VISUAL WORKING MEMORY SUPPORTS PERCEPTUAL STABILITY ACROSS SACCADIC EYE MOVEMENTS

BY

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DISSERTATION

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ABSTRACT

Vision is suppressed during saccadic eye movements. To create a stable perception of the visual world we must stitch together the gaps in visual input caused by this suppression. Early theories of perceptual stability proposed that information about the position of the eye could be used to cancel out changes in the retinal information resulting from a saccade. In contrast, more contemporary theories have proposed that perceptual stability relies on object correspondence across saccades, perhaps limited to the saccade target alone. According to these views, the visual system encodes features of the saccade target object into visual working memory (VWM) before a saccade is made. After the saccade, participants attempt to locate those features within a small region near the fovea. If this locating process succeeds, perceptual stability is maintained. The present study investigated directly whether perceptual stability does indeed rely on VWM. If it does, then perceived stability should be impaired when VWM is loaded with other visual information. Six experiments were conducted in which participants detected saccade target displacements while simultaneously maintaining a VWM or auditory working memory load (AWM). The VWM load negatively impacted participants' ability to detect saccade target displacements and the saccade target displacement task negatively impacted memory for VWM task items. Neither of these effects were apparent when AWM was loaded. These results support the hypothesis that visual working memory supports perceptual stability across saccadic eye movements.

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CHAPTER 1: INTRODUCTION

Saccadic eye movements are among our most frequent behaviors, occurring thousands of times each day. With each saccade, new objects are brought into foveal vision so that their features can be processed in detail. When our eyes leave an object in route to a new one, there is a brief drop in visual sensitivity called saccadic suppression (Volkman, 1986). For this reason, and despite our perception of a continuous, stable visual world, the visual system's sensory input is best described as a series of snapshots. How the visual system stitches those snapshots together into a stable perceptual experience has been a topic of research for decades.

Early theories of perceptual stability proposed that information about the position of the eye could be used to cancel out changes in the retinal information resulting from a saccade. These cancellation theories of perceptual stability describe two possible sources of information about eye position: neural inflow and neural outflow. Neural inflow, or proprioceptive information from stretch receptors in the extraocular muscles, could in principle be used to determine the change in the eyes' position during a saccade and thus to cancel out any corresponding shift in retinal information to maintain perceptual stability (Sherrington, 1898; 1918). However, there is little evidence to support this assertion as the proprioceptive signal is weak during saccades, and would reach the brain too late to modulate perception in most cases (Bridgeman, Van der Heijden, & Velichkovsky, 1994; Grüsser, et al. 1987; Wurtz, 2008).

More evidence is available for a cancellation mechanism using neural outflow to support perceptual stability. When a movement command is sent to the eyes, a secondary signal, often referred to as the corollary discharge or efference copy, is sent to visual cortex

(Sperry, 1950; von Holst & Mittelstaedt, 1950; 1971). The most compelling evidence supporting a role for neural outflow in perceptual stability comes from two simple, classic experiments. First, when the corner of our eye is tapped lightly to produce a small involuntary eye movement, we perceive a disruption in the stability of our visual perception. In contrast, when a similar small motion is made by a saccade, our visual system can discount the eye movement (thanks to the corollary discharge) and no disruption of stability is experienced (e.g., Helmholtz 1867, Bridgeman et al., 1994; Stark & Bridgeman, 1983).

While cancellation using neural outflow clearly can play a role in supporting perceptual stability across eye movements, it does not seem to have a major role under normal viewing conditions (Stark & Bridgeman, 1983). Bridgeman, Hendry, and Stark (1975) showed that participants had difficulty detecting large saccade target object displacements (up to 33% of the saccade length), suggesting a reliance on the available visual information, as opposed to just oculomotor information, for maintaining perceptual stability (see also, Bridgeman & Graziano, 1989; Hayhoe et al., 1991; Deubel et al., 1998). These findings suggest that the visual system prefers to utilize reference points from the environment, such as the relative positions of objects, to perceive stability across saccades.

Early iterations of theories describing the role of visual information in perceptual stability, known as object correspondence theories, proposed that the relative positions of any/all objects in a scene (Gibson, 1950, 1966, 1979; Haber, 1985) or a detailed representation of the visual field pre-saccade (Breitmeyer, Kropfl, & Julesz, 1982; Jonides, Irwin, & Yantis, 1982; Wolf, Hauske, & Lupp, 1978, 1980) could be integrated with the post-saccade view to create perceptual stability. More recent research has challenged the idea of a detailed transsaccadic representation, as much information seems to be lost from memory when a saccade is made (e.g., Irwin, 1992b; MacKay, 1973; O'Regan & Levy-Schoen, 1983). Memory for visual information across a saccade, or transsaccadic memory, seems to be able to maintain only a small number of items (Irwin, 1991, 1992a, 1996; Irwin & Andrews, 1996; Irwin & Robinson, 2015). Additionally, instead of precise details, transsaccadic memory maintains an abstract representation of select components of the visual field. For instance, the representation that is maintained across a saccade seems to contain relational information about the objects in view (Carlson-Radvansky, 1999; Irwin, 1991; Germeys, De Graef, Panis, Van Eccelpoel, & Verfaillie, 2004; Verfaillie, 1997; Irwin & Robinson, 2014; 2015) as opposed to precise spatial information (e.g., Bridgeman & Stark, 1979; Mack, 1970; Pollatsek, Rayner, & Henderson, 1990), and displacement of the saccade target itself or items near it during a saccade are detected more easily than displacements occurring elsewhere in the display (Bridgeman, 1981; Brune & Lücking, 1969; Deubel, 2004; Deubel, Bridgeman, & Schneider, 1998; Deubel, Schneider, & Bridgeman, 1996; Deubel, Wolf, & Hauske, 1984; McConkie & Currie, 1991). For example, Currie and colleagues (2000) found that participants were twice as likely to detect a displacement of the saccade target object during a saccade than a displacement of the background of the image. Bridgeman (1981) found a similar result when the entire image was shifted during a participant's saccade—participants only detected a displacement of the saccade target object, not of the rest of the image.

More evidence for a limited transsaccadic memory store come from studies of neural activity across eye movements. It is thought that the corollary discharge triggers a remapping of neuron's receptive fields in areas in extrastriate visual, parietal (LIP) and frontal (FEF) cortex such that neurons that will represent an object after a saccade begin representing that object before or during the saccade (e.g., Duhamel et al, 1992; Colby et al., 1995; Goldberg & Bruce, 1990; Cavanaugh et al. 2016). However, and consistent with the cognitive limitations of transsaccadic memory, Melcher (2008) demonstrated adaptation aftereffects for attended objects across saccadic eye movements, but not for objects that were unattended, again suggesting that only information about attended objects is maintained and remapped across a saccade. Indeed, only neurons maintaining information about attended objects in lateral intraparietal cortex (LIP) exhibit receptive field remapping in the anticipation of a saccade (Gottlieb, et al., 1998).

McConkie and Currie's (1996) saccade target theory provides a description of transsaccadic memory that accounts for these findings. They propose that, instead of a detailed representation of the entire scene, the visual system only encodes features of the saccade target object before a saccade is made. After the saccade, participants attempt to locate those features of the saccade target within a small region near the fovea to establish object correspondence. If the maintained saccade target features are successfully located after the saccade, perceptual stability is maintained. If the saccade target features cannot be located near the fovea after the saccade, object correspondence cannot be established, and perceptual stability is broken. Recently, Irwin & Robinson (2014) demonstrated saccade-contingent changes made to objects near the saccade target could also be detected after a saccade. These results expand the reliance of perceptual stability on object correspondence to include objects near the saccade target in addition to the saccade target itself. In sum, features of a limited number of objects, typically including the saccade target, can be maintained across a saccade, compared to the post-saccade view to establish object correspondence, and therefore used to support perceptual stability.

Regardless of how much information around the saccade target is maintained across a saccade, many accounts of transsaccadic integration, including McConkie and Currie's (1996), implicitly or explicitly assume that visual working memory (VWM) is responsible for maintaining information about the saccade target across saccades, and thus for creating perceptual stability (e.g., Carlson-Radvansky & Irwin, 1995; Hollingworth, Richard, & Luck, 2008; Irwin, 1992b; Irwin & Brown, 1987; Irwin & Robinson, 2014; 2015). Despite this assumption, few studies have directly tested whether visual working memory maintains saccade target features across saccades. If this is the case, loading VWM prior to making a saccade should lead to decrements in participants' ability to notice changes to their saccade target across a saccade, decrements to the representations of the original VWM load, or both. Hollingworth, Richard, and Luck (2008) examined the role of VWM in gaze correction (a task that relies on transsaccadic memory for the location of the anticipated saccade end-point) in their Experiment 3. Participants completed a color memory task, a gaze correction task, and a dual task condition that combined both tasks. For the color memory task, participants were briefly presented with five color patches. A test display in which one of the colors may have changed was presented afterwards, and participants responded 'same' or 'changed' to indicate if they did or did not detect a color change. The gaze correction task consisted of a circular array of eight objects centered around fixation. An object in the array temporarily expanded to cue the participant to move their eyes from fixation to that object. On some trials, while the participant made their saccade, the array rotated slightly. Participants responded 'same' if they did not detect a rotation or 'changed' if a rotation was detected. Participants' accuracy on the color memory (77.2%) and the gaze correction tasks (90.2%) significantly dropped (70.7% and 80.8%, respectively) during the dual task condition. In addition, participants took 25 ms longer to correct their gaze after their initial saccade and were more likely to correct their gaze to a distractor instead of the target when their VWM was loaded.

While VWM has been implicated in information integration and gaze correction across saccades, its role in perceived stability across saccades has not been directly investigated. Much of the research on perceptual stability has been done using a saccade target displacement detection task, which is slightly different than Hollingworth and colleagues' gaze correction task and thus may rely on a slightly different mechanism. The present study sought to further elucidate VWM's role in the perception of a stable visual world by loading VWM while participants attempted to detect changes in the position of their saccade target. In Experiment 1, we attempted to extend the results of Hollingworth and colleagues' (2008) Experiment 3 using the same color memory task and a saccade target object displacement detection task. Experiment 2 attempted to further extend the findings of Hollingworth et al. (2008) by employing a spatial task to load VWM instead of a simple feature task. Experiment 3 examined whether any performance decrements in the dual-task conditions of Experiments 1 and 2 were due to interference between the two tasks as opposed to a general dual-task cost by investigating whether the detection of saccade target displacement and a task that loaded auditory working memory (AWM) instead of VWM interfered with each other..

Experiments 4 and 5 extended the findings of the first three experiments by using a different kind of saccade target displacement task. Finally, Experiment 6 was an attentional operating characteristic (AOC) study using tasks similar those of Experiments 4 and 5,. AOC studies allow experimenters to determine the extent to which two tasks rely on the same resource by manipulating the instructions given to participants performing both tasks at the same time (Kowler, Anderson, Dosher, & Blaser, 1995; Norman & Bobrow, 1975; Navon & Gopher, 1979; Sperling & Melchner, 1978; Sperling & Dosher, 1986). An AOC design further allows experimenters to differentiate between performance decrements due to both tasks' reliance on a shared resource from decrements due to a general dual-task cost. In our case, participants were asked during some sessions to maximize their accuracy on the saccade task used in Experiments 4 and 5, during other sessions to maximize their accuracy on the VWM (Experiment 4) or AWM (Experiment 5) task, and in others to weight their performance on each task equally. Participants also performed the saccade task and the WM task in a single-task condition. If performance when the tasks were completed at the same time was worse than performance when the tasks were completed alone, this would indicate that both tasks rely on the same resource. We predicted that this would be the outcome when participants completed a VWM task and a saccade task, based on the hypothesis that the same resource, VWM, is required for both tasks. If, instead, performance on either task did not differ across single-task and dual-task conditions, this would indicate that the two tasks do not rely on the same resource. We predicted this outcome would be the case for the AWM and saccade task. The instruction to prioritize one task over the other under dual task conditions reveals the extent to which participants can selectively allocate resources to one task over the other. Several studies have shown that saccade programming causes visual attention to shift in an obligatory fashion to the saccade target location (e.g., Deubel & Schneider, 1996; Hoffman & Subramanian, 1995;

Irwin & Gordon, 1998; Kowler, Anderson, Dosher, & Blaser, 1995), so it may not be possible for participants to prioritize the saccade task over the memory task.

