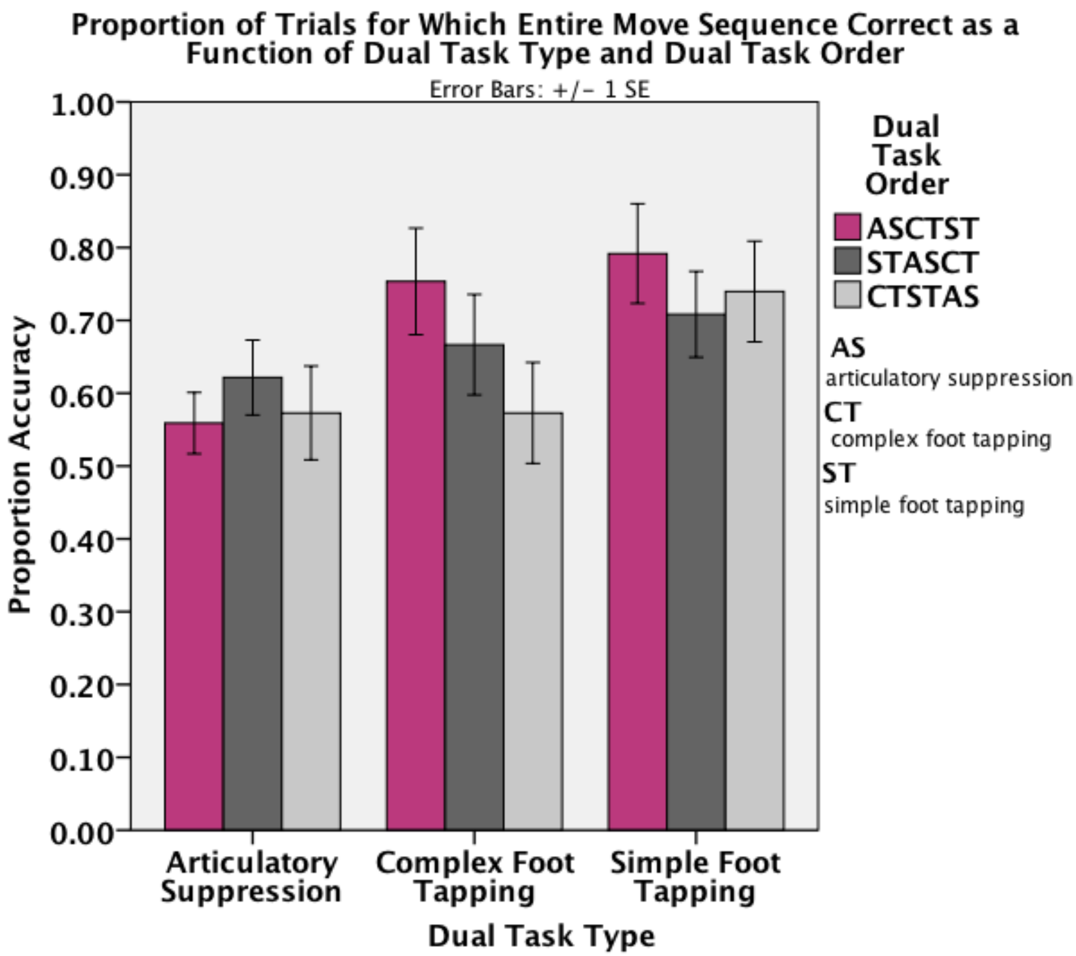

Figure 10. Experiment 4b: verbal modality effect holds but spatial modality effect does not. Proportion correct as a function of dual task type, and dual task order.

Locus of verbal modality effect. The interaction of stimulus type, dual task type, and dual task timing was not significant, $F(4,36) = .875$, MSE = .011, $p = .488$, $\eta_p^2 = .089$. See Figure 9.

Effect of dual task type on accuracy for words only. Arrows were removed from the analysis and the overall ANOVA for effect of dual task type on accuracy was repeated for words only.

Robust verbal modality effect and apparent-spatial modality effect for word. A robust verbal modality effect was found for words. For the main effect of dual task type, performance under articulatory suppression (*M* = .64) was .24 less than for the simple foot tapping control (*M* = .88), and an apparent spatial modality effect was found for words wherein performance under complex foot tapping (*M* = .81) was .07 less than for the simple foot tapping control (*M* = .88), $F(2,18) = 35.776$, MSE = .007, $p < .001$, $\eta_p^2 = .799$. See Figure 11.

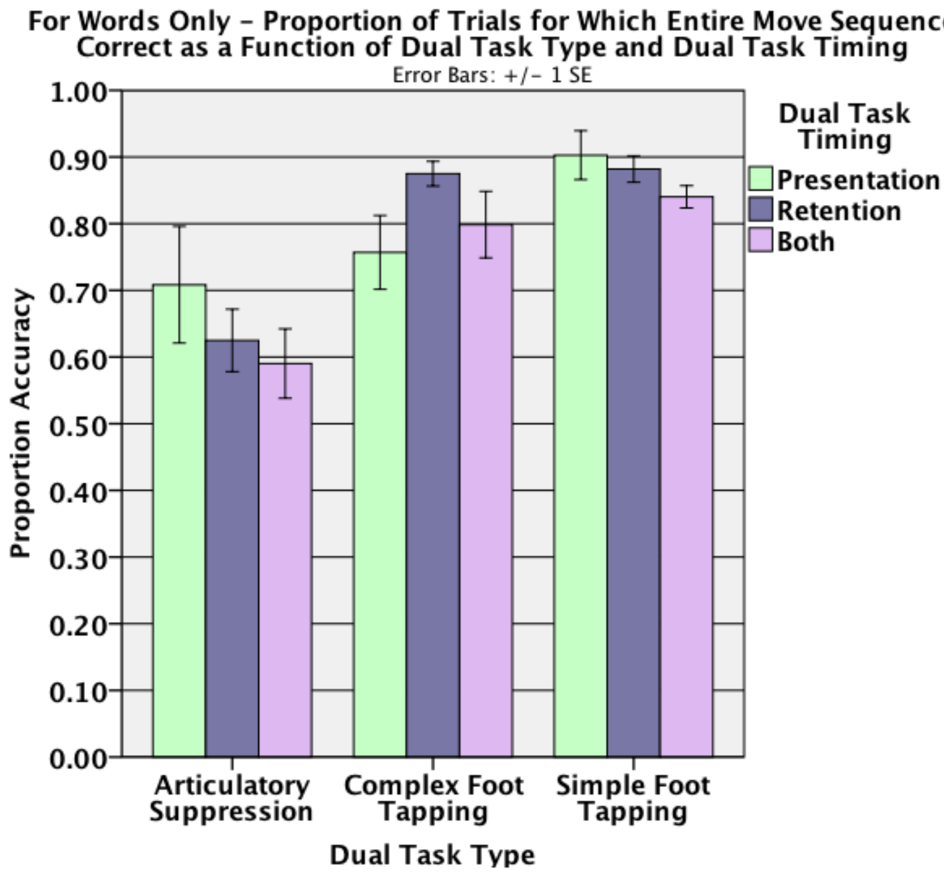

Figure 11. Experiment 4b: verbal modality effect. Proportion correct as a function of dual task type, and dual task timing for words only.

The marginally significant interaction of dual task type and dual task order shows that the drop in performance for complex foot tapping for words only occurred when complex foot tapping was in the first block suggesting that the apparent spatial effect was actually a training effect for learning the navigation task, $F(4,18) = 2.737$, MSE = .007, $p = .061$, $\eta_p^2 = .378$. Articulatory suppression negatively impacted performance regardless of which block (Block 1, 2 or 3) the dual task occurred in. See Figure 12.

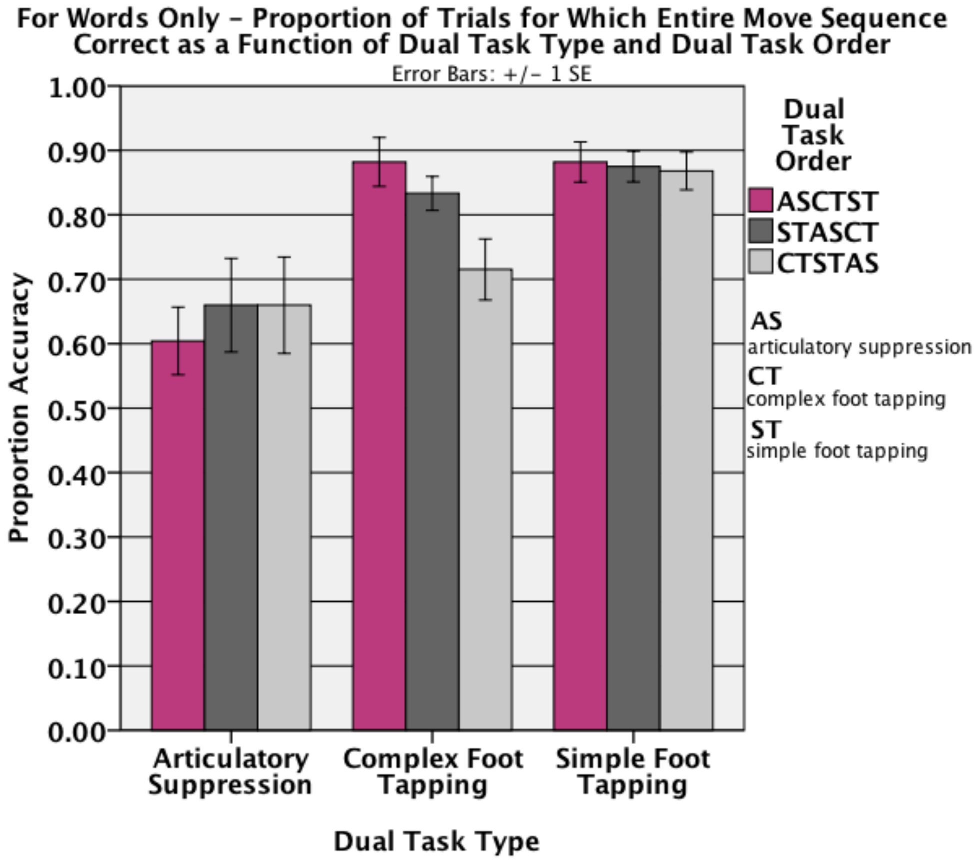

Figure 12. Experiment 4b: verbal modality effect and pseudo spatial modality effect for words only. Proportion correct as a function of dual task type, and dual task order for words only.

Per the marginal interaction of dual task type and dual task timing, the impact of articulatory suppression on words was stronger for dual task timing conditions weighted towards rehearsal (retention interval, both) than the presentation condition, $F(4,18) = 2.414$, MSE = .007, $p = .087$, $\eta_p^2 = .349$. See Figure 11.

Effect of performing two tasks at the same time on accuracy across blocks. Accuracy was .22 higher for words ($M = .84$) than for arrows ($M = .62$), $F(1,43) = 15.528$, MSE = .083, $p < .001$, $\eta_p^2 = .261$, and performance was significantly higher for subjects who had no dual tasks (*M* = .79) than subjects who conducted two tasks at the same time (*M* = .67), $F(1,43)$ = 5.329, MSE = .083, p =.026, η_p^2 = .108. The interaction of stimulus type and dual task presence was marginally significant, $F(1,43)$ .002, MSE = .083, p = .083, η_p^2 = .000. However, the drop in performance when a dual task took place was virtually the same for arrows (M_{diff} = .13) and words (M_{diff} = .14). There was a main effect of block, wherein learning of the tasks appeared to occur in the first block (*M* = .66), which was lower in accuracy compared to Block 2 (*M* = .78) and Block 3 (*M* = .75), which were comparable in performance, $F(2,88)$ = 7.504, MSE = .017, p = .001, η_p^2 = .146. The lower accuracy in the first 24 trials for Block 1 was robust in that the increase in performance from Block 1 to Block 2 occurred independent of what stimulus type was trained on, $F(2,88)$ = .821, MSE = .022, p = .443, η_p^2 = .018, or whether a dual task occurred or not, $F(2,88)$ = .361, MSE = .022, p = .698, η_p^2 = .008. See Figure 13.