CHAPTER 2: EXPERIMENT 1

In this experiment, we attempted to extend the findings of Hollingworth and colleagues (2008) on gaze correction to perceptual stability per se. Participants reported whether or not their saccade target changed position across fixations while they simultaneously maintained a VWM load. Finding that these two tasks interfered with each other would provide direct evidence that VWM plays a role in perceptual stability across saccades.

2.1 METHOD

2.1.1 Participants

A power analysis was conducted based on the results of Irwin and Robinson (2015), who examined displacement perception when participants had to remember the positions of 2 vs. 4 or 2 vs. 6 items in order to determine whether one of the items had been displaced during a saccade. This presumably also depends on visual working memory, in this case for the contents of the display, and Irwin and Robinson found that displacement perception accuracy declined as the number of items that had to be monitored across the saccade increased, yielding an effect size f(U) = 2.06 in the experiment that compared performance for 2 vs. 6 items and f(U) = 1.07 in the experiment that compared performance for 2 vs. 4 items (the G*Power analysis program (Faul, Erdfelder, Lang, & Buchner, 2007) was used to calculate these effect sizes, using the F-test repeated measures ANOVA option employing partial η^2 as in SPSS). Based on these values, G*Power estimated that between 6 and 15 participants were required to achieve 95% power. To be conservative, and to allow for the occasional dropped participant, we ran more than 15.

Twenty-one University of Illinois undergraduate students participated in Experiment 1. All participants reported normal or corrected to normal vision. Participants received monetary compensation for completing two 1-hour sessions, however three participants dropped out before the second session and were not included in the analysis, leaving 18 analyzed participants.

2.1.2 Apparatus, Stimuli, and Procedure

Eye movements were recorded with an EyeLink II eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada). The tracker recorded with a temporal resolution of 500 Hz, at a spatial resolution of 0.1°, and pupil size resolution of 0.1% of pupil diameter. Stimuli were presented on a 21-inch CRT monitor with a resolution of 800 x 600 pixels and refresh rate of 85 Hz. A chinrest positioned 49 inches from the monitor was used to stabilize participants' heads. Participants responded manually with a Microsoft SideWinder USB gamepad that interfaced with the eye-tracking computer. The experiment was programmed in Experiment Builder (SR Research Ltd).

Participants completed three experimental tasks in each session: A VWM task (memory task), a saccade-target displacement detection task (saccade task), and a dual-task condition combining both the VWM and saccade target tasks (dual task). The order of the three tasks was counterbalanced across participants using a Latin square design. The block order a participant received on their second session could not match the block order of their first session. A 5-point calibration procedure was completed prior to the start of the saccade target and dual task portions of the experiment. Participants initiated each trial of all three conditions by pressing a button on the game pad while fixating a central fixation dot. During the saccade and dual task blocks, an automatic drift correction was performed upon this button press. Participants were asked to engage in articulatory suppression throughout the experiment by subvocally repeating 'ABCDABCD…'.

During memory task trials (Figure 1), a fixation cross was presented at the center of the screen, followed 1000 ms later by 5 color patches. Each color patch subtended 3.49° of visual angle and could be one of 9 colors: red (255,0,0), green (0,128,0), blue, (0,0,255), yellow (255,255,0), lavender (204,102,255), light green (0,255,128), light blue (0,255,255), orange (255,144,27), or pink (255,0,255). The color patches remained on the screen for 200 ms, disappeared for 1506 ms, and reappeared until participants made a response. On 50% of the trials, one of the color patches changed color upon reappearing. The new color was randomly selected from the 4 colors unused in the first set of color patches. Participants indicated whether they detected a change in the color patches by pressing one of two response keys. Participants completed 100 memory task trials across the two sessions (50 trials per session).

Saccade-task trials (Figure 1) began with a black fixation cross subtending 0.8° by 0.8° presented at the center of the white screen. After 506 ms, the fixation cross moved 6° or 8° to the left or right. Participants then moved their eyes to the new location of the fixation cross. While they moved their eyes, the screen blanked for 247 ms, and then the fixation cross reappeared either in the same location it was in before the saccade and the blank (20% of trials), or in a new location either 1° or 2° to the left or to the right of its pre-saccade position (20% of trials for each combination of degrees and direction moved). Participants responded 'change' if they thought the fixation cross had moved during their saccade, or 'no change' if they thought it stayed in the same location. Participants completed 60 trials per displacement condition across two sessions, for a total of 300 experimental trials (150 per session).

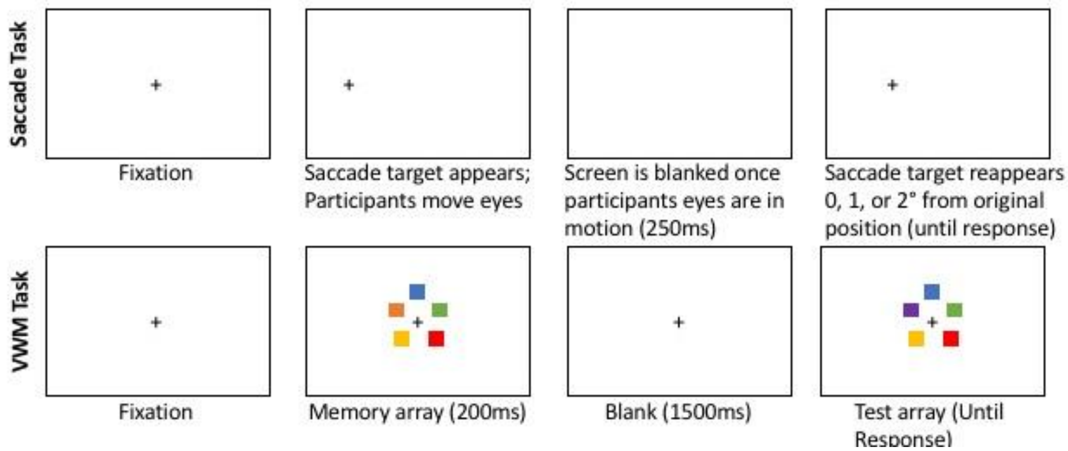


Figure 1. Saccade target displacement detection task (top) and VWM task (bottom). Participants respond 'move' or 'no move' in response to the final screen of the saccade task. Participants respond 'change' or 'no change' in response to the final screen of the VWM task.

Trials in the dual-task condition began with a fixation cross at the center of the screen for 506 ms. The VWM display (as described above) was presented for 200 ms. After its offset, the fixation cross reappeared at the center of the display for 506 ms, and the trial proceeded as described for the saccade-only trials above. Immediately after participants indicated whether or not they thought the saccade target had moved during their saccade, the VWM test display was presented at the center of the screen until response. Participants indicated if they thought one of the colors in the array had changed or not changed. Participants completed 300 trials across two sessions. There were 60 trials per saccade target displacement distance. Change and no-change VWM trials were split equally across the five types of displacement trials for a total of 150 change trials and 150 no change trials.

2.2 RESULTS

Participants were excluded from analysis if their false alarm rate was greater than their hit rate for any saccade target displacement distance (1° or 2°) on either eye movement task (saccade task or dual task). One person was excluded for this reason. Data for another person were lost due to computer malfunction, leaving 16 participants for further analysis. For each participant, individual trial data were excluded from analysis if the participant did not follow instructions or if the experimental program failed to detect that a saccade had been made or updated the display too slowly. For example, trials were excluded if the initial saccade was not directed at the saccade target location (saccade task: 14.2% of trials, dual task: 6.2% of trials). Because sensitivity to stimulus displacement depends on saccade amplitude, trials were also excluded if the saccade amplitude was less than 4° or greater than 10° (saccade task: 31.3% of trials, dual task: 18.4% of trials). To eliminate anticipatory saccades and saccades delayed by attention lapses, trials with saccade latencies less than 100 ms or greater than 500 ms (saccade task: 24.4% of trials, dual task: 16.5% of trials) were also excluded from analysis (the 500 ms cutoff roughly approximated three standard deviations from the mean saccade latency for both task conditions). The display change was not always completed during the saccade to the target location, either because the software did not detect the saccade or because the time required to detect saccade onset and to update the display was longer than the saccade duration. In these cases the display change occurred within a fixation (i.e., during the post-saccadic fixation) rather than across fixations so these data were also excluded from analysis (saccade task: 23.9% of trials, dual task: 6.9% of trials). Note that these criteria are not independent of each other (e.g., short latency saccades tended to have small amplitudes as well that did not allow enough time for the display change to occur) so any given trial might have failed to meet more than one of these criteria. After these exclusions, 56.1% of saccade task trials and 72.6% of dual task trials were available for analysis.

2.2.1 Saccade Task vs. Dual Task

Mean saccade latencies, durations, amplitudes, average velocities, and peak velocities are displayed in Table 1. In this experiment, the saccade target was displayed 6 or 8 degrees to the left or right of fixation only to prevent subjects from making predictive saccades. Any effect of the distance or direction of the saccade target from fixation were not of theoretical interest and will not be considered here. A paired t-test on saccade latencies revealed a significant effect of task condition, $t(15)=4.01$, $p=0.001$, $d=1.00$, indicating that participants initiated a saccade to the saccade target significantly more quickly under single task conditions compared to dual task conditions. Paired t-tests on saccade amplitude, $t(15)=5.19$, $p<0.001$, $d=1.29$, average saccade velocity, $t(15)=5.61$, $p<0.001$, $d=1.40$, and peak saccade velocity, $t(15)=3.71$, $p=0.002$, $d=0.93$, also revealed significant effects of task condition: participants made shorter, slower saccades under dual task conditions. These results indicate that the need to hold information in VWM interfered with saccade performance to some extent. A similar paired test on saccade duration was not significant, $t(15)=1.55$, $p=0.14$, $d=0.39$.

Table 1

Mean saccade performance measures in Experiment 1 (standard errors in parentheses)

Task	Latency	Amplitude	Duration	Average Velocity	Peak Velocity
Saccade Task	143.02 (13.12)	6.73 (0.41)	41.37 (2.09)	162.77 (10.90)	298.38 (42.15)
Dual Task	183.26 (39.92)	5.72 (0.77)	39.75 (4.40)	139.10 (14.12)	262.96 (46.08)

To determine if there was an effect of task condition on displacement detection, a 2 (task condition) X 2 (saccade target displacement distance) X 2 (displacement direction) repeated measures ANOVA was performed on the proportion of trials subjects correctly responded 'change' (means for significant effects are shown in Table 2). Proportion change responses are plotted against displacement distance and direction in Figure 2; negative x values indicate displacements in the opposite direction of the saccade (e.g., participant saccaded to the left, saccade target was displaced to the right), while positive x values indicate displacements in the same direction as the saccade. There were significant main effects of task condition, $F(1, 15)=7.05$, $p=0.017$, $f=0.66$, $p_{BIC}=0.82$, displacement direction, $F(1, 15)=94.98$, $p<0.001$, $f=2.43$, $p_{BIC}>0.99$, and displacement distance, $F(1,15)=291.83$, $p<0.001$, $f=4.27$, $p_{BIC}>0.99$. The interaction between saccade target displacement distance and displacement direction was also significant, $F(1, 15)=12.46$, $p=0.003$, $f=0.88$, $p_{BIC}=0.96$. Participants responded 'change' more frequently under single task conditions than under dual task conditions, indicating they were more sensitive to displacements of the saccade target when they did not have a VWM load. Participants were also more likely to detect displacements of the saccade target when the target moved in the opposite direction as their eye movement (i.e., 'negative' displacements) compared to displacements in the same direction as their eye movement ('positive' displacements). This increased sensitivity to negative displacements is consistent with the findings of others who have used this saccade target displacement detection task (e.g., Irwin & Robinson, 2014, 2015). Unsurprisingly, participants were more likely to detect 2° displacements than 1° displacements.