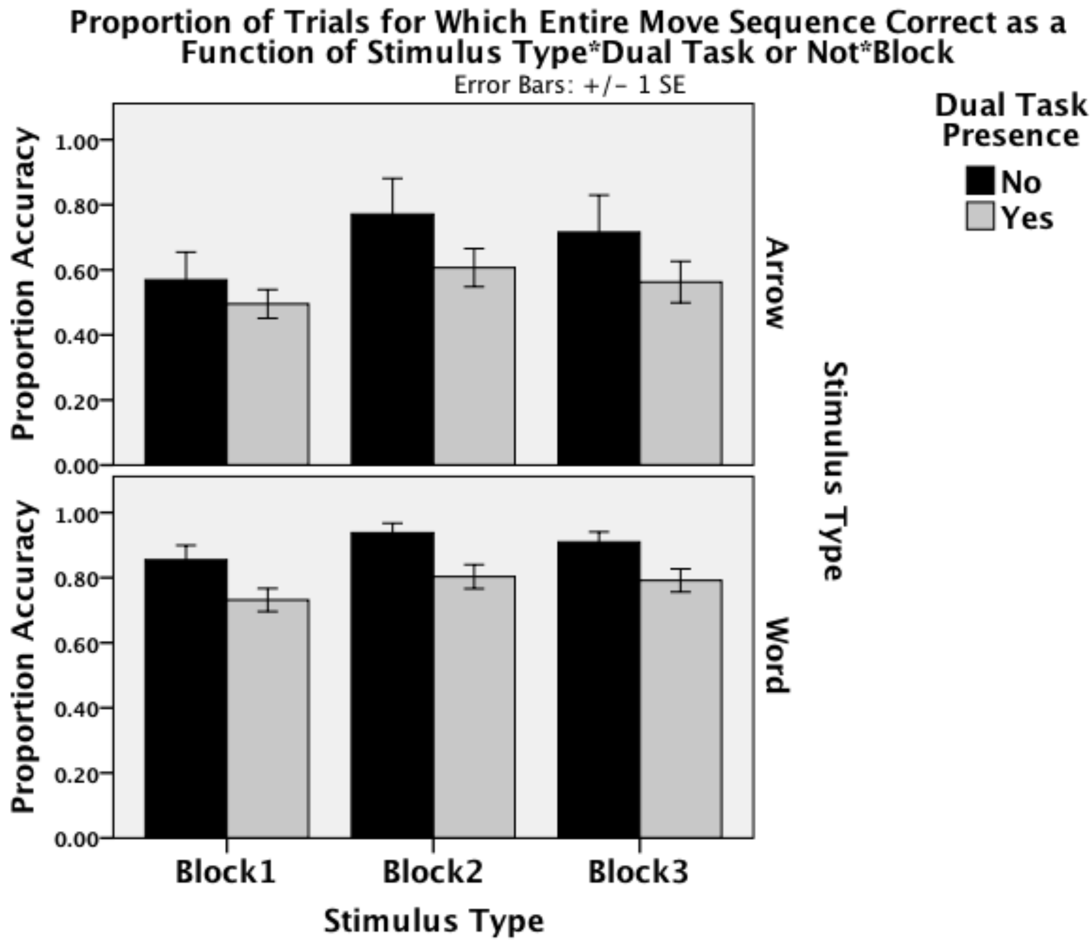

Figure 13. Experiment 4b: effect of performing two tasks at the same time. Proportion correct as a function of stimulus type, dual task presence, and block. Only the main effects of stimulus type, dual task or not, and block were significant.

Experiment 4b Discussion

Stimulus presentation time was doubled from 1250 ms to 2500 ms to provide more opportunity for subjects to acquire the more novel arrow stimuli such that the selective impact of impeding spatial rehearsal on arrows compared to words might be replicated. Accuracy of move recall for the more novel arrow stimuli did improve although it was still lower than for words

(*Mdiff* = .22). See Figure 13. Consequently, replicating Experiment 4a, under suppressed performance, no modality effects were found. However, the verbal modality effect was replicated for words. Performance declined under articulatory suppression of verbal rehearsal. Our interpretation of this result is that words were weakly mapped to the unimpeded spatial modality in LTM such that spatial rehearsal was less successful for words than when verbal rehearsal could be utilized for the simple foot tapping control. See Figure 9.

Replicating Experiment 4a, there appeared to be some impact of complex foot tapping impeding spatial rehearsal, which we could not predict because words map well onto the unimpeded verbal modality in LTM. However, this slight drop in performance can be explained by the interaction of dual task type and dual task order. Because the relatively smaller decline in performance for words for complex foot tapping occurred only in the first block, it was most likely due to a general training effect wherein verbal rehearsal was being improved upon in the first block. Because the drop in performance for words for articulatory suppression occurred across all blocks, it was likely due to the relative ineffectiveness of spatial rehearsal compared to verbal rehearsal regardless of practice. See Figure 10.

In Experiment 4a, the locus of the influence of asymmetries in modality bias in LTM on success of spatial rehearsal under articulatory suppression of verbal rehearsal appeared to be at rehearsal. This verbal modality effect occurred exclusively for the retention interval and both conditions, wherein most systematic rehearsal took place. See Figure 5. However, in this experiment the locus of the verbal modality effect shifted to include stimulus presentation wherein encoding takes place. Consequently, the interaction of stimulus type, dual task type, and dual task timing was not significant. See Figure 9. When arrows were removed from the analysis, the interaction became marginally significant. However, the verbal modality effect clearly occurred at stimulus presentation as well as at the rehearsal-weighted retention interval, when compared to the simple foot tapping control. See Figure 11.

We suspect that due to doubling stimulus presentation from 5 s to 10 s subjects had more opportunity to rehearse at stimulus presentation. This post-hoc interpretation comports with the hypothesis that pre-existing modality bias in LTM for words and arrows was incorporated into WM representations, such that subsequent rehearsal of those representations in particular modalities was impacted by such modality-bias. In Experiment 4a, when subjects were less likely to rehearse during stimulus presentation due to shorter stimulus presentation time, performance would have been reliant on rehearsal during the subsequent retention interval. Such rehearsal would have benefited from no modality of rehearsal being impeded so that no verbal modality effect would have been found at encoding. In Experiment 4b, when subjects likely rehearsed at stimulus presentation, items would have been reinforced during rehearsal while a modality was impeded, reinforcing asymmetries in representations resultant from pre-existing biases in LTM for the unimpeded modality.

Discussion of Self-reported Rehearsal Strategies and Systematic Error

Our interpretation of the modality effects discussed so far is contingent on subjects' favoring modalities of rehearsal that are not dual task-impeded. Frequency counts of subjects' self-reported use of verbal, spatial, and dual rehearsal in both modalities indicate that subjects favored the unimpeded modalities when verbal rehearsal was impeded by articulatory suppression and spatial rehearsal was impeded by complex foot tapping. See Figures 14-21.

Various post-hoc statistical analyses were conducted to examine if changes in self-reports depended on experimental manipulations, and were not arbitrary.

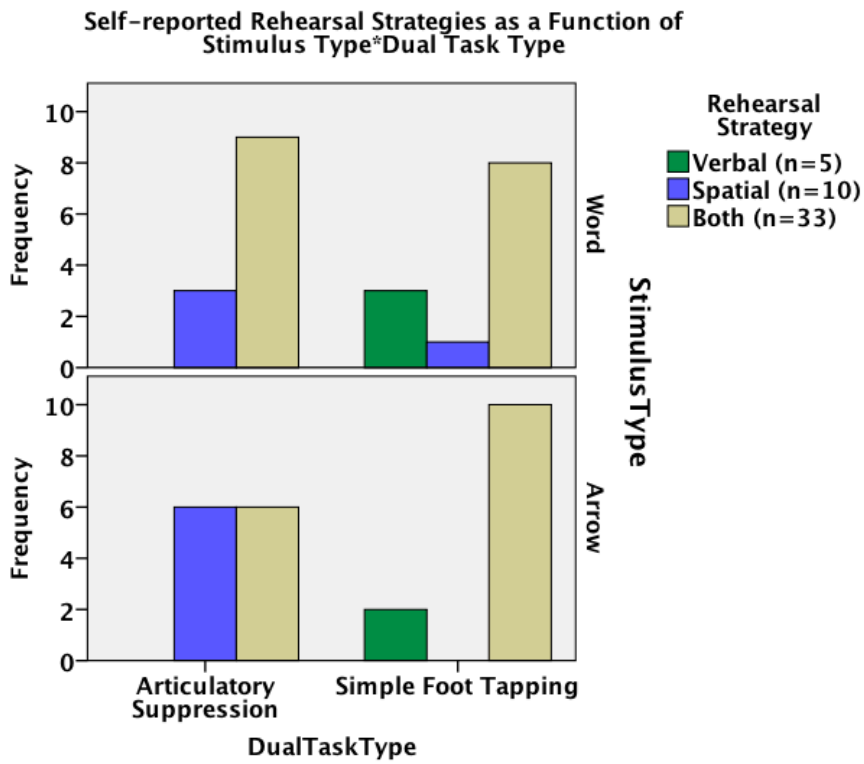

Figure 14. Experiment 2: rehearsal strategies and stimulus preference. Graph of frequencies for subjects' self-reported use of either (a) verbal, (b) spatial, or (c) both modalities in their rehearsal strategies, as a function of stimulus type and dual task type.

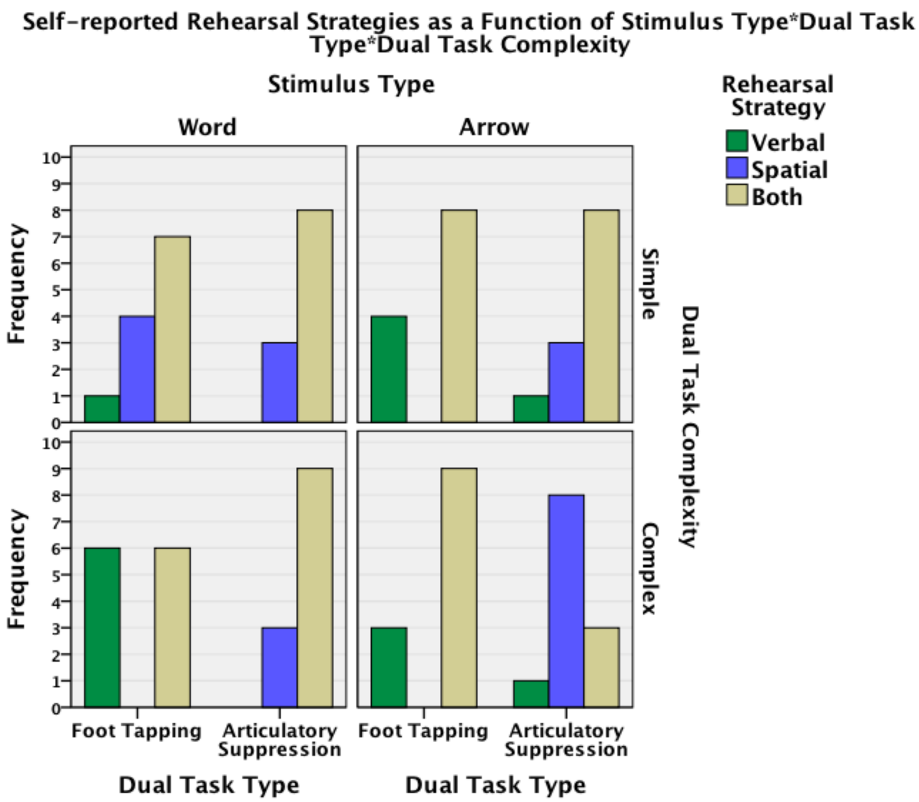

Figure 15. Experiment 3: rehearsal strategies. Graph of frequencies for subjects' self-reported use of either (a) verbal, (b) spatial, or (c) both modalities in their rehearsal strategies, as a function of stimulus type, dual task type, and dual task complexity.