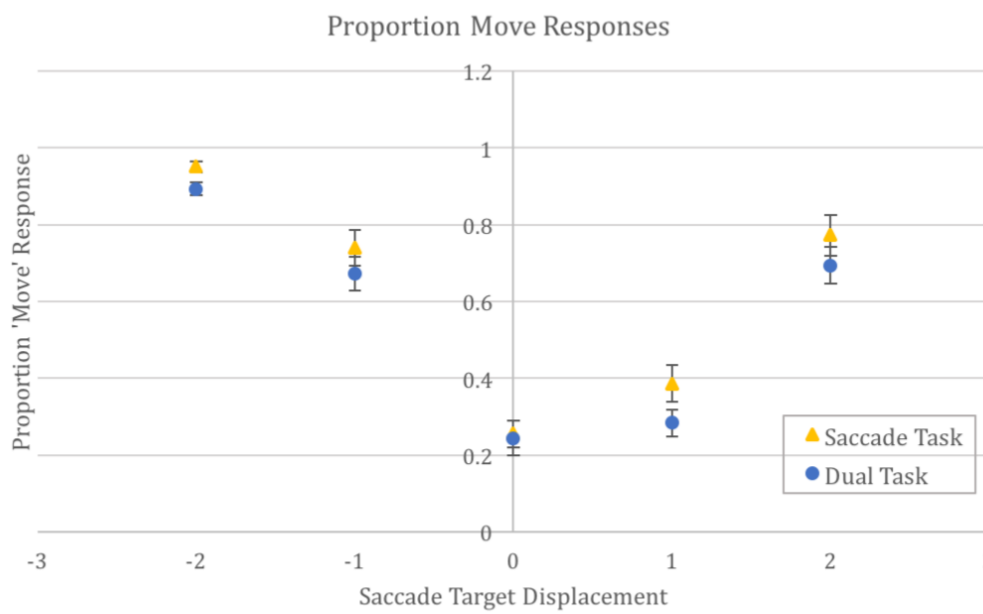


Figure 2. Proportion of trials on which participants responded 'move'. When the saccade target displacement was equal to 0, participants were no more likely to respond 'move' under single or dual task conditions. However, when the saccade target was displaced, participants were more likely to detect the displacement under single task conditions, when VWM was not loaded.

Table 2

Proportion 'Change' Response Analysis for Experiment 1

Main Effects	Mean	Standard Deviation (SD)
Task Condition		
Single Task	0.73	0.12
Dual Task	0.64	0.12
Displacement Direction		
Forward/Positive	0.53	0.14
Backward/Negative	0.82	0.10
Displacement Distance		
1°	0.53	0.13
2°	0.83	0.10
Interaction	**Mean**	**SD**
Direction X Distance		
Positive 1°	0.34	0.14
Positive 2°	0.73	0.17
Negative 1°	0.71	0.16
Negative 2°	0.92	0.05

Importantly, the proportion of change responses on trials in which the saccade target was not displaced (i.e., false alarms) did not differ between single- and dual-task conditions, (single task: mean = 0.29, SD = 0.12; dual task: mean = 0.27, SD = 0.17),

$t(15)=0.46$, $p=0.66$, $d=0.11$. This suggests participants were not biased to respond 'change' more often on dual-task trials than on single task trials or vice versa. We collapsed participants' proportion change responses across distance and direction to generate an overall hit rate (see Figure 3): Participants were significantly more likely to get a hit under single task conditions (mean = 0.73, SD = 0.11) than under dual task conditions (mean = 0.64, SD = 0.12), $t(15)=2.20$, $p=0.04$, $d=0.55$. To assess confidence in this result we calculated a Bayes Factor based on a Cauchy distribution prior scaled at r=.55 (the effect size in this experiment), which quantifies evidence in favor of the null conditionalized on the observed data and sample size (Rouder et al., 2009). The result of this test indicated the data are 1.8 times more likely to occur under the alternative hypothesis than under the null.

In sum, participants were more likely to correctly detect a displacement under single task conditions than under dual task conditions, as indicated by the significant effect of task on the proportion of change responses and hit rates, indicating that a VWM load interfered with participants' ability to perceive displacements across saccades.

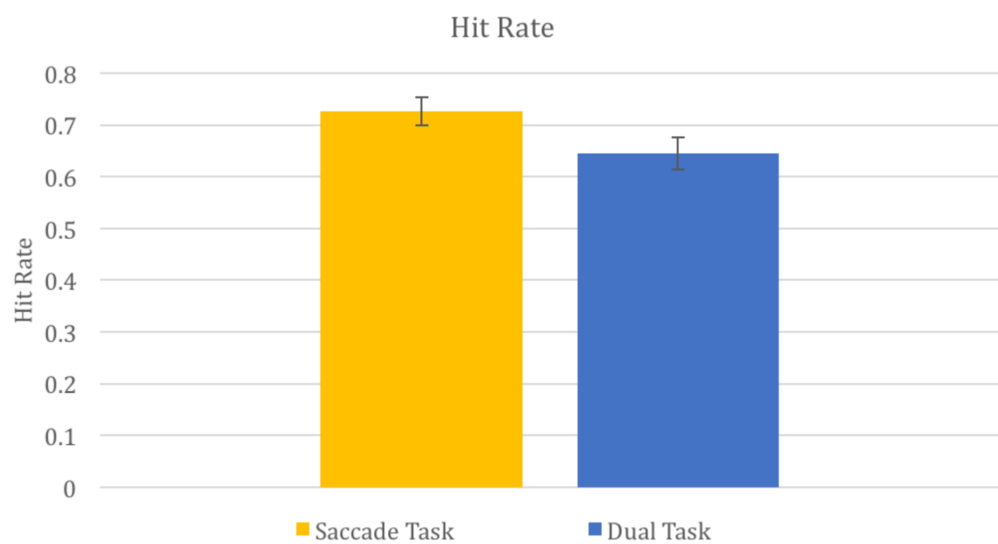


Figure 3. Hit rates collapsed across saccade target displacement distances and directions. Participants were more sensitive to displacements of the saccade target when VWM was not loaded.

2.2.2 Memory Task + Dual Task.

A paired t-test revealed that participants were significantly more likely to make an error on the memory task under dual task conditions (mean = 0.34, SD=0.07) than under single task conditions (mean = 0.30, SD = 0.07), $t(15)=3.57$, $p=0.003$, $d=0.89$. The Bayes Factor calculated for these data suggest the data are 15.76 times more likely under the alternative than under the null (Figure 4). To estimate how much memory task information was lost under dual task conditions, we calculated Pashler's K, a measure of the number of items in working memory (Pashler, 1988), using the formula K = N((hit rate – false alarm rate)/(1 – false alarm rate)), where K = capacity and N = display size (5, in this experiment). This formula is appropriate for calculating K when using a whole-display change detection procedure (Rouder, Morey, Morey, & Cohen, 2011). For the memory task alone K=2.54 items, and for the dual task, K=1.92 items. A paired t-test showed that these K values were significantly different, $t(15)=4.58$, $p<0.001$, $d=1.14$, Bayes Factor in favor of the alternative = 97.19. The difference between the Pashler's K values for the memory only condition and the dual task condition indicates a loss of approximately 0.62 items from working memory when participants were simultaneously performing the saccade target displacement detection task in addition to the working memory task.

One possible concern regarding the comparison of memory performance under single task and dual task conditions is that the interval between the presentation of the memory array and the presentation of the test array differed across these conditions. In the memory alone condition the retention interval between the memory array and the test array was fixed at 1506 ms, whereas in the dual task condition the interval varied dependent on how quickly participants responded in the displacement detection task, which preceded presentation of the test array. In this experiment the mean retention interval on dual task trials was 1845 ms (SD = 581 ms). Previous research has shown that the precision of visual working memory representations is unchanged for retention intervals at least as long as 4 seconds (Zhang & Luck, 2009), so it seems unlikely that the difference in accuracy between the memory alone and dual task conditions was due to differences in the retention interval.

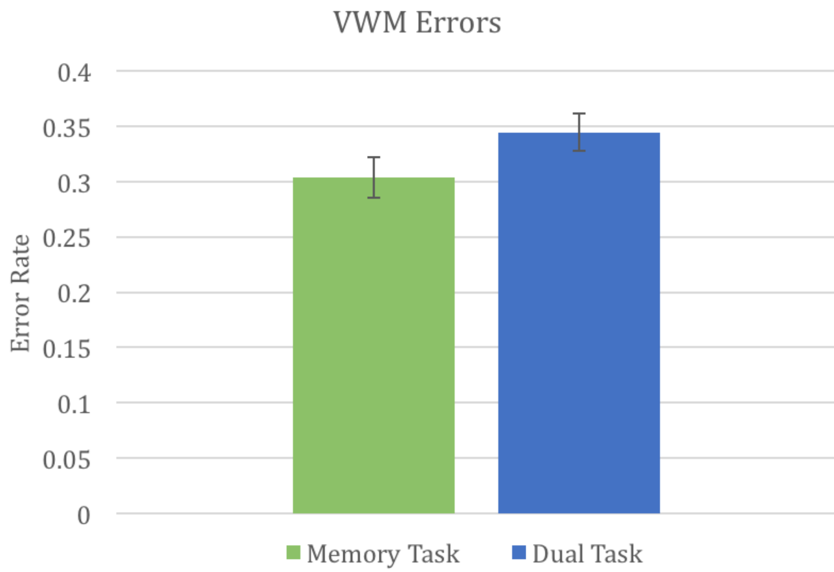


Figure 4. Participants made significantly more errors on the VWM task under dual task conditions than under single task conditions.

2.3 DISCUSSION

In this experiment, participants' performance on dual task trials was impaired compared to their performance on memory-only task trials and compared to their performance on saccade-only task trials. Subjects were less accurate in reporting that a color patch had changed colors when they also had to detect a saccade target displacement, and they were less likely to detect a saccade target displacement when they were also required to detect a color change. They were also slower to initiate a saccade and made shorter and slower saccades in the dual-task condition than in the saccade-only condition.

As described in the introduction, object correspondence theories of perceptual stability assume that we recruit VWM to help maintain a stable perception of the world across saccades (e.g., Carlson-Radvansky & Irwin, 1995; Hollingworth, Richards, & Luck, 2008; Irwin, 1992b, Irwin & Brown, 1987; Irwin & Robinson, 2014, 2015). In this experiment, the fact that the saccade displacement detection task interfered with performance on the subsequent VWM test (and vice versa) suggests that VWM resources are indeed used in the assessment of perceptual stability across saccades. Hollingworth and colleagues have found similar results using a gaze correction task (Hollingworth, Richard, & Luck, 2008).

The effect of task condition on saccade latency, amplitude, and velocity measures may imply that participants in this experiment prioritized speed over accuracy in their performance of the saccade task. Spending more time preparing a saccade leads to better performance on displacement detection tasks (Zimmermann, Morrone, & Burr, 2013). Participants under dual task conditions in this experiment spent longer at fixation before moving their eyes to the saccade target than in the saccade task condition, which may have actually reduced the deleterious effect of the working memory load to some extent and made it harder to find the interference that we found. In other words, participants' priorities may have affected the extent to which the saccade target displacement detection task and the VWM task interfered with each other. Thus, the results of this experiment may actually underestimate the degree to which a VWM load interferes with saccade target displacement detection performance.

CHAPTER 3: EXPERIMENT 2

This experiment was identical to Experiment 1 save for the VWM task that was performed. The VWM task employed in Experiment 1 could have been performed solely on the basis of featural information, namely color, because change trials involved the presentation of a color that had not appeared in the first array. In Experiment 2, participants indicated whether two memory items out of five switched places from one memory display to the next. In this way, the task required participants to bind features to locations, taxing both the feature and spatial sub-systems of VWM (Logie, 1995).

3.1 METHOD

3.1.1 Participants.

Eighteen naïve University of Illinois students participated in two experimental sessions for monetary compensation.

3.1.2 Apparatus, Stimuli, and Procedure.

The apparatus and procedure used in this experiment was the same used in Experiment 1 save for the VWM task (Figure 5). Instead of attempting to detect if one of the five colors in the memory array had changed color, participants reported if they noticed that two of the five colors had switched places. Which two colors switched places was randomly selected for each trial. On 50% of trials, no switching occurred. All other aspects of the experimental procedures were equivalent to those used in Experiment 1 (i.e., each participant completed memory task, saccade task, and dual task conditions).