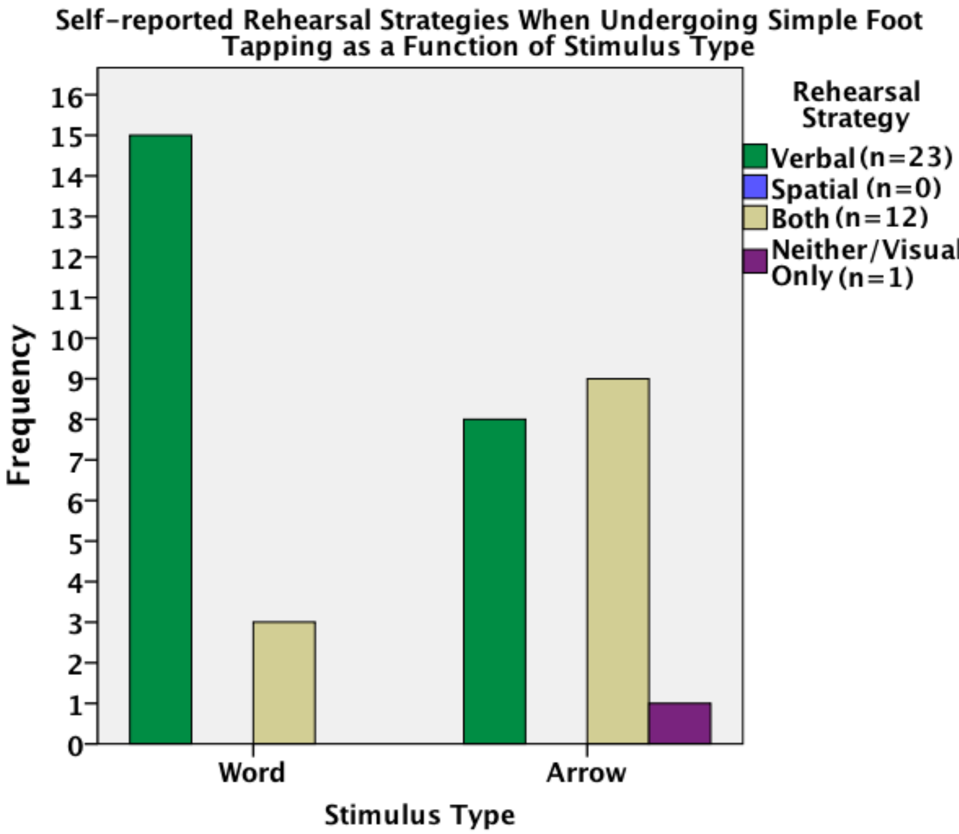

Figure 16. Experiment 4a: rehearsal strategies. For simple foot tapping control: graph of frequencies for subjects' self-reported use of either (a) verbal, (b) spatial, (c) both modality, or (d) neither modalities (visual) in their rehearsal strategies, as a function of stimulus type.

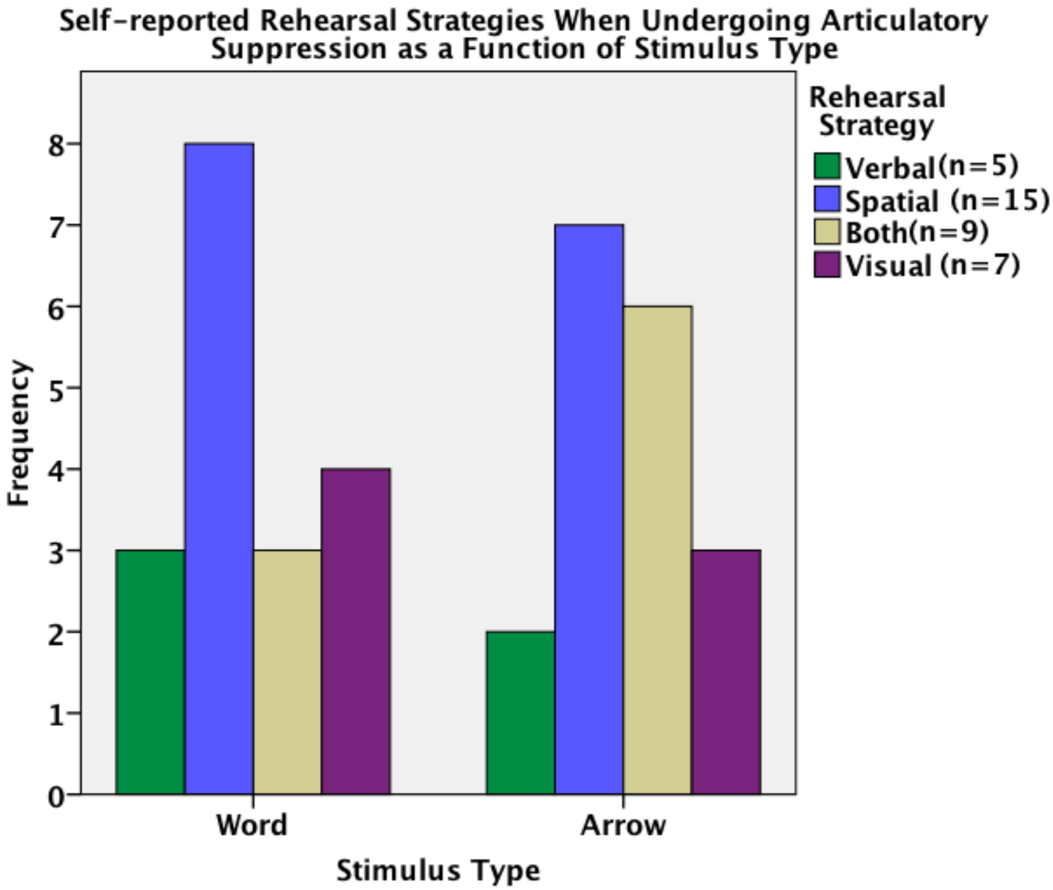

Figure 17. Experiment 4a: rehearsal strategies. For articulatory suppression: graph of frequencies for subjects' self-reported use of either (a) verbal, (b) spatial, (c) both modality, or (d) neither modalities (visual) in their rehearsal strategies, as a function of stimulus type.

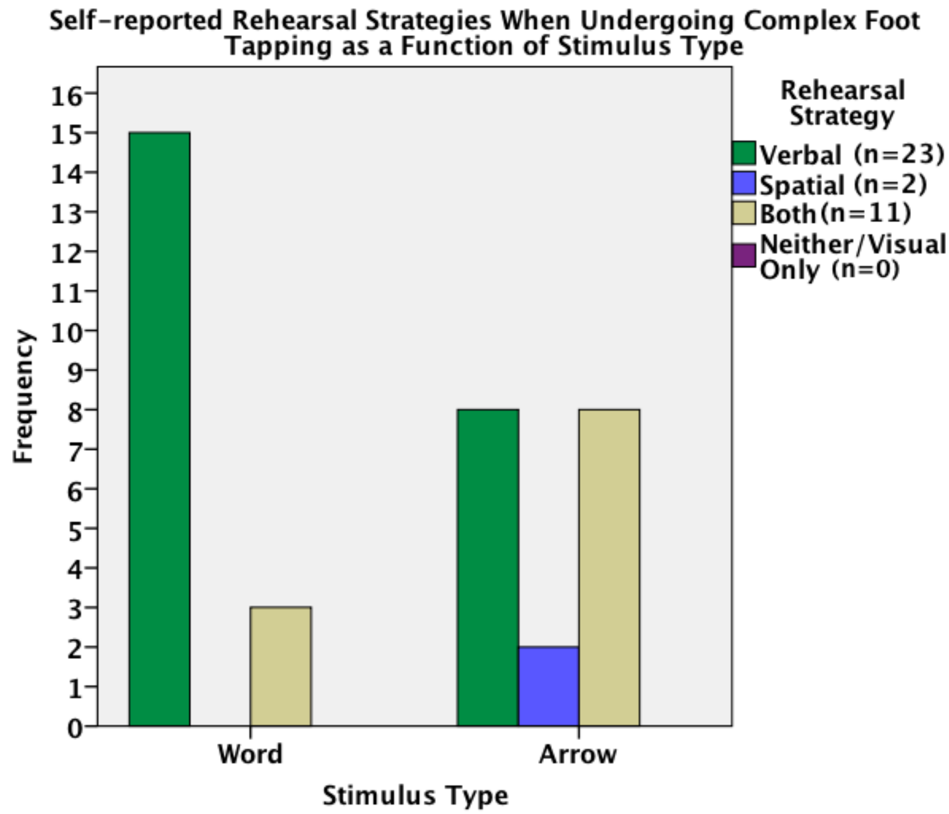

Figure 18. Experiment 4a: rehearsal strategies. For complex foot tapping: graph of frequencies for subjects' self-reported use of either (a) verbal, (b) spatial, (c) both modality, or (d) neither modalities (visual) in their rehearsal strategies, as a function of stimulus type.

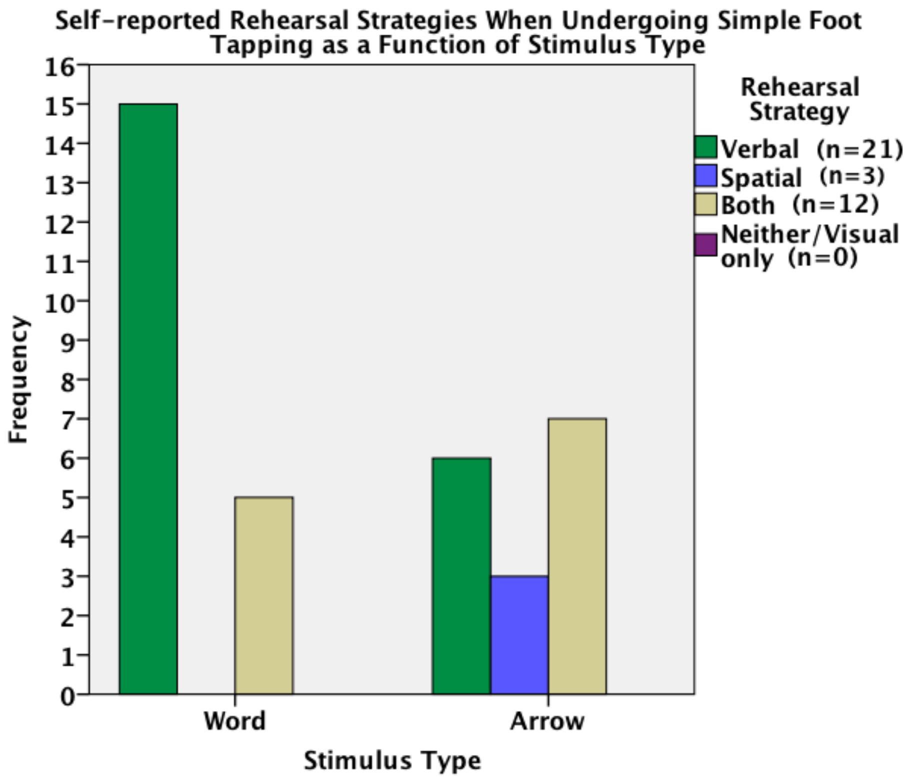

Figure 19. Experiment 4b: rehearsal strategies. For simple foot tapping control: graph of frequencies for subjects' self-reported use of either (a) verbal, (b) spatial, (c) both modality, or (d) neither modalities (visual) in their rehearsal strategies, as a function of stimulus type.