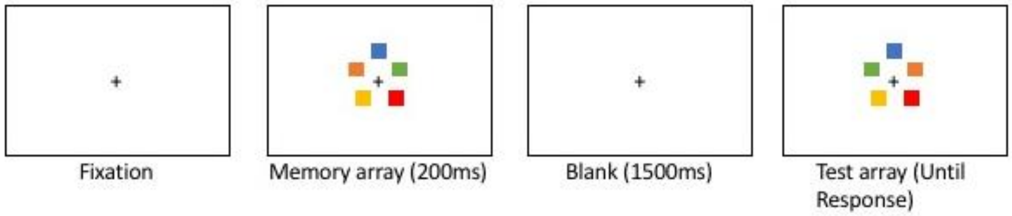


Figure 5. Spatial working memory single task condition. Participants detect whether two color patches from the memory array have traded places at test.

3.2 RESULTS

Participants were excluded from analysis if their false alarm rate was greater than their hit rate for any saccade target displacement distance (1° or 2°) on either eye movement task (saccade task or dual task). Two people were excluded for this reason. Two additional participants were excluded because under dual task conditions their displacement detection thresholds were greater than 67% of the maximum 8° saccade distance (5.4°), which is substantially poorer sensitivity than any reported in the literature. Typically, people are sensitive to saccade target displacements that are 10% - 33% of the size of their saccade (e.g., Bridgeman, Hendry, & Stark, 1975; Li & Matin, 1990). Thus, all reported analyses were conducted on 14 participants. As in Experiment 1, for each participant, individual trial data were excluded from analysis if the subject did not follow instructions or if the experimental program failed to detect that a saccade had been made or updated the display too slowly. Trials were excluded if the initial saccade was not directed at the saccade target location (saccade task: 14.0% of trials, dual task: 10.1% of trials), if the saccade amplitude was less than 4° or greater than 10° (saccade task: 33.6% of trials, dual task: 28.7% of trials), if the saccade latency was less than 100 ms or greater than 500 ms (saccade task: 31.0% of trials, dual task: 26.3% of trials), or if the display change was not completed during the saccade to the target location (saccade task: 21.5% of trials, dual task: 10.0% of trials). Following these exclusions, 54.2% of saccade task trials and 62.4% of dual task trials were available for analysis.

3.2.1 Saccade Task + Dual Task.

Mean saccade latency, duration, amplitude, average velocity, and peak velocity are displayed in Table 3. As in Experiment 1, the saccade target was displayed 6 or 8 degrees to the left or right of fixation only to prevent subjects from making predictive saccades. Any effect of the distance or direction of the saccade target from fixation were not of theoretical interest and will not be considered here. A paired t-test revealed a significant effect of task condition on saccade latency, $t(13)=5.63$, $p<0.001$, $d=1.50$, indicating participants moved their eyes from fixation significantly faster on saccade task trials than on dual task trials. A paired t-test on saccade duration was also significant, $t(13)=2.22$, $p=0.045$, $d=0.59$, indicating participants made longer-duration saccades under dual task conditions than under single task conditions. Paired t-tests on saccade amplitude, $t(13)=1.12$, $p=0.28$, $d=0.30$, average saccade velocity, $t(13)=0.33$, $p=0.75$, $d=0.09$, and peak saccade velocity, $t(13)=0.14$, $p=0.89$, $d=0.04$, were not significant.

Table 3

Mean saccade performance measures in Experiment 2 (standard errors in parentheses)

	Latency	Amplitude	Duration	Average Velocity	Peak Velocity
Saccade Task	152.59 (16.87)	6.75 (0.67)	40.65 (3.52)	162.71 (17.12)	312.55 (58.94)
Dual Task	190.38 (23.64)	6.71 (0.73)	41.85 (2.15)	160.76 (19.52)	307.59 (62.17)

To determine if there was an effect of task condition on displacement detection, a 2 (task condition) X 2 (saccade target displacement distance) X 2 (displacement direction) repeated measures ANOVA was performed on the proportion of trials participants correctly responded 'change' (Table 4). Proportion change responses are plotted against displacement distance and direction in Figure 6. As in Experiment 1, we found significant main effects of task condition, $F(1,13)=9.185$, $p=0.008$, $f=0.735$, $p_{BIC}=0.85$, displacement direction, $F(1,13)=57.21$, $p<0.001$, $f=1.83$, $p_{BIC}>0.99$, and displacement distance, $F(1,13)=123.09$, $p<0.001$, $f=2.70$, $p_{BIC}>0.99$. The interaction between saccade target displacement distance and displacement direction was also significant, $F(1,13)=41.24$, $p<0.001$, $f=1.56$, $p_{BIC}>0.99$. The interaction between task and direction approached significance, $F(1,13)=4.00$, $p=0.062$, $f=0.48$, $p_{BIC}=0.53$. Once again, participants responded 'change' more frequently under single task conditions than under dual task conditions, indicating they were more sensitive to displacements of the saccade target when they did not have a VWM load. There was a trend suggesting that participants' VWM load affected their ability to detect positive displacements better than negative displacements, but it was not significant. This marginal interaction may have been due to the fact that participants reached near-ceiling performance when the saccade target moved against the direction of their saccade (a negative displacement), leaving little room for better performance on single task trials. The interaction between direction and distance again suggests that participants were more likely to notice a saccade target displacement that occurred in the same direction as their saccade at larger (2°) displacements.

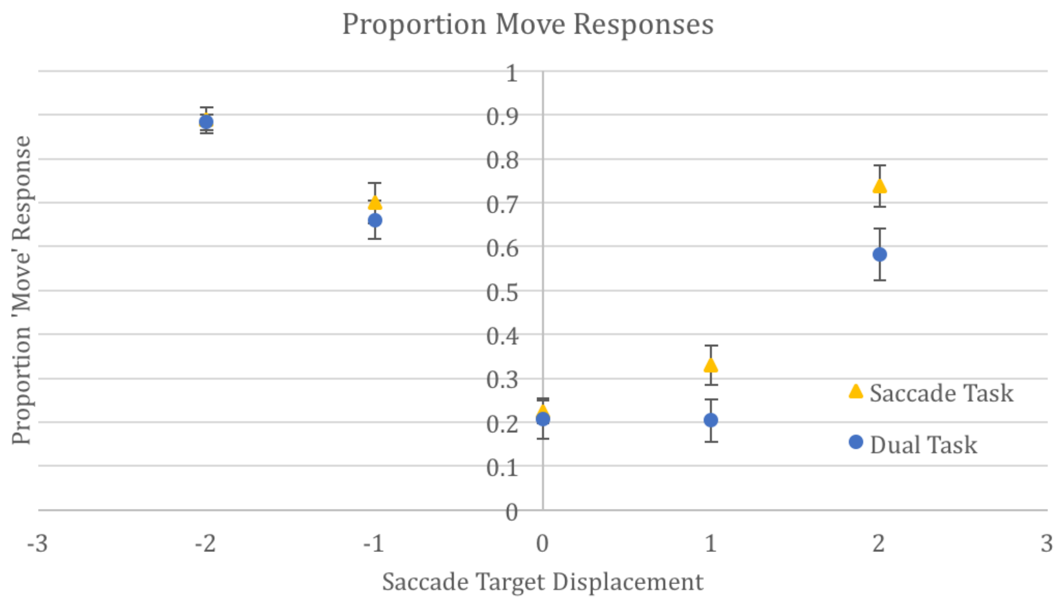


Figure 6. Proportion of trials on which participants responded ‘move’, indicating they detected a saccade target displacement. The points falling at 0 represent participants’ false alarm rate—participants were not significantly more likely false alarm under either task condition. Participants were significantly more likely to detect saccade target displacements under single task conditions.

Table 4

Proportion 'Change' Response Analysis for Experiment 2

Main Effects	Mean	Standard Deviation
Task Condition		
Single Task	0.67	0.09
Dual Task	0.58	0.12
Displacement Direction		
Forward/Positive	0.48	0.15
Backward/Negative	0.81	0.10
Displacement Distance		
1°	0.51	0.12
2°	0.77	0.09
Interactions		
Direction X Distance		
Positive 1°	0.54	0.10
Positive 2°	0.82	0.16
Negative 1°	0.49	0.09
Negative 2°	0.73	0.10
*Task X Direction**		
Single Task Positive	0.53	0.16
Single Task Negative	0.82	0.12

Table 4 (cont.)

Dual Task Positive	0.43	0.17
Dual Task Negative	0.79	0.10

*Task X Direction interaction approached significance (p=0.062)

The effect of task condition was also significant when proportion change responses were collapsed across displacement distances and directions (i.e., overall hit rate; Figure 7), $t(13)=3.28$, $p=0.006$, $d=0.87$. The Bayes Factor calculated from these data suggest the data are 8.56 times more likely under the alternative than under the null hypothesis. Participants were more likely to detect displacements of the saccade target in the single task condition (mean =0.67, SD = 0.09) than in the dual task condition (mean = 0.58, SD = 0.12). As in Experiment 1, there was no effect of task condition on false alarm rates (single task: mean = 0.26, SD = 0.08; dual task: mean = 0.23, SD = 0.17, $t(13)=0.55$, $p=0.59$, $d=0.15$, showing that participants on saccade task trials were not simply biased to respond ‘change’, but instead were more likely to detect saccade target displacements.

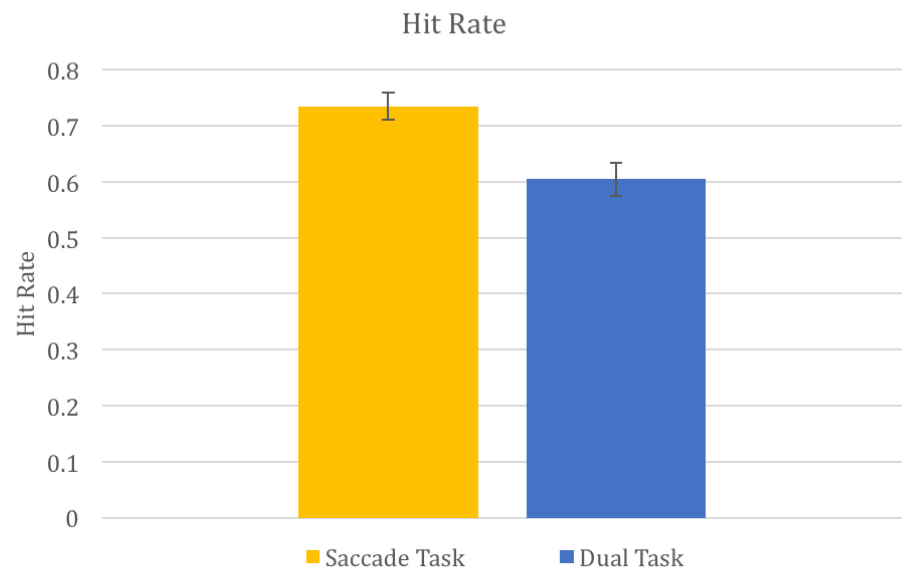


Figure 7. Hit rate across all saccade target displacement conditions were significantly higher under single task conditions than under dual task conditions. Participants with a SpWM load were significantly less likely to detect displacements of the saccade target.

3.2.2 Memory Task + Dual Task.

A paired t-test revealed that participants were significantly more likely to make an error on the memory task in the dual task condition (mean= 0.27, SD = 0.062) than in the single task condition (mean=0.191, SD = 0.057), $t(13)=5.31$, $p<0.001$, $d=1.42$. The Bayes Factor calculated for these data indicates the data are 244.32 times more likely under the alternative than under the null hypothesis (Figure 8). To estimate how much memory task information was lost under dual task conditions, we again calculated Pashler's K. Under dual task conditions, K=2.76 (SD = 0.68) items while under single task conditions K=3.51 (SD = 0.49) items, a difference of 0.75 items. A t-test on this difference was significant, $t(13)=6.17$, $p<0.001$, $d=1.45$, Bayes Factor in favor of the alternative = 944.36, indicating that participants remembered significantly more working memory items under single task conditions than under dual task conditions. However, both calculated K values are likely overestimations of VWM contents because on change trials two items changed (i.e., switched positions). Thus, participants did not need to remember all 5 memory items to perform this task successfully; remembering half of the memory items would suffice (but, see Chen & Cowan, 2013). The mean retention interval was 1941 ms (SD = 563 ms) on dual-task trials, within the range at which little difference in change detection performance is expected.