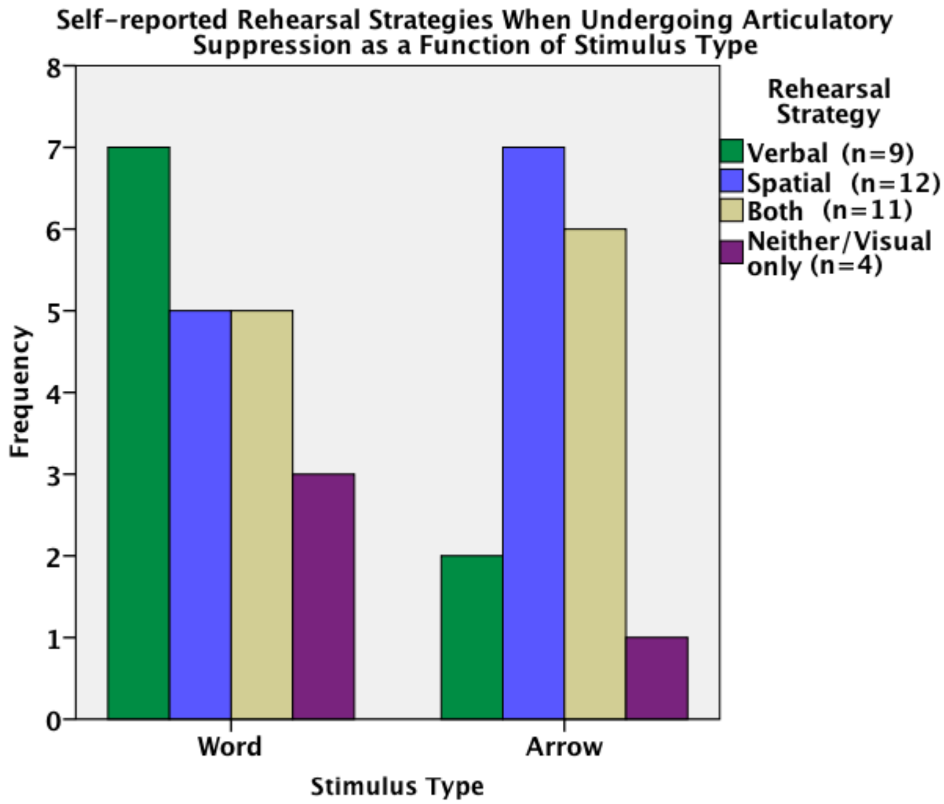

Figure 20. Experiment 4b: rehearsal strategies. For articulatory suppression: graph of frequencies for subjects' self-reported use of either (a) verbal, (b) spatial, (c) both modality, or (d) neither modalities (visual) in their rehearsal strategies, as a function of stimulus type

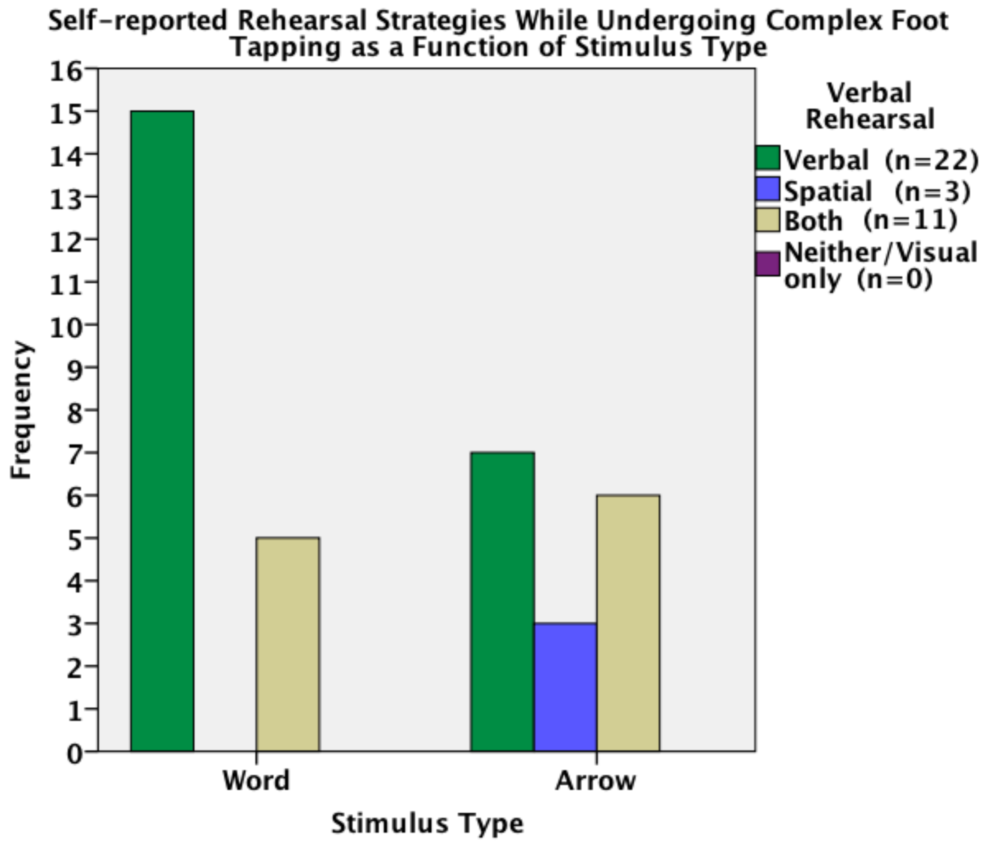

Figure 21. Experiment 4b: rehearsal strategies. For complex foot tapping: graph of frequencies for subjects' self-reported use of either (a) verbal, (b) spatial, (c) both modality, or (d) neither modalities (visual) in their rehearsal strategies, as a function of stimulus type.

In Experiments 2 and 3, wherein robust modality effects were found, subjects were significantly more likely to report using a dual rehearsal strategy. The same bias towards dual rehearsal was found previously in this paradigm for verbal and spatial stimuli when no dual tasks took place (Schneider, et al., 2011). By default, rehearsing in both modalities means that when a modality is impeded, the unimpeded modality will always be used. Consistent with the interpretation that processing resources were more constrained in Experiments 4a and 4b, subjects were significantly more likely to report using only one modality of rehearsal. See Appendix G. Subvocalized rehearsal of a sequence is overly practiced, whereas forming a spatial path on the matrices is a relatively novel strategy. Consequently, in Experiments 4a and 4b, when controlled processing was more resource-limited subjects favored verbal rehearsal.

Demonstrating the veracity of dual tasks for impeding rehearsal modalities, regardless of the bias towards dual rehearsal in Experiments 2 and 3, and the bias towards verbal rehearsal in Experiments 4a and 4b, subjects were significantly more likely to report including a spatial component than a verbal component in their rehearsal for articulatory suppression. Conversely, they were significantly more likely to report including a verbal component than a spatial component in their rehearsal for complex foot tapping. See Appendix H and Figures 22-25. Thus, the dual task-impeded modality consistently predicted a bias towards rehearsal in the alternate, unimpeded modality.

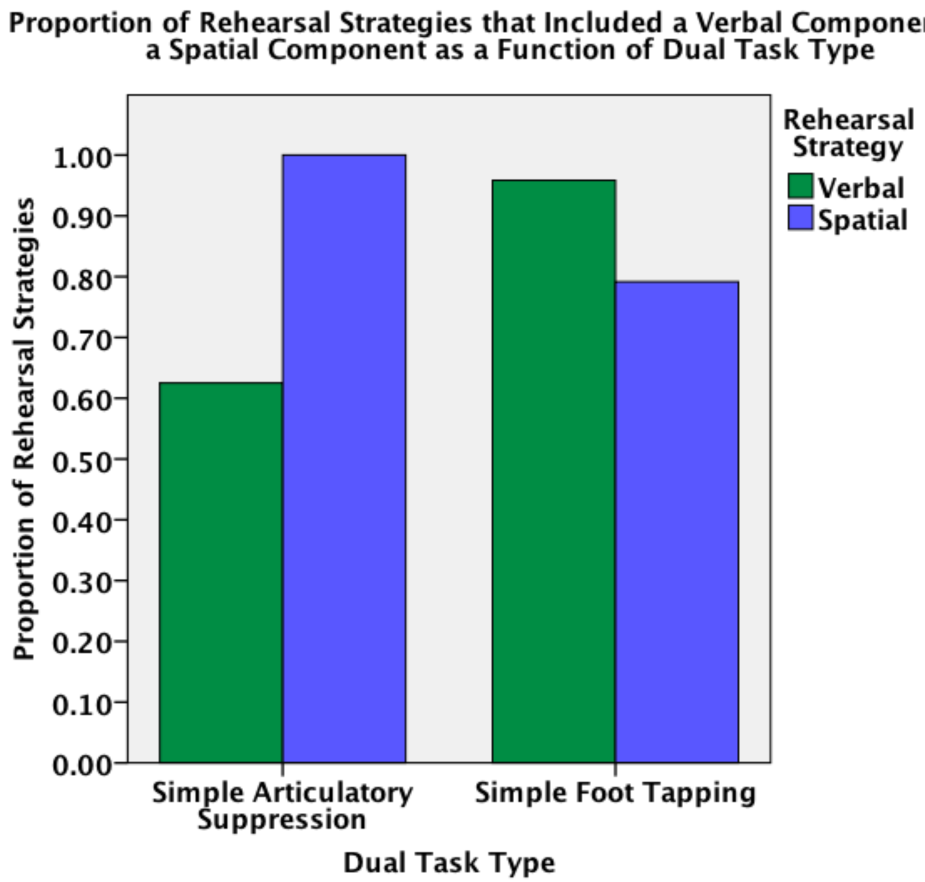

Figure 22. Experiment 2: rehearsal strategies. Proportion of rehearsal strategies that included a verbal component and a spatial component as a function of dual task type.

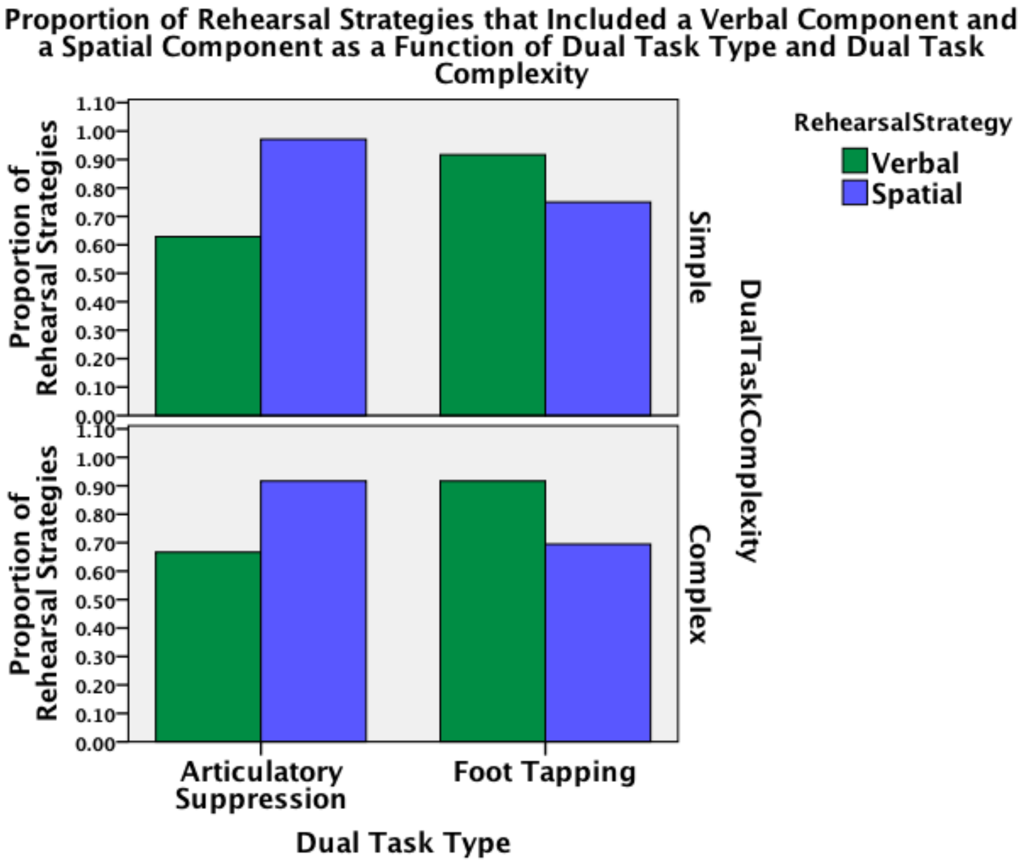

Figure 23. Experiment 3: rehearsal strategies. Proportion of rehearsal strategies that included a verbal and a spatial component as a function of dual task type and dual task complexity. Only the interaction of dual task type and rehearsal strategy was significant.

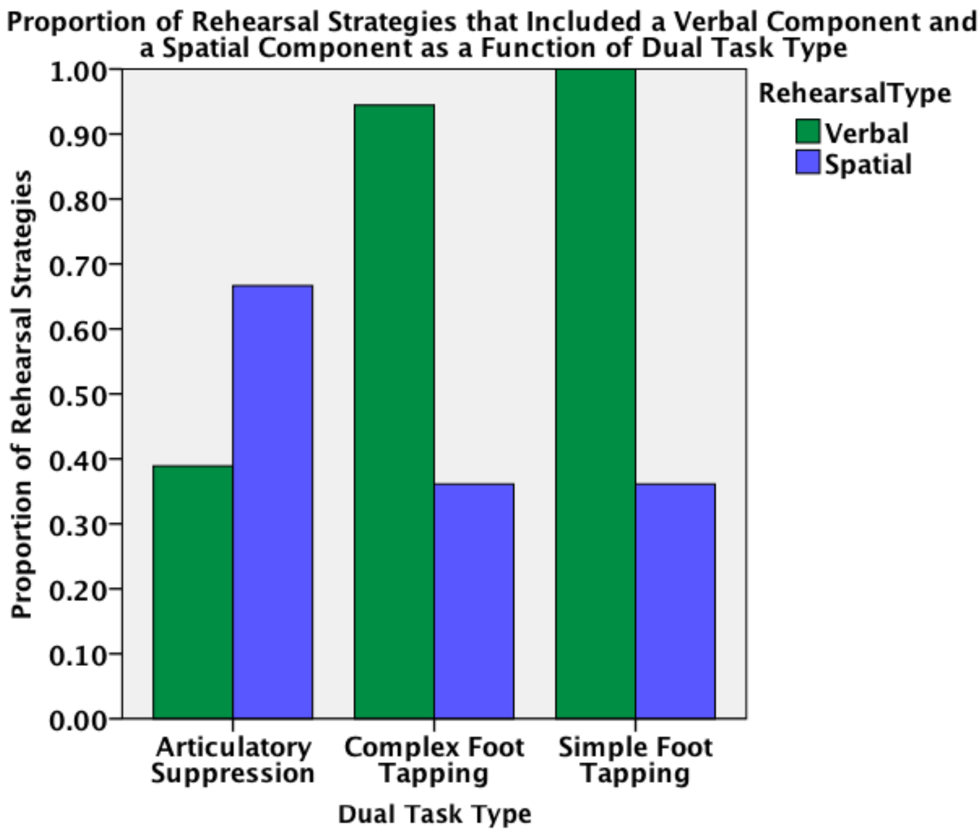

Figure 24. Experiment 4a: rehearsal strategies. Proportion of rehearsal strategies that included a verbal and a spatial component as a function of dual task type.

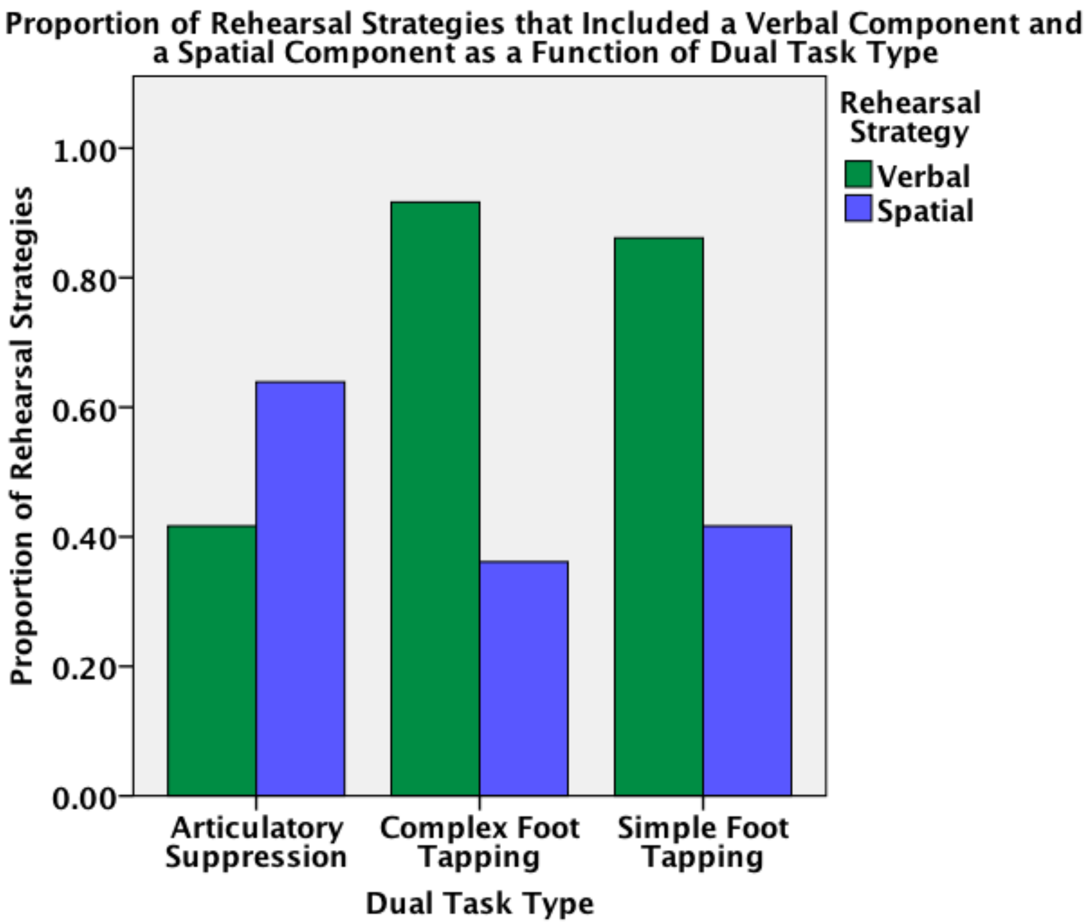

Figure 25. Experiment 4b: rehearsal strategies. Proportion of rehearsal strategies that included a verbal and a spatial component as a function of dual task type.

The proportion of incorrect trials was examined within which the rest of the moves were correct after the first error. In Experiments 2 and 3, this error was significantly more associated with verbal rehearsal than with strategies that include spatial rehearsal. See Appendix C for a demonstration of this error. After the first error, the subvocalized move sequence will result in landing on the wrong coordinates. Therefore, this error type is associated with verbal rehearsal because spatially rehearsing a visualized pathway on the matrices likely corrects the tendency to continue enacting subvocalized moves during the response once the first error had been made. In

Experiments 4a and 4b however, spatial rehearsal was not as effective in correcting this error type resulting in comparable error counts regardless of rehearsal modalities. This finding suggests that the reason subjects did not favor the more novel spatial strategy in Experiments 4a and 4b is that it was not as viable an option. See Appendix I for statistics, and Figures 26-29.

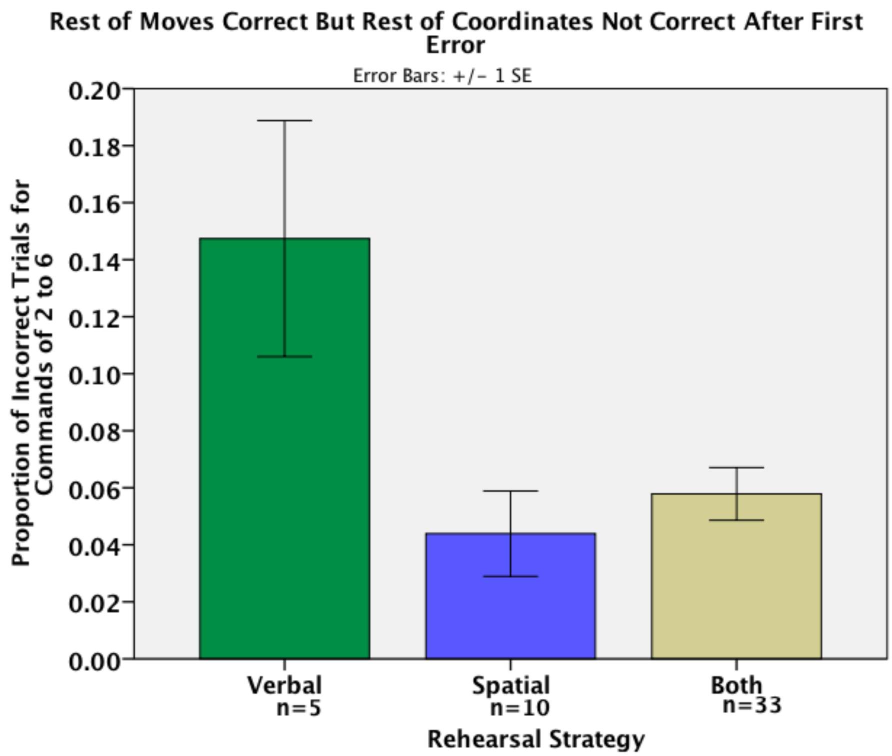

Figure 26. Experiment 2: systematic errors. After first error, proportion of incorrect trials for which the rest of the moves were correct but the rest of the coordinates were not correct, as a function of rehearsal strategy.

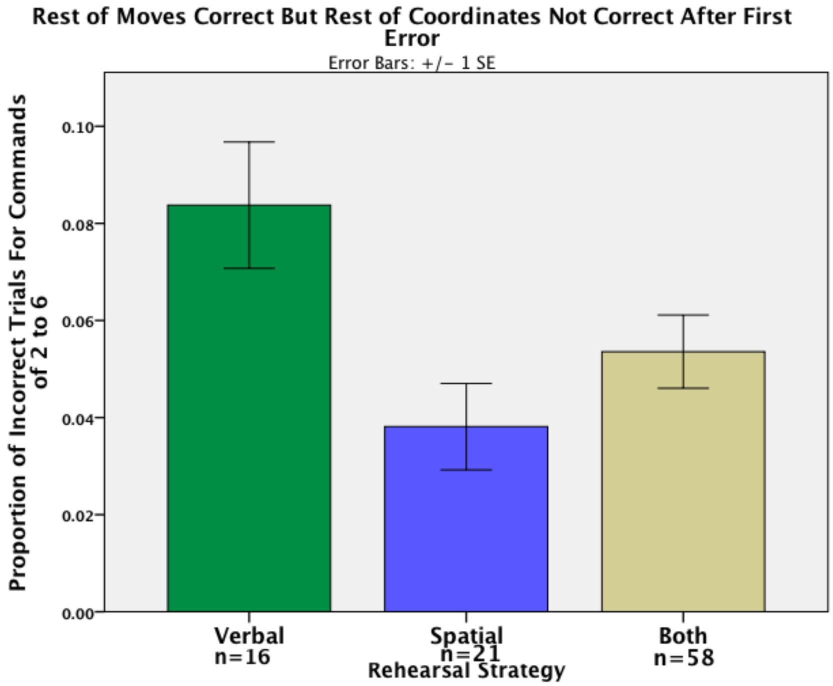

Figure 27. Experiment 3: systematic errors. After the first error, proportion of incorrect trials for which the rest of the moves were correct but the rest of the coordinates were not correct, as a function of rehearsal strategy.

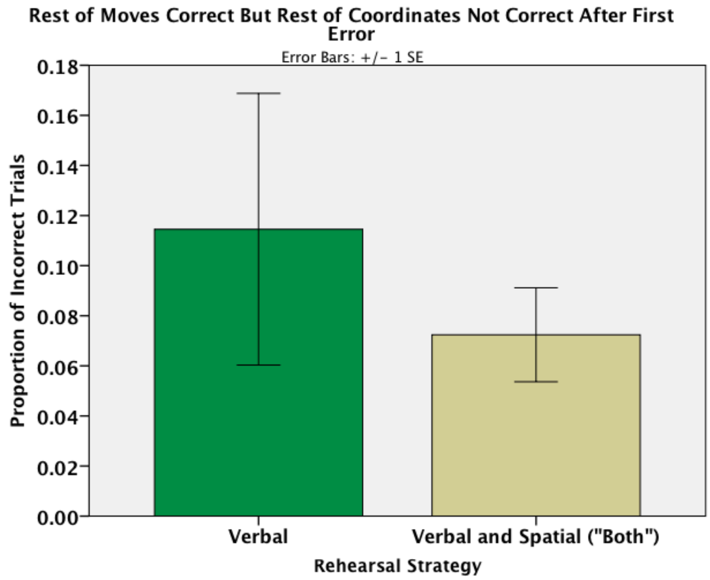

Figure 28. Experiment 4a: systematic errors. After the first error, proportion of incorrect trials for which the rest of the moves were correct but the rest of the coordinates were not correct, as a function of rehearsal strategy (verbal and both).