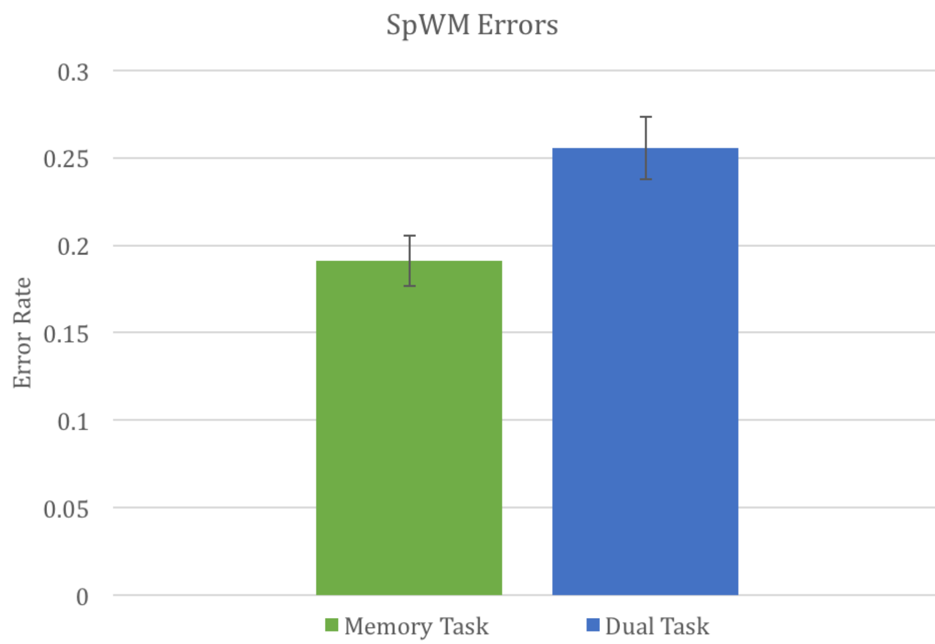


Figure 8. Participants were significantly more likely to make a mistake on the memory task when they simultaneously had to perform a saccade target displacement detection task.

3.3 DISCUSSION

Loading VWM again significantly decreased participants' ability to detect a saccade-target displacement when one occurred. Furthermore, as in Experiment 1, participants were significantly impaired on the memory task when they also had to detect a saccade target displacement. On average, participants lost information from their working memory when simultaneously performing the saccade task. These results are consistent with the hypothesis that VWM resources are used in the perception of stimulus displacements across saccades. As in Experiment 1, saccade latency was also longer in the dual task condition than in the saccade task condition, suggesting that the need to maintain information in VWM slowed saccade initiation. Note that this difference in saccade latency actually worked against our finding a dual-task cost in displacement detection because longer saccade latencies have been shown to improve displacement detection (Zimmermann, Morrone, & Burr, 2013).

Somewhat unexpectedly, VWM single task accuracy was higher in this experiment than in the first, even though participants had to remember location information as well as feature information in Experiment 2. This most likely occurred because there were two ways that participants could detect a change in the memory array in Experiment 2 given that two items changed position, whereas in Experiment 1 only one item changed.

The results of Experiments 1 and 2 show that a VWM load can interfere in detecting changes that occur during a saccade, suggesting VWM is likely involved in maintaining a stable perception of the visual world across eye movements. However, it is possible that our findings could be explained by a more general dual-task cost instead of by an effect of VWM load. For this reason, Experiment 3 attempted to replicate Experiments 1 and 2 with a verbal working memory (AWM) task in place of the VWM task.

CHAPTER 4: EXPERIMENT 3

The purpose of this experiment was to rule out the possibility that the effects found in Experiments 1 and 2 were simply due to general dual-task interference, and not due to overlapping demands on visual working memory systems from the VWM and saccade target displacement detection tasks. Instead of performing a VWM task, participants performed a verbal working memory (AWM) task. If perceptual stability relies on visual working memory, there should be no (or less) interference between the AWM task in this experiment and the saccade target displacement detection task.

4.1 Method

4.1.1 Participants

Eighteen experimentally naïve undergraduate students from the University of Illinois at Urbana-Champaign participated in two 50 minute sessions in exchange for course credit. One additional participant did not complete the second session.

4.1.2 Apparatus, Stimuli, and Procedure

The apparatus and procedure used in this experiment was the same used in Experiments 1 and 2 save for the VWM task, which was replaced by an AWM task, described below.

In the AWM single task condition (Figure 9), participants initiated each trial with a button press. A fixation cross was presented at the center of the display for 506 ms. Then, 7 randomly selected consonants (drawn from the set B, C, D, F, G, H, J, K, L, M, N, P, Q, R, S, T, V, W, X, Z) were sequentially presented at the center of the display for 2142 ms (306 ms per letter). The letters subtended a maximum of 1.48 degrees of visual angle in width, and 1.07 degrees of visual angle in height and were displayed in black. A black and white checkerboard mask subtending 2 degrees of visual angle was presented at the center of the display for 506 ms following the offset of the final letter. A fixation cross replaced the mask and remained on screen for 1506 ms. A single consonant then appeared at the center of the display and participants were asked to indicate if that consonant was present in their original set or not. On half the trials, the test letter was a new consonant, randomly selected from the 13 consonants not used in the memory array. The test letter remained on screen until the participant's response.

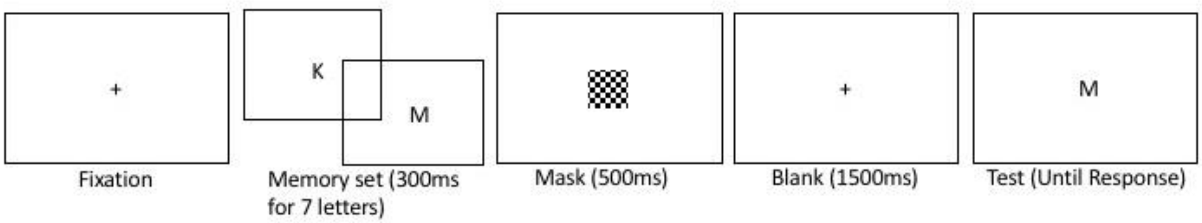


Figure 9. Auditory working memory single task condition.

The dual-task condition for this experiment was largely equivalent to the dual-task conditions described in Experiments 1 and 2. Instead of the VWM tasks used in Experiments 1 and 2, the saccade task was sandwiched by the AWM task described above. In addition, there was a 1000 ms delay between the letter memory array and the onset of the fixation cross signaling the beginning of the saccade task. This delay was 500 ms longer than the corresponding delay in Experiments 1 and 2 to mirror the longer delay used in the AWM single task condition.

4.2 RESULTS

Participants were excluded from analysis if their false alarm rate was greater than their hit rate for any saccade target displacement distance (1° or 2°) on either eye movement task (saccade task or dual task). One subject was excluded for this reason. A second subject was excluded for having a greater false alarm rate than hit rate on the memory task. A third subject did not complete the second session of the experiment and a fourth subject's data were lost due to computer malfunction, leaving 15 subjects' data available for analysis. As in Experiments 1 and 2, for each participant, individual trial data were excluded from analysis if the initial saccade was not directed at the saccade target location (saccade task: 13.0% of trials, dual task: 4.3% of trials), if the saccade amplitude was less than 4° or greater than 10° (saccade task: 27.5% of trials, dual task: 16.0% of trials), if the saccade latency was less than 100 ms or greater than 500 ms (saccade task: 24.6% of trials, dual task: 13.5% of trials), or if the display change was not completed during the saccade to the target location (saccade task: 24.7% of trials, dual task: 11.9% of trials). Following these exclusions, 49.5% of saccade task trials and 75.2% of dual task trials were available for analysis.

4.2.1 Saccade Task + Dual Task

Means for saccade performance measures are presented in Table 5. A paired t-test on saccade latency was not significant, $t(14)=0.21$, $p=0.84$, $d=0.054$. Unlike the prior two experiments, participants in this experiment did not take longer to move their eyes away from fixation under dual task conditions compared to single task conditions. A paired t-test on saccade amplitude revealed a significant effect of task condition, $t(14)=2.63$, $p=0.02$, $d=0.68$, indicating participants moved their eyes further in the single task condition than in the dual task condition. This effect was not reflected in saccade durations, $t(14)=0.09$, $p=0.93$, $d=0.02$, average saccade velocities, $t(14)=1.83$, $p=0.09$, $d=0.47$, nor peak saccade velocities, $t(14)=1.47$, $p=0.16$, $d=0.38$.

Table 5

Mean saccade performance measures in Experiment 3 (standard errors in parentheses)

Task	Latency	Amplitude	Duration	Average Velocity	Peak Velocity
Saccade Task	152.96 (21.55)	6.89 (0.55)	42.15 (2.02)	162.20 (12.81)	290.57 (30.19)
Dual Task	153.55 (22.16)	6.61 (0.42)	42.02 (1.89)	157.39 (12.02)	279.06 (32.83)

To determine if there was an effect of task condition on displacement detection, a 2 (task condition) X 2 (saccade target displacement distance) X 2 (displacement direction) repeated measures ANOVA was performed on the proportion of trials participants correctly responded 'change' (Table 6). Proportion change responses are plotted against displacement distance in Figure 10. In contrast to our findings in Experiments 1 and 2, we found no effect of task condition, $F(1, 14)=0.59$, $p=0.46$, $f=0.20$, $p_{BIC}=0.26$. As in Experiments 1 and 2, there were significant main effect of direction, $F(1,14)=46.45$, $p<0.001$, $f=1.82$, $p_{BIC}>0.99$, and distance, $F(1,14)=146.95$, $p<0.001$, $f=3.24$, $p_{BIC}>0.99$, as well as an interaction between direction and distance, $F(1,14)=54.32$, $p<0.001$, $f=1.97$, $p_{BIC}>0.99$. Unexpectedly, there were also significant interactions between task and distance, $F(1,14)=6.99$, $p=0.019$, $f=0.71$, $p_{BIC}=0.85$, and task and direction, $F(1,14)=9.73$, $p=0.008$, $f=0.83$, $p_{BIC}=0.93$. The error term from each interaction was used to construct a Scheffe 95% confidence interval for comparing two means; this value was ± .030 for the task x distance interaction and ± .052 for the task x direction interaction. Based on these confidence intervals, dual task performance (.60) was significantly *better* than single task performance (.55) at the 1°

displacement distance but there was no difference between dual task (.82) and single task (.83) performance at the 2° displacement distance. In addition, dual task performance (.92) was significantly better than single task performance (.85) for negative displacements but there was no difference between dual task (.50) and single task (.53) performance for positive displacements. The three-way interaction was not significant, $F(1,14)=0.57$, $p=0.46$, $f=0.20$, $p_{BIC}=0.26$. In sum, participants were not more likely to detect displacements of the saccade target overall in either task condition, but participants were somewhat more likely to detect 1° displacements and negative displacements under dual task conditions than under single task conditions. It is unclear how an AWM load might facilitate saccade target displacement detection to produce these results. Recall that in Experiments 1 and 2, participants were more likely to detect saccade target displacements when they did not have a VWM load, across all task conditions. Here, an AWM load paradoxically seemed to boost performance for small and negative displacements. It is possible that participants were more aroused under dual task conditions in this experiment and that this boosted performance (Yerkes & Dodson, 1908). The saccade task used in these experiments is not particularly engaging. By adding a second task that does not use overlapping resources (the AWM task) we may have found improved performance because participants were more aroused or engaged by the dual task than they were by the saccade task on its own. Most importantly for present purposes, there was no evidence that a verbal working memory load interfered with the detection of saccade target displacements.

Figure 10. Participants were more likely to respond ‘move’ under single task conditions for large and positive displacements, but less likely to respond ‘move’ for small and negative displacements. This pattern of results differs from those of Pilot Experiments 1 and 2, suggesting an AWM load interacts with saccade target displacement detection differently than a VWM load.