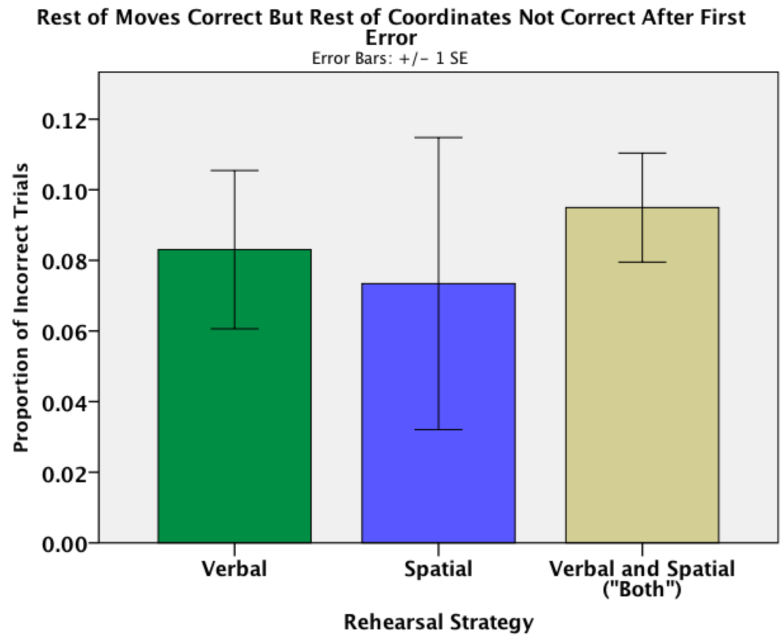

Figure 29. Experiment 4b: systematic errors. After the first error, proportion of incorrect trials for which the rest of the moves were correct but the rest of the coordinates were not correct, as a function of rehearsal strategy (verbal and both).

In Experiments 4a and 4b, instead of spatial rehearsal, a number of subjects compensated for verbal processing being impeded with a novel visual strategy of retaining snapshots of the stimuli. This novel strategy also suggests that spatial rehearsal was not as viable in Experiments 4a and 4b.

In summary, subjects' rehearsal strategies were biased toward rehearsal in the modalities that were unimpeded by dual tasks: (a) regardless of whether they naturally favored a dual rehearsal strategy or verbal rehearsal strategy, (b) regardless of how poor performance was, and (b) regardless of how low the utility of the rehearsal strategy was. This finding is particularly compelling for Experiments 4a and 4b, because each subject did all dual tasks within-subjects such that strategy changes were less likely to be arbitrary. Thus, the predicted modality effects that were found for words and arrows were likely due to success of rehearsal in the unimpeded modality.

Follow-up Experiment

An important question to be answered is whether the impact of pre-existing modality biases in LTM on rehearsal occur when rehearsal occurs after encoding has already taken place at stimulus presentation. Such a finding would suggest that declarative items maintained in WM may incorporate pre-existing biases from LTM such that subsequent operations performed on them that are also modality-biased could be impacted. Rehearsal is modality-specialized and would be affected by modality biases in the WM representations that it reinforces for subsequent recall.

For this reason, we plan on conducting Experiment 5. See Appendix D for the design. We will manipulate item load from 1 to 6 moves and significantly increase training trials to bring performance for arrows and the use of spatial rehearsal back to optimal levels. We will manipulate stimulus presentation time (e.g., from 750 ms to 1250 ms to 2500 ms to 3000 ms) with stimulus type, dual task type, and dual task timing as factors (presentation, retention interval, both, neither). We will administer questionnaires to assess when subjects rehearsed in the time course of the trial. For 750 ms stimulus presentation time, rehearsal is unlikely to occur during stimulus presentation due to time constraints. If the modality effects are not at rehearsal, then the effects of modality biases from LTM are likely on the efficiency of encoding and not on the modality bias of WM representations. If they do occur at rehearsal, then modality effects are likely incorporated into WM representations such that they impact subsequent rehearsal of such representations. The 1250 ms and 2500 ms stimulus presentation times are the stimulus presentation times for Experiments 4a and 4b, and provide the opportunity to examine whether prior results for dual task timing will be replicated. At 3000 ms stimulus duration, modality effects will disappear if the effects are at encoding, because more time is afforded for encoding of stimuli that are weakly mapped to the unimpeded modality of rehearsal. The modality effects will not disappear if the effects are at rehearsal, because pre-existing asymmetries in LTM should be incorporated into WM representations no matter how much time is available for encoding of the stimuli.

CHAPTER 4

General Discussion

Success of recall in these WM tasks was predicted by pre-existing asymmetries in modality bias in LTM for stimuli. If the stimuli were strongly mapped to a modality in LTM, rehearsal in that modality was more successful for recall than when stimuli were weakly mapped to a modality in LTM. Importantly, the differences in accuracy of recall were found at rehearsal and not at encoding. Therefore, it appears that modality biases in LTM were incorporated into WM representations at encoding such that subsequent rehearsal of such representations in particular modalities was also impacted. One possible explanation for the impact of pre-existing modality biases in LTM on rehearsal is that strongly mapped procedural response codes associated with modality-biased stimuli might facilitate rehearsal because rehearsal is highly procedural and modality-biased.

A caveat from this research is the importance of examining subjects' self-reported rehearsal strategies in WM tasks. Before analyzing subjects' self-reports, based on the data, we expected subjects to report verbal rehearsal for words and spatial rehearsal for arrows. Such an interpretation would explain the data but would not be accurate. Other researchers have found important information when self-reports of verbal, spatial and dual rehearsal strategies were examined for blind and non-blind subjects in a navigational matrix task. It was discovered that mixed results in the literature for the mental imagery abilities of the visually-impaired may be attributable in part to variations in the modalities in which subjects rehearse (Cornoldi, Tinti, Mammarella, Re, & Varotto, 2009; Vanlierde, & Wanet-Defalque, 2004). Without examining questionnaires, we would not have discovered that the reason for differences in performance was not due to subjects rehearsing words verbally and arrows spatially. Rather, under dual task conditions, subjects were favoring the unimpeded modality for rehearsal, regardless of stimulus type. As such, success of recall was predicted by pre-existing biases of stimulus type for the unimpeded modality in LTM.

The title of this thesis is “A potential new locus of WM modality effects”. Traditionally, WM modality effects are found when performance drops when rehearsal of one task and processing of another task occur in the same modality but not when they are conducted in different modalities. Of debate is whether or not such effects indicate the existence of specialized mechanisms for verbal and visuospatial rehearsal within WM (Baddeley, 2012). Given that (a) the impact of pre-existing modality biases in LTM is on rehearsal in our experiments, and (b) it is debatable that such rehearsal is facilitated within WM, the modality effects that were found in these experiments may not be considered to be “WM” modality effects.

The contribution of this research might be better characterized as contributing to our understanding of the nature of WM representations themselves. It is acknowledged by most modern models of WM that WM representations (including items, and the operations performed on such items) consist of recruited LTM (Anderson, 1983; Baddeley, 2012; Cowan, 2005; Oberauer, 2010; Ruchkin, Grafman, Cameron, & Berndt, 2003). It not unreasonable to posit that properties of LTM, such as asymmetries in mapping of stimuli to modalities might be dynamically incorporated into declarative items maintained in WM. The important implication of declarative items containing asymmetrically mapped response code is that pre-existing modality bias in LTM may not just impact encoding. It may also impact performance depending on the modality of the operations performed on such representations once they are encoded. This series of experiments suggests that such operations include rehearsal, an activity that is highly modality-specialized.

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Appendix A

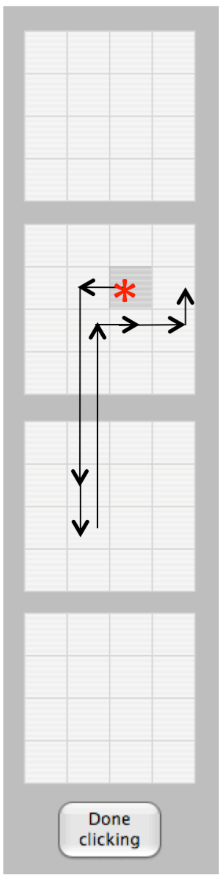
TABLE OF EXPERIMENTS

No.	Research Question	Status
1	Do novel arrow stimuli require more processing time than words (double presentation of move sequence) for performance to be comparable to words?	Complete*
2	Is the verbal modality effect stronger for words than arrows under articulatory suppression?	Complete
3	Is the verbal modality effect replicated? Is the spatial modality effect stronger for arrows than words under complex foot tapping?	Complete
4a	Are the verbal and spatial modality effects replicated? Is the locus of the impact of pre-existing modality biases in long-term memory on recall at encoding or at rehearsal?	Complete
4b	Is the finding regarding the locus of the impact of pre-existing modality biases in long-term memory on recall replicated? Will doubling presentation time for each stimulus improve performance for the novel arrow stimuli?	Complete
5	Do the modality effects occur at rehearsal when rehearsal occurs after stimulus presentation? When ms stimulus duration is manipulated: (a) At 750 ms there should be no opportunity for rehearsal at stimulus presentation. Do the modality effects still occur at the retention interval because modality biases are incorporated into WM representations at encoding such that they influence subsequent rehearsal of such representations at the retention interval? (b) At 1250 ms and 2500 ms, when the dual tasks only occur at stimulus presentation, do the modality effects only occur when rehearsal occurs at stimulus presentation, confirming our post-hoc explanation of the locus of modality effects in Experiments 4a and 4b? (c) At 3000 ms, do the modality effects disappear because enough time is afforded to encode stimuli less well-mapped to a modality of rehearsal making up for less efficient encoding processes? Conversely, do the modality effects remain because modality biases in long-term memory will be incorporated into WM representations regardless of how much time is given to encode the stimuli?	Proposed*

*Referred to but not included in the thesis.

Appendix B

Below is a demonstration of the correct order of moves to be clicked with the mouse on the matrices depicted on the computer screen in response to commands. The commands, from an actual trial, are presented here in the two alternate formats – word or arrow.