Table 6

Proportion ‘Change’ Response Analysis for Experiment 3

Main Effects	Mean	SD
*Task Condition**		
Single Task	0.69	0.08
Dual Task	0.71	0.08
Displacement Direction		
Forward/Positive	0.52	0.15
Backward/Negative	0.88	0.09

Table 6 (cont.)

	Mean	SD
Displacement Distance		
1°	0.58	0.08
2°	0.82	0.07
Interactions	Mean	SD
Direction X Distance		
Positive 1°	0.33	0.15
Positive 2°	0.70	0.16
Negative 1°	0.82	0.14
Negative 2°	0.94	0.04
Task X Direction		
Single Task Positive	0.53	0.17
Single Task Negative	0.85	0.14
Dual Task Positive	0.50	0.15
Dual Task Negative	0.92	0.07
Task X Distance		
Single Task 1°	0.55	0.09
Single Task 2°	0.83	0.10
Dual Task 1°	0.60	0.09
Dual Task 2°	0.82	0.08

*was not significant, p=0.46

When change responses were collapsed across saccade target displacements and directions, we did not find a significant effect of task condition on overall hit rates, $t(14)=0.25$, $p=0.81$, $d=0.06$. The Bayes Factor calculated from these data (using the average effect size from Experiments 1 and 2 (0.71) as the scale factor) suggest the data are 3.72 times more likely under the null than under the alternative hypothesis (Figure 11). This result again contrasts with the results found for participants under a VWM load in Experiments 1 and 2—in those experiments participants were more likely to detect a saccade target displacement under single task conditions than under dual task conditions. As in the prior two experiments, false alarm rates in Experiment 3 were not significantly different from each other in the two task conditions, indicating participants were not biased to respond 'change' more often on dual-task trials than on single task trials, $t(14)=0.79$, $p=0.45$, $d=0.20$.

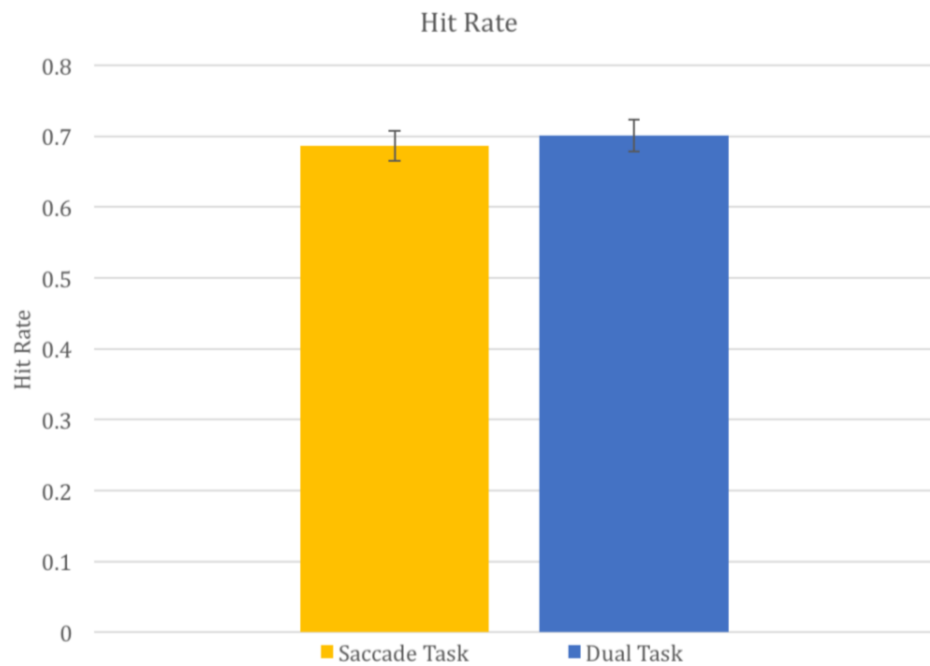


Figure 11. Participants were no more likely to detect displacements of the saccade target under single task conditions than under dual task conditions with an AWM load when hit rates were averaged over all possible saccade target displacements.

4.2.2 Memory Task + Dual Task.

A paired t-test revealed that participants were no more likely to make an error on the memory task under dual task conditions (mean = 0.27, SD = 0.07) than under single task conditions (mean = 0.25, SD = 0.08), $t(14)=0.27$, $p=0.79$, $d=0.07$. The Bayes Factor calculated from these data (using the average effect size from Experiments 1 and 2 (1.16) as the scale factor) suggests the data are 5.68 times more likely under the null than under the alternative hypothesis (Figure 12). Importantly, the memory task error rates under single task conditions fell between the error rates for the VWM tasks in Experiments 1 and 2, indicating that the VWM and AWM tasks were of similar difficulty. As in Experiments 1 and 2, we wanted to determine the number of items maintained in WM during our single and dual task conditions. Unlike the memory tasks used in Experiments 1 and 2, the verbal working memory task only asked participants to respond to whether they recognized one of the seven possible memory items. For this reason, we calculated Cowan's K in place of Pashler's K (Cowan, 2001). Cowan's K is calculated as K = N * (Hits – False Alarms), where N is the number of items in the memory array (7, in our experiment). Under dual task conditions, K=3.15 items while under single task conditions K=3.36 items, a difference of 0.21 items. A t-test on this difference was not significant, $t(14)=0.77$, $p<0.46$, $d=0.20$, Bayes Factor (using the average effect size from Experiments 1 and 2 (1.3) as the scale factor) in favor of the null = 4.89, indicating that participants did not remember significantly more working memory items under single task conditions than under dual task conditions.

The retention interval (timed from the offset of the final letter in the sequence) was longer under dual task conditions (2507.9 ms, sd = 850.3 ms) than under single task conditions (2012 ms). It was also longer than the corresponding retention interval that occurred in the first 2 experiments, which employed a VWM test (average = 1893 ms). Given that verbal information can be rehearsed indefinitely in auditory working memory and that there appears to be little to no decay over time (Lewandowsky, Oberauer, & Brown, 2009), it seems unlikely that these retention interval differences could explain the differences in performance across tasks and conditions.

4.2.2.1 Comparison to Experiments 1 and 2

As noted above, error rates on the VWM (average = 0.25) and AWM (0.25) tasks did not differ from each other under single task conditions. This is important because it indicates that the lack of an effect of the AWM task on displacement detection in Experiment 3 was not due to the AWM task being easier than the VWM tasks used in the first two experiments. To evaluate the extent to which the VWM tasks from Experiments 1 and 2 interfered with the saccade task *more* than the AWM task from Experiment 3, we conducted an ANOVA on the saccade task hit rates with task condition (single vs. dual) as a within subject factor and memory task (VWM vs. AWM) as a between subjects factor (the data from the first 2 experiments were pooled to form a single VWM group for this analysis). The main effect of task condition was significant, $F(1,43)=8.84$, $p=0.005$, $f=0.45$, whereas the between group main effect of memory task was not significant, $F(1,43)=1.90$, $p=0.175$, $f=0.21$. Most importantly, the interaction between task condition and memory task was significant, $F(1,43) = 13.29$, $p=0.001$, $f=0.56$, due to hit rates in the dual task condition being lower when a VWM task was used (.625) than when an AWM task was used (.71).

Similarly, to evaluate the extent to which the saccade task interfered more with the VWM tasks from Experiments 1 and 2 than with the AWM task from Experiment 3, we conducted an ANOVA on the memory task error rates with task condition (single vs. dual) as a within subject factor and memory task (VWM vs. AWM) as a between subjects factor (again pooling the data from the first 2 experiments to form a single VWM group for this analysis). The main effect of task condition was significant, $F(1,43)=17.5$, $p<0.001$, $f=0.64$, $p_{BIC}=0.90$, whereas the between group effect of memory task was not significant, $F(1,43)=0.60$, $p>0.44$, $f=0.12$, $p_{BIC}=0.17$. Most importantly, the interaction between task condition and memory task was significant, $F(1,43) = 6.07$, $p=0.018$, $f=0.38$, $p_{BIC}=0.76$, due to the saccade task causing a greater increase in the VWM error rate (.06) than in the AWM error rate (.02).

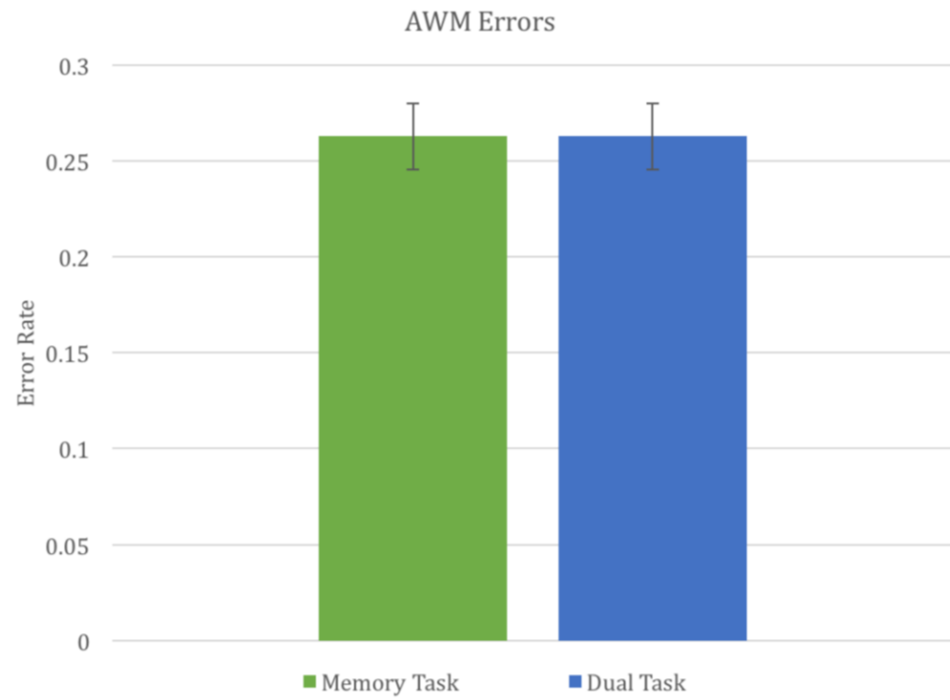


Figure 12. Participants were no more likely to make an error on the AWM task under either task condition. Simultaneously performing a saccade target displacement task and an AWM task did not significantly impact AWM task performance.

4.3 DISCUSSION

When participants were trying to detect a displacement of a saccade target while simultaneously maintaining information in AWM, neither AWM nor displacement detection were impeded. This result lies in direct contrast with the results of Experiments 1 and 2, where VWM task performance was significantly impeded when participants simultaneously performed a saccade target displacement detection task. In Experiments 1 and 2, we also found evidence for impairment of saccade target displacement detection performance under dual task conditions: participants had higher hit rates across all displacement and direction conditions under single task conditions in both experiments. This was not the case when participants' AWM was loaded. Furthermore, cross-experiment comparisons showed that the VWM task interfered with the saccade task significantly *more* than the AWM task, and that the saccade task interfered significantly more with the VWM task than with the AWM task.

The differing pattern of results in Experiment 3 compared to Experiments 1 and 2 suggests the impairment of WM and saccade task performance under dual task conditions described in Experiments 1 and 2 is unlikely to have been caused by a general dual task cost. Instead, it seems likely that when we make a saccade, VWM resources are recruited to hold onto information about the features of the saccade target, thereby influencing the perception of stability across the saccade.

CHAPTER 5: EXPERIMENT 4

This experiment replicated Experiment 1 with a different saccade task. Instead of judging whether the saccade target was displaced or not, participants in this Experiment had to discriminate the displacement direction of the saccade target (e.g., Deubel, Schneider, & Bridgeman, 1996). Participants reported whether the saccade target moved in the same direction as their eye movement (forwards) or opposite the direction of their eye movement (backwards). Irwin and Robinson (2018) showed that performance in this task is very similar to performance in the displacement detection task used in Experiments 1-3, with this task having the advantage of alleviating concerns over possible differences in false alarm rates across conditions.