WORD commands:

left one square

down one level

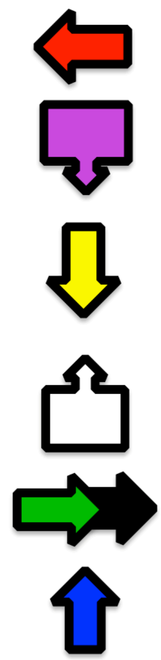
back one step

up one level

right two squares

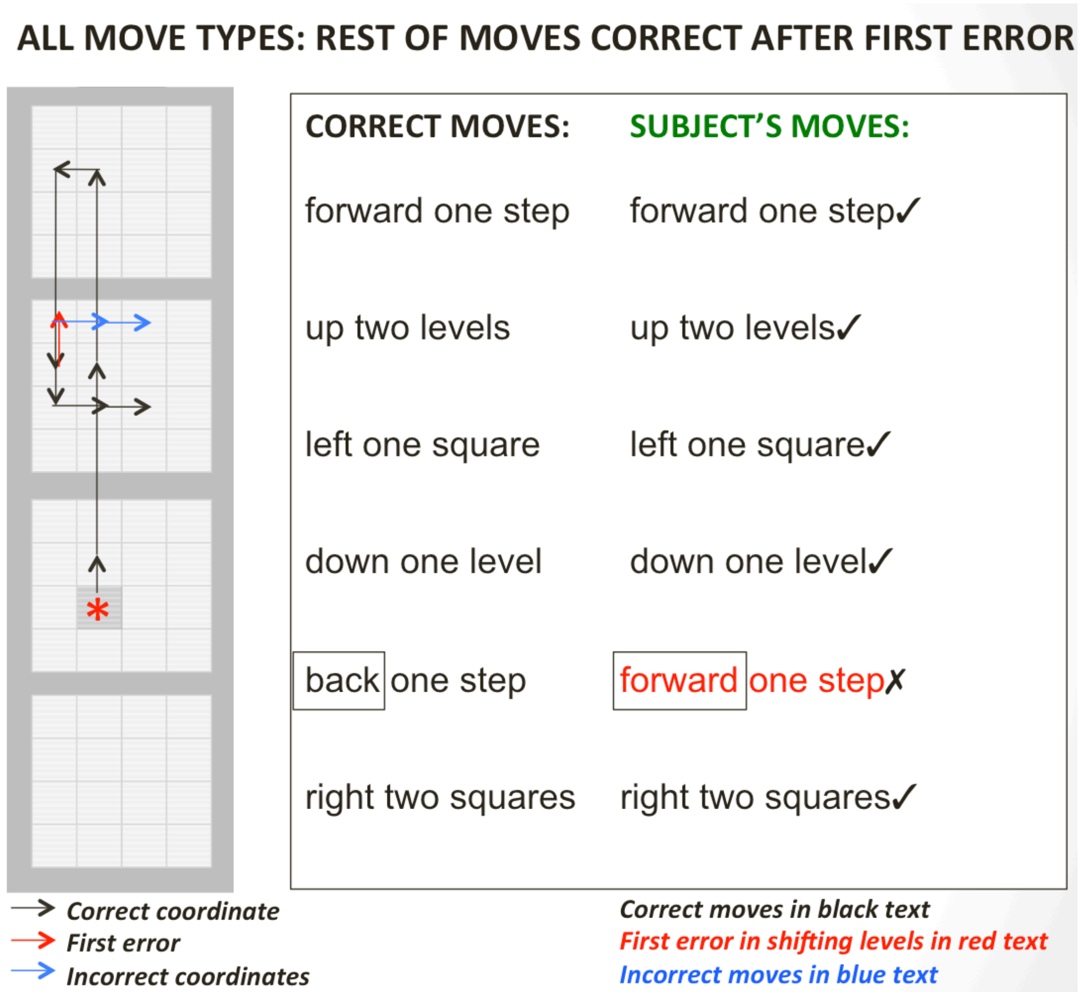
forward one step

ARROW commands:



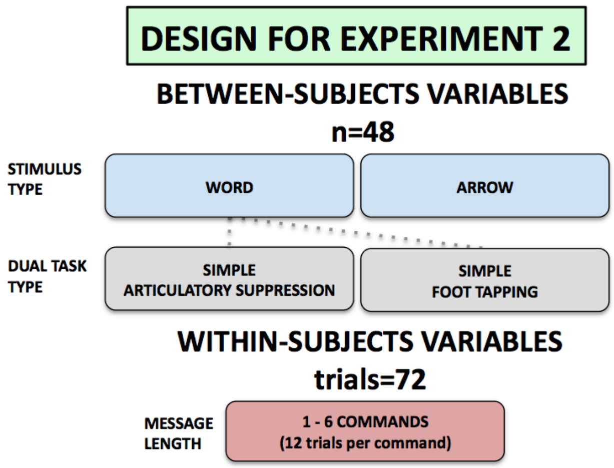
Appendix C

After the first error, rest of moves correct but rest of coordinates not correct.

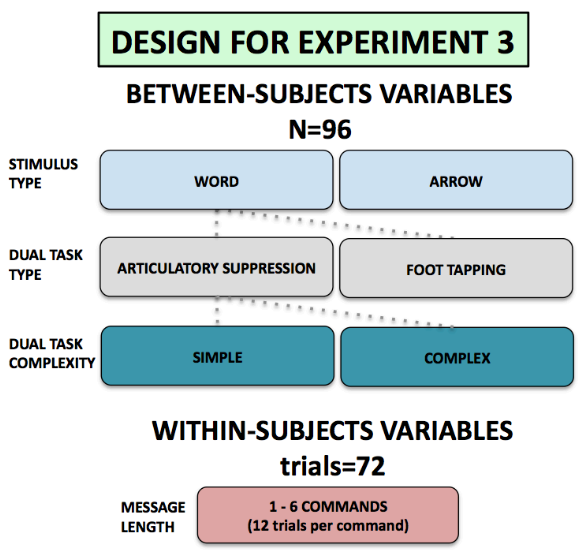


Appendix D

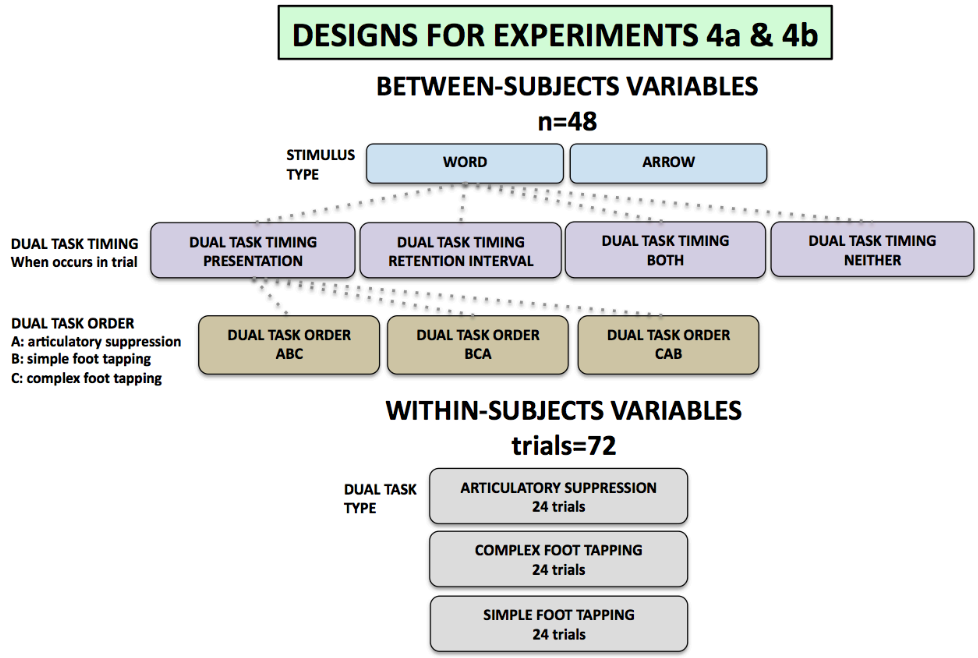
The designs and research questions for each experiment



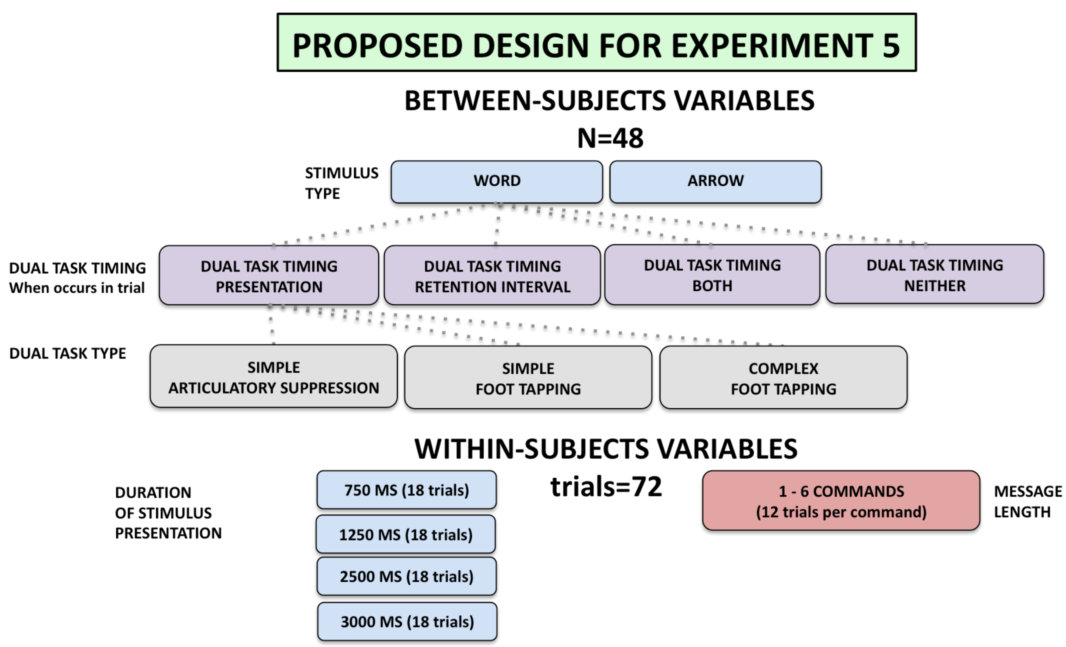
Question: Is the verbal modality effect stronger for words than arrows under articulatory suppression?



Question: Is the spatial modality effect stronger for arrows than words under complex foot tapping?
Is the verbal modality effect replicated?



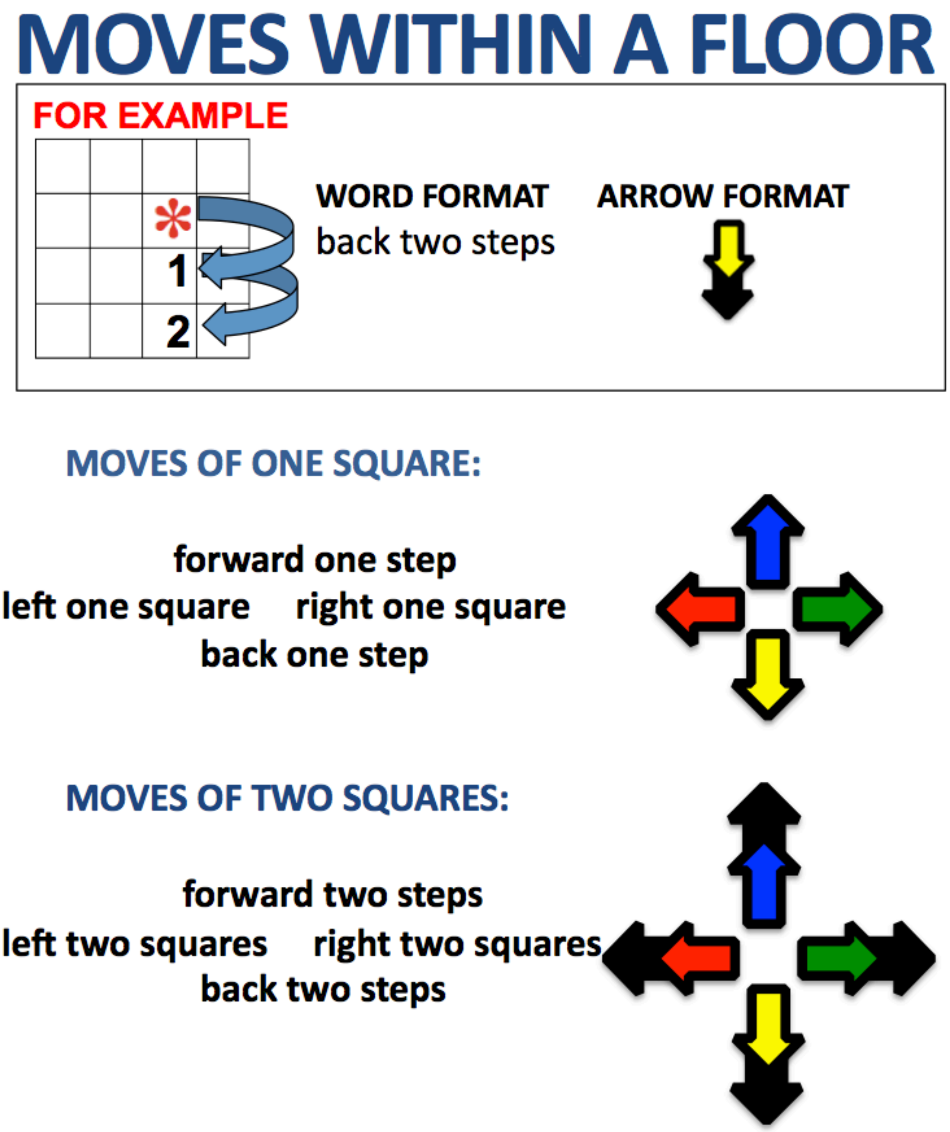
Question: Do the modality effects occur at encoding or during rehearsal?



(a) At 750 ms do the modality effects disappear because there is not enough time for rehearsal to occur at stimulus presentation?
(b) At 1250 ms and 2500 ms, do modality effects only occur when rehearsal occurs at stimulus presentation?
(c) At 3000 ms, do the modality effects disappear from item span because they are only influential at higher cognitive load when stimulus presentation is fast-paced?

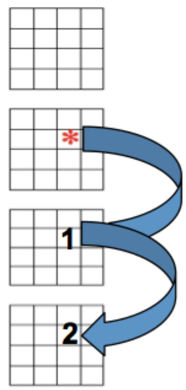
Appendix E

Below are all the possible commands for moves within and between matrices for Experiments 2 and 3. Arrows were colored.



MOVES TO DIFFERENT FLOORS

FOR EXAMPLE



WORD FORMAT
down two levels
ARROW FORMAT

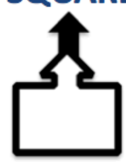
MOVES OF ONE SQUARE:

up one level

down one level

MOVES OF TWO SQUARES:

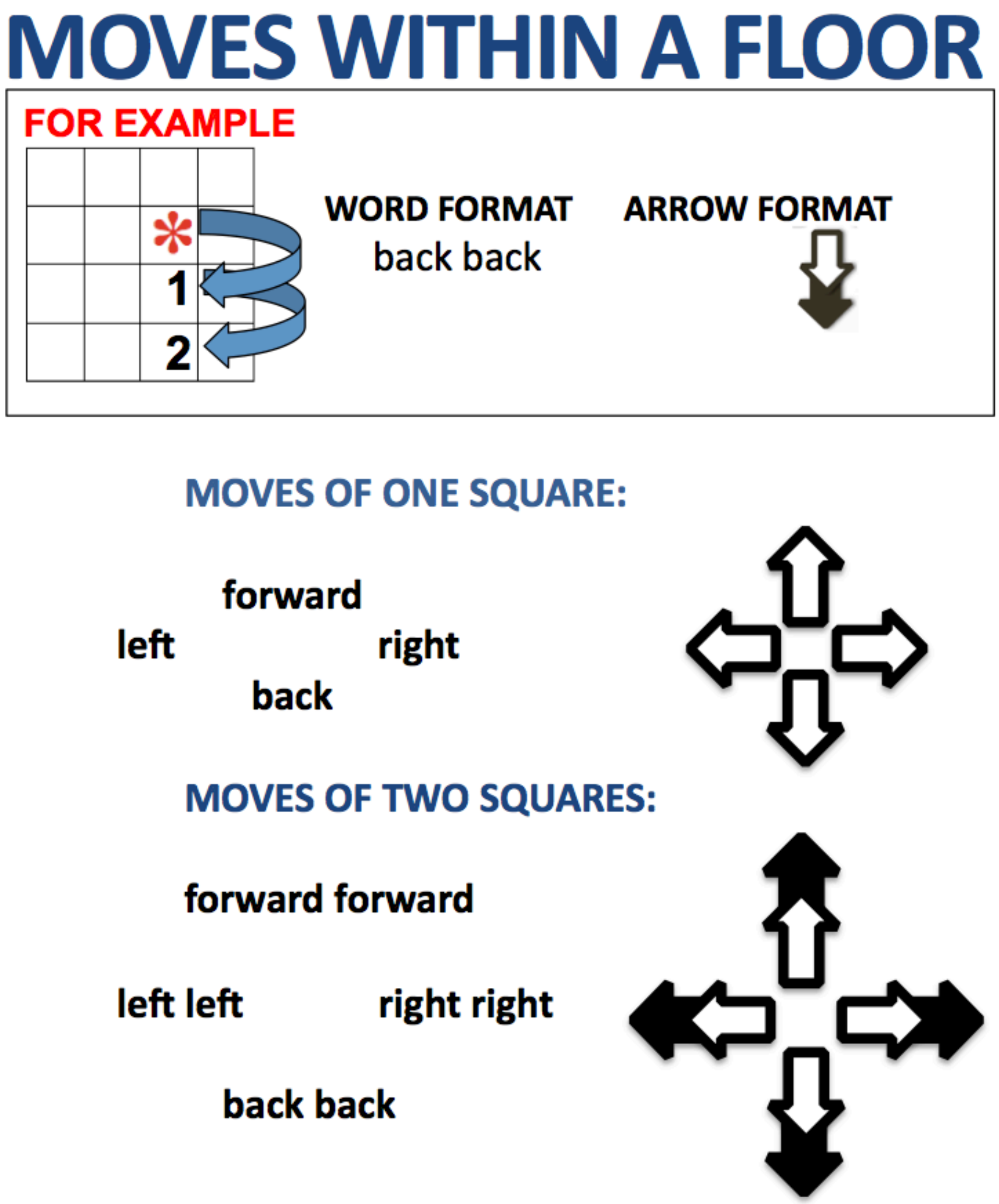
up two levels



down two levels

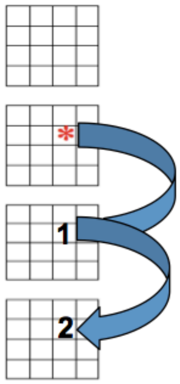
Appendix F

Below are all the possible commands for moves within and between matrices for Experiments 4(a) and 4(b). Arrows were not colored.

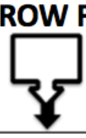


MOVES TO DIFFERENT FLOORS

FOR EXAMPLE



WORD FORMAT
down down
ARROW FORMAT



MOVES OF ONE SQUARE:

up 

down 

MOVES OF TWO SQUARES:

up up 

down down 

Appendix G

Post-hoc analysis of bias towards either (a) dual rehearsal modalities or (b) a single rehearsal modality

Analysis type. In Experiments 2 and 3, a binary logistic regression analysis using stimulus type and dual task type as predictors was conducted to predict subjects' self-reported use of both modalities (verbal and spatial) versus one modality (verbal or spatial) for rehearsal of moves. In Experiments 4a and 4b, a general estimating equations analysis was performed with exchangeable correlations between dual task type and self-reported use of both modalities (verbal and spatial) versus one modality of rehearsal (verbal or spatial).[6]

Experiment 2. Subjects were more likely to report choosing a dual modality rehearsal strategy than a single modality rehearsal strategy, Wald $\chi^2 = 6.411$, $df = 1$, $p = .011$, B = .788, OR = 2.200. The subjects' bias towards a dual rehearsal strategy occurred regardless of stimulus type or whether a particular modality of rehearsal was impeded by the dual tasks, $\chi^2 = .976$, $df = 2$, $p = .614$.

Experiment 3. Subjects were more likely to report choosing a dual modality rehearsal strategy than a single modality rehearsal strategy, Wald $\chi^2 = 4.565$, $df = 1$, $p = .033$, B = .450, OR = 1.568. Subjects' bias towards utilizing a dual rehearsal strategy occurred regardless of stimulus modality or whether a particular modality of rehearsal was impeded by the dual tasks, $\chi^2 = 1.337$, $df = 3$, $p = .720$.

Experiment 4a. Subjects were more likely to report choosing a single modality rehearsal strategy than a dual modality rehearsal strategy, Wald $\chi^2 = 4.515$, $df = 1$, $p = .034$, B = -.799. Stimulus type did not significantly contribute to the model, and was removed. Dual task type did

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[6] Across all experiments, if pure visual rehearsal of snapshots of stimuli was used, a 0 count was applied to both levels of the within-subjects rehearsal variable.

not significantly predict the use of dual versus a single modality of rehearsal, Wald $\chi^2 = 2.127$, $df = 2$, $p = .345$.

Experiment 4b. Subjects were more likely to report choosing a single modality rehearsal strategy than a dual modality rehearsal strategy, Wald $\chi^2 = 10.934$, $df = 1$, $p = .001$, B = .956. Stimulus type did not significantly contribute to the model, and was removed. Dual task type did not significantly predict the use of dual versus single modality of rehearsal, Wald $\chi^2 = .497$, $df = 2$, $p = .780$.

Appendix H

Post-hoc analysis of whether dual task type biases inclusion of a spatial or verbal component in within-subjects rehearsal strategy.

Analysis type. In all experiments, a general estimating equations analysis, which adjusted for exchangeable correlations between within-subjects inclusion of a verbal and spatial rehearsal component was conducted. Dual task type was the independent variable and rehearsal modality was the dependent variable.

Experiment 2. Subjects reported a bias towards including verbal rehearsal more than spatial rehearsal for the foot tapping task and inclusion of spatial rehearsal more than verbal rehearsal for the articulatory suppression task, Wald χ^2 = 11.283, *df* = 1, p = .001, B = -.661, OR = .516. See Figure 22.

Experiment 3. Subjects reported a bias towards including verbal rehearsal more than spatial rehearsal for foot tapping tasks and inclusion of spatial rehearsal more than verbal rehearsal for articulatory suppression tasks, Wald χ^2= 11.421, *df* = 1, *p* = .001, B = -.117. See Figure 23.

Experiment 4a. Across dual tasks, subjects reported a bias towards including a verbal component in their rehearsal strategy, Wald χ^2 = 13.666, *df* = 1, *p* < .001, B = .297. However, subjects favored inclusion of verbal rehearsal more than spatial rehearsal for foot tapping tasks and inclusion of spatial rehearsal more than verbal rehearsal for the articulatory suppression task, Wald χ^2 = 17.133, *df* = 2, *p* < .001, B = -.947. See Figure 24.

Experiment 4b. Across dual tasks, subjects reported a bias towards including a verbal component in their rehearsal strategy, Wald χ^2 = 4.301, *df* = 1, *p* = .038, B = .726. However, subjects favored inclusion of verbal rehearsal more than spatial rehearsal for foot tapping tasks and inclusion of spatial rehearsal more than verbal rehearsal for the articulatory suppression task, Wald $\chi^2 = 21.656$, df = 2, $p < .001$, B = .206. See Figure 25.

Appendix I

Post-hoc analysis of the error type – rest of moves correct but rest of coordinates not correct for moves of 2 to 6.

Analysis type. In all experiments, a between-subjects ANOVA was conducted with rehearsal strategy (verbal, spatial, both) as the independent variable and error type as the dependent variable. In Experiments 4a and 4b subjects who did no dual task were not included in the analysis to keep this analysis consistent across experiments. Additionally, in Experiment 4a, spatial rehearsal was not a level of rehearsal strategy because no subjects did pure spatial rehearsal across dual tasks.

Experiment 2 results. Subjects who reported using a pure verbal rehearsal strategy tended to get all of the moves correct after their first error, in spite of the subsequent pathway being incorrect, more than subjects who incorporated visualizing the pathway on the matrices into their rehearsal strategies, $F(1,44) = 6.229$, MSE = .020, $p = .004$, $\eta_p^2 = .217$. See Figure 26.

Experiment 3 results. Subjects who reported using a pure verbal rehearsal strategy tended to get all of the moves correct after their first error, in spite of the subsequent pathway being incorrect, more than subjects who incorporated visualizing the pathway on the matrices into their rehearsal strategies, $F(2,91) = 3.392$, MSE = .003, $p = .038$, $\eta_p^2 = 069$. See Figure 27.

Experiment 4a results. Subjects who reported using a pure verbal rehearsal strategy tended to get all of the moves correct after their first error, in spite of the subsequent pathway being incorrect, more than subjects who reported incorporating verbal and spatial modalities into rehearsal. However the difference was not significant, $F(1,34) = .601$, MSE = .006, $p = .444$, $\eta_p^2 = 017$. See Figure 28.

Experiment 4b results. Subjects who reported using a pure verbal rehearsal strategy tended to get all of the moves correct after their first error, in spite of the subsequent pathway being incorrect. However, subjects who incorporated visualizing the pathway on the matrices into their rehearsal strategies executed comparable amounts of this error type, $F(1,32) = .177$, MSE = .005, $p = .838$, $\eta_p^2 = .011$. See Figure 29.