This experiment also addressed a possible criticism of Experiments 1 and 2, which is that the articulatory suppression used in Experiments 1 and 2 effectively made the dual task condition a triple task condition—a VWM task, a saccade task, and an articulatory suppression task. In contrast, the dual task condition for Experiment 3 did not have an equivalent third task because articulatory suppression was not used. Several studies have shown that visual change detection performance is no better when articulatory suppression is not required compared to when it is required (e.g., Luck & Vogel, 1997; Luria, et al., 2010; Mate, Allen, & Baqués, 2012; Morey & Cowan, 2004, 2005; Sense et al, 2016; Vogel, Woodman, & Luck, 2001), so in this experiment we did not require participants to engage in articulatory suppression.

If performance on this saccade task is similarly diminished by a concurrent VWM task and vice versa, we will have more evidence that VWM is involved in the perception of a stable visual world.

5.1 METHOD

5.1.1 Participants

Eighteen undergraduates from the University of Illinois at Urbana-Champaign participated in this experiment. All subjects reported normal or corrected-to-normal vision. Participants received monetary compensation for participating in two 1-hour sessions.

5.1.2 Apparatus, Stimuli, and Procedure.

Eye movements were recorded with an EyeLink 1000 Plus eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada). The tracker records with a temporal resolution of 1000 Hz, at a spatial resolution of 0.05°, and pupil size resolution of 0.1% of pupil diameter. Stimuli were presented on a 24-inch LCD monitor with a resolution of 1920 x 1080 pixels and a refresh rate of 144 Hz. A chinrest positioned 30 inches from the monitor stabilized participants' heads. The experimental stimuli and design were identical to Experiment 1 except for the following changes. In the Dual Task and Saccade Task conditions, participants reported whether the target moved 'forwards' (as in, further away from the center of the screen) or 'backwards' (closer to the center of the screen). In Experiment 1, participants reported whether they detected a movement or not. Participants *were not asked* to subvocalize the alphabet during this experiment, as they were in Experiments 1 and 2.

5.2 RESULTS

Participants were excluded from analysis if their accuracy on the saccade task was below chance. Two participants were excluded based on this criterion. An additional participant was excluded for performing below chance on the memory task. As in Experiment 1, for each participant, individual trial data were excluded from analysis if the subject did not follow instructions or if the experimental program failed to detect that a saccade had been made or updated the display too slowly. Trials were excluded if the initial saccade was not directed at the saccade target location (saccade task: 0.8% of trials, dual task: <.01% of trials), if the saccade amplitude was less than 4° or greater than 10° (saccade task: 4.8% of trials, dual task: 3.8% of trials), if the saccade latency was less than 100 ms or greater than 500 ms (saccade task: 12.1% of trials, dual task: 21.5% of trials), or if the display change was not completed during the saccade to the target location (saccade task: 4.6% of trials, dual task: 9.10% of trials). Following these exclusions, 85.14% of saccade task trials and 76.11% of dual task trials were available for analysis.

5.2.1 Saccade Task vs. Dual Task.

Mean saccade latency, duration, amplitude, average velocity, and peak velocity are displayed in Table 7. Paired sample t-tests revealed significant effects of task on saccade latency, $t(14)=2.711$, $p=0.017$, $d=0.92$, saccade amplitude, $t(14)=3.954$, $p=0.001$, $d=0.46$, and average saccade velocity, $t(14)=3.068$, $p=0.008$, $d=0.40$ There was no difference in saccade durations, $t(14)=1.351$, $p=0.623$, $d=0.06$, or peak velocities $t(14)=0.838$, $p=0.416$, $d=0.07$. Participants under dual task conditions initiated saccades more slowly and made shorter, less rapid saccades than participants under single task conditions. Participants in Experiments 1 and 2 also showed slower latencies under dual task conditions, but participants in Experiment 3 did not.

Table 7

Mean saccade performance measures in Experiment 4 (standard errors in parentheses)

Task	Latency	Amplitude	Duration	Average Velocity	Peak Velocity

Table 7 (cont.)

Saccade Task	183.51 (25.52)	6.90 (0.60)	43.61 (4.38)	158.09 (20.28)	309.19 (50.33)
Dual Task	213.02 (37.35)	6.61 (0.65)	43.87 (4.60)	150.01 (19.64)	305.52 (55.36)

A paired samples t-test comparing dual task (mean=0.88, SD=0.083) and saccade task (mean=0.91, SD=0.06) accuracy revealed significantly better performance under single task conditions, $t(14)=3.342$, $p=0.005$, $d=0.41$. The Bayes Factor calculated for these data suggest the data are 9.21 times more likely under the alternative than under the null hypothesis. This result replicates those of Experiments 1 and 2: a concurrent VWM task interferes with performance on the saccade task. Saccade displacement accuracies are plotted in Figure 13.

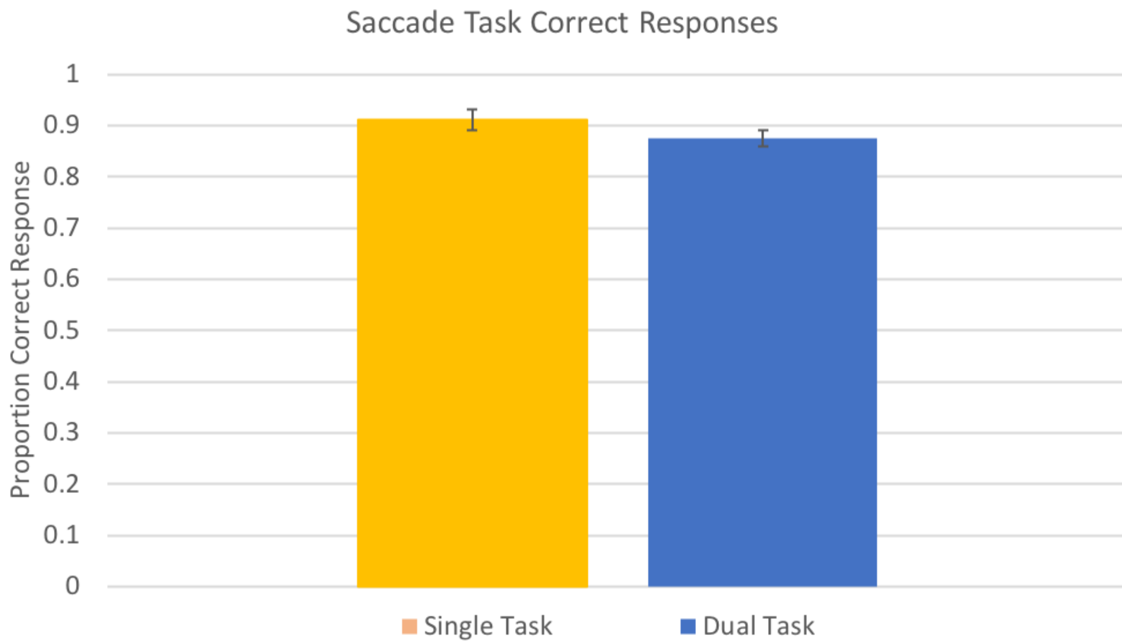


Figure 13. Participants were more likely to respond correctly on the saccade task under single task conditions than dual task conditions. Simultaneously performing a VWM task interfered with participants' ability to detect the direction of the saccade target's displacement. Error bars are standard error of the mean.

5.2.2 Memory Task vs. Dual Task.

As in Experiments 1 and 2, a paired t-test revealed that participants were significantly more likely to make an error on the memory task in the dual task condition (mean = 0.34, SD = 0.09) than in the single task condition (mean = 0.25, SD = 0.08), $t(14)=4.93$, $p<0.001$, $d=0.97$. The Bayes Factor calculated from these data indicate the data are 154.97 times more likely under the alternative than under the null. This finding is consistent with the results of Experiments 1 and 2: performance on a VWM task suffered when participants had to simultaneously perform the saccade task. Memory task error rates are plotted in Figure 14.

As in Experiments 1 and 2, Pashler's K was calculated to assess the amount of information in memory under single and dual task conditions. Participants under single task conditions remembered significantly more items (mean = 2.89, SD = 0.87) than participants under dual task conditions (mean = 1.95, SD = 1.03), $t(14) = 4.502$, $p>0.001$, $d=0.99$, Bayes Factor in favor of the alternative hypothesis = 74.74. Under dual task conditions, participants lost nearly a full item's (0.94 items) worth of information from memory. This result is consistent with the results of Experiments 1 and 2, where we also saw information loss under dual task conditions.

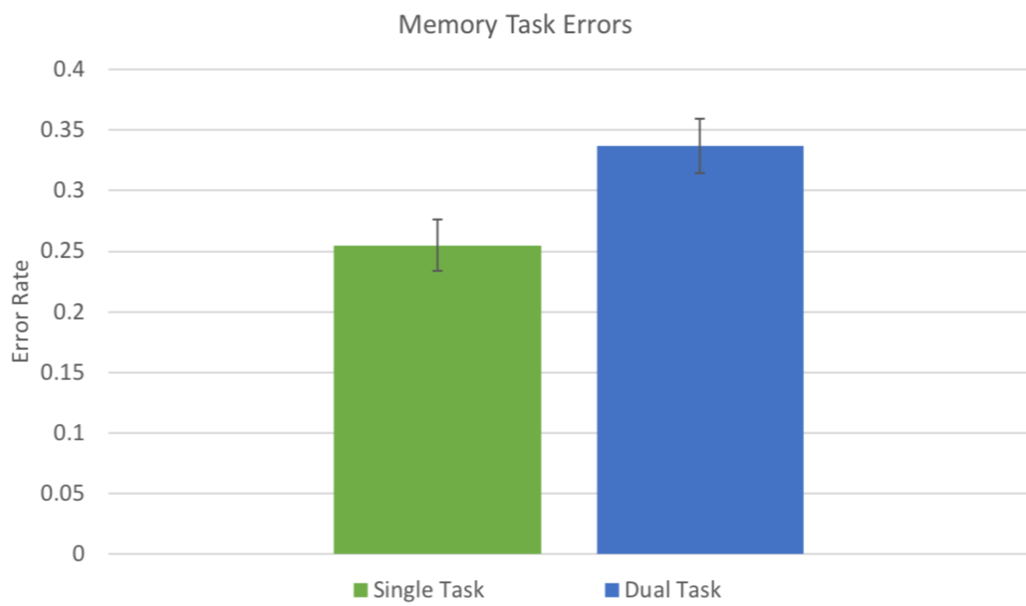


Figure 14. Participants were less likely to make an error on the VWM task under single task conditions than dual task conditions. Simultaneously performing a saccade task interfered with participants' ability to correctly detect changes to the VWM array. Error bars are standard error of the mean.

As in Experiments 1 and 2, the retention interval was longer under dual task conditions (mean = 2337 ms, SD = 850.3) than under single task conditions (1506 ms). This is within the 4-second range during which little difference in change detection performance is expected, however, so it seems unlikely to be responsible for the error rate differences in this experiment.

5.3 DISCUSSION

As in Experiments 1 and 2, participants were significantly worse at discriminating saccade target displacements and at detecting changes to a VWM array under dual task conditions. In this experiment, participants lost nearly an entire item's worth of information from VWM, which is consistent with the idea that the saccade target is being placed in VWM at the expense of information that is already there (e.g., Tas, Luck, & Hollingworth, 2016). These results again support a role for VWM in performing a saccade target displacement detection task, and thus suggest that VWM plays a role in maintaining perceptual stability across eye movements.

CHAPTER 6: EXPERIMENT 5

This experiment replicated Experiment 3 with the displacement discrimination saccade task used in Experiment 4. The purpose of this experiment was to determine whether the results of Experiment 4 could be due to a simple dual task cost, and not due to interference between the VWM Memory Task and the Saccade Task.

6.1 METHOD

6.1.1 Participants

Nineteen undergraduates from the University of Illinois at Urbana-Champaign participated in this experiment. All subjects reported normal or corrected-to-normal vision. Participants received monetary compensation for participating in two 1-hour sessions. One subject dropped out before the second session, leaving 18 subjects for analysis.

6.1.2 Apparatus, Stimuli, and Procedure.

The experimental stimuli and procedure were identical to those of Experiment 3 except for the following changes. In the Dual Task and Saccade Task conditions, participants reported whether the target moved 'forwards' (as in, further away from the center of the screen) or 'backwards' (closer to the center of the screen). In Experiment 3, participants reported whether they detected a movement or not. We used the same set of letters for the memory task as in Experiment 3, but the letter stimuli were presented in an auditory fashion (as .wav files) in a male voice over Harman/Kardon HK206 speakers at a rate of one letter every 500 ms.

6.2 RESULTS

Participants were excluded if their accuracy on the eye movement task or on the memory task was below chance. Two participants were excluded based on these criteria.

As in Experiment 1, for each participant, individual trial data were excluded from analysis if the subject did not follow instructions or if the experimental program failed to detect that a saccade had been made or updated the display too slowly. Trials were excluded if the initial saccade was not directed at the saccade target location (saccade task: 0.4% of trials, dual task: 0.04% of trials), if the saccade amplitude was less than 4° or greater than 10° (saccade task: 6.1% of trials, dual task: 1.0% of trials), if the saccade latency was less than 100 ms or greater than 500 ms (saccade task: 28.5% of trials, dual task: 31.8% of trials), or if the display change was not completed during the saccade to the target location (saccade task: 20.4% of trials, dual task: 21.8% of trials). Following these exclusions, 68.9% of saccade task trials and 67.7% of dual task trials were available for analysis.

6.2.1 Saccade Task vs. Dual Task.

Mean saccade latency, duration, amplitude, average velocity, and peak velocity are displayed in Table 8. A paired samples t-test revealed a significant effect of task on average saccade velocities, $t(15)=3.782$, $p=0.002$, $d=0.21$. Participants moved their eyes significantly faster under single task conditions than dual task conditions, but the effect was quite small (4°/sec). There were no differences in latency, $t(15)=0.690$, $p=0.500$, $d=0.15$, duration, $t(15)=0.678$, $p=0.508$, $d=0.21$, amplitude, $t(15)=1.884$), $p=0.079$, $d=0.31$, or peak velocity, $t(15)=0.063$, $p=0.951$, d=0.004. As was the case in Experiment 3, participants did not vary the speed with which they moved their eyes away from central fixation. These results contrast with Experiments 1, 2, and 4, where saccade latencies were significantly longer under dual task conditions.

Table 8

Mean saccade performance measures in Experiment 5 (standard errors in parentheses)

Task	Latency	Amplitude	Duration	Average Velocity	Peak Velocity
Saccade Task	166.14 (28.67)	6.94 (0.47)	44.99 (4.67)	159.55 (18.49)	313.56 (62.52)
Dual Task	170.52 (29.22)	6.78 (0.55)	46.10 (5.78)	155.79 (17.90)	313.28 (62.73)

A paired samples t-test comparing dual task (mean=0.88, SD=0.063) and saccade task (mean=0.88, SD=0.076) accuracy revealed no difference in saccade task performance under dual task conditions, $t(15)=0.424$, $p=0.678$, $d=0.11$. The Bayes Factor calculated from these data (using the corresponding effect size from Experiment 4 (0.41) as the scale factor) suggest the data are 2.42 times more likely under the null than under the alternative hypothesis. Proportion correct are plotted in Figure 15. This result contrasts with the results of Experiment 4—the auditory memory load in this experiment did not impair performance on the saccade task, whereas a VWM load did impair saccade task performance. This result is also consistent with the results of Experiment 3.

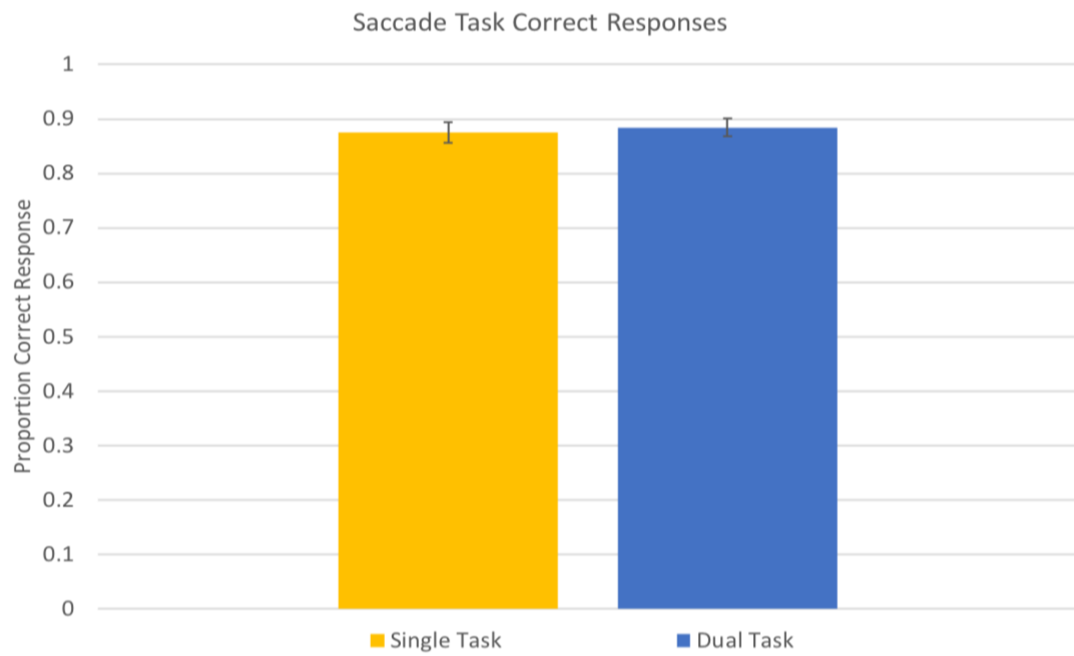


Figure 15. Participants' performance on the saccade task was not significantly impaired by a concurrent AWM task. Participants were able to discriminate the direction of the saccade target's motion equally well under both task conditions. Error bars are standard error of the mean.

6.2.2 Memory Task vs. Dual Task.

A paired samples t-test of dual task (mean = 0.17, SD = 0.05) and memory task (mean = 0.15, SD = 0.06) was not significant, t(15)=1.201, p=0.248, *d*=0.37. The Bayes Factor calculated from these data (using the corresponding effect size from Experiment 4 (0.97) as the scale factor) suggest the data are 2.67 times more likely under the null than under the alternative hypothesis. Participants' performance on the verbal memory task was not significantly impaired by performing a concurrent saccade task. This is consistent with the results of Experiment 3—where performance on a similar verbal memory task did not suffer under dual task conditions—and contrasts with the results of our VWM experiments, where we found consistent decrements in performance under dual task conditions.

As in Experiment 3, we calculated Cowan's K to assess the amount of information stored in memory during single and dual task conditions. Participants under single task conditions (mean = 4.83 items, SD = 0.80) remembered the same amount of information as participants under dual task conditions (mean = 4.62 items, SD = 0.61), $t(15)=1.225$, $p=0.240$, $d= 0.30$, Bayes Factor (using the corresponding effect size from Experiment 4 (0.99) as the scale factor) = 2.64 in favor of the null hypothesis. This result is consistent with the results of Experiment 3, and contrasts with the results of our VWM experiments where we consistently saw a decrease in the number of items maintained in memory under dual task conditions.

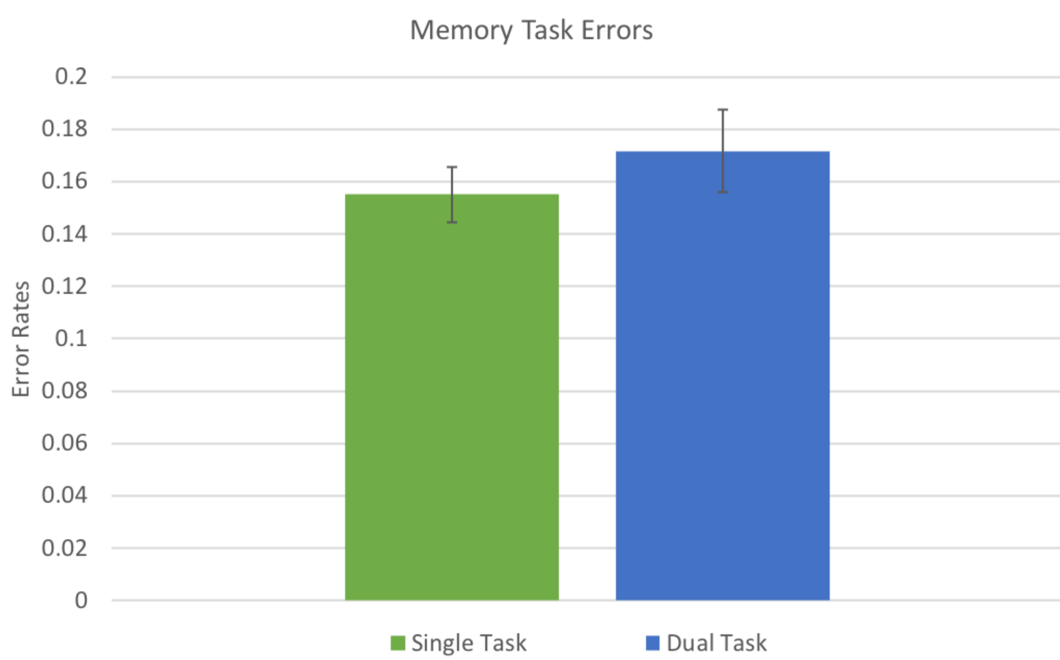


Figure 16. Participants were no more likely to make an error on the AWM task under dual task conditions compared to single task conditions. The concurrent saccade task did not significantly interfere with memory task performance. Error bars are standard error of the mean.

6.2.3 Comparison to Experiment 4

A mixed ANOVA was performed on proportion correct responses from the saccade tasks of Experiments 4 and 5. Unlike in the comparison between Experiments 1, 2, and 3, the interaction between Experiment and task was only marginally significant, $F(1,29)=3.45$, $p=0.073$, $f=0.34$, $p_{BIC}=0.49$. Saccade displacement accuracy was considerably higher in the forward/backward displacement detection task used in Experiments 4 and 5 (close to 90%) compared to the move/no move displacement detection task used in Experiments 1-3 (approximately 67%) so a ceiling effect may be partially responsible for the lack of significance in this comparison. We were also not well powered (observed power = 43.5%) to detect the small difference in accuracy apparent in the data from Experiments 4 and 5. A mixed ANOVA performed on the working memory results of Experiments 4 and 5 did yield a significant interaction, however, $F(1,29)=9.42$, $p=0.005$, $f=0.57$, $p_{BIC}=0.93$, indicating that the saccade task had a greater deleterious effect on VWM (9%) than on AWM (2%). The main effect of Experiment was also significant, however, $F(1,29)=34.41$, $p<.001$, $f=1.09$, $p_{BIC}>0.99$, because overall performance on the AWM task (error rate = 16%) was better than that on the VWM task (error rate = 30%).

The mean retention interval (timed from the offset of the final letter in the sequence) was longer under dual task conditions (2495 ms, sd = 1169 ms) than under single task conditions (1506 ms). It was slightly longer than the corresponding retention interval that occurred in Experiment 4 (mean = 2337 ms, sd = 751 ms), and thus seems unlikely to be the reason for the differences between the experiments.

6.2.4 Experiments 1 – 5: Does good performance on one task interfere with performance on the other task?

If the memory and saccade tasks interfere with each other, one might assume that there would be a negative correlation between performance on the saccade task and performance on the memory task in the dual task conditions: that is, participants' whose memory task performance suffered more under dual task conditions (relative to their single task performance) might have better performance on the saccade task in the dual task condition and vice versa. We would expect such a negative correlation when participants had to perform the VWM task and the saccade task at the same time, but not when they had to perform the AWM task and the saccade task at the same time. To increase our sample size we pooled the data from the 3 VWM experiments for one correlation and the data from the 2 AWM experiments for another. The differences between single and dual task conditions in saccade task accuracy and VWM error rates were significantly correlated ($r = -0.392$, $p=0.008$), whereas those between saccade task accuracy and AWM error rates were not ($r = -0.080$, $p = 0.67$). These results suggest that performance on one task suffered when performance on the other task was high when a VWM task was used, but there was no tradeoff between tasks when an AWM task was used.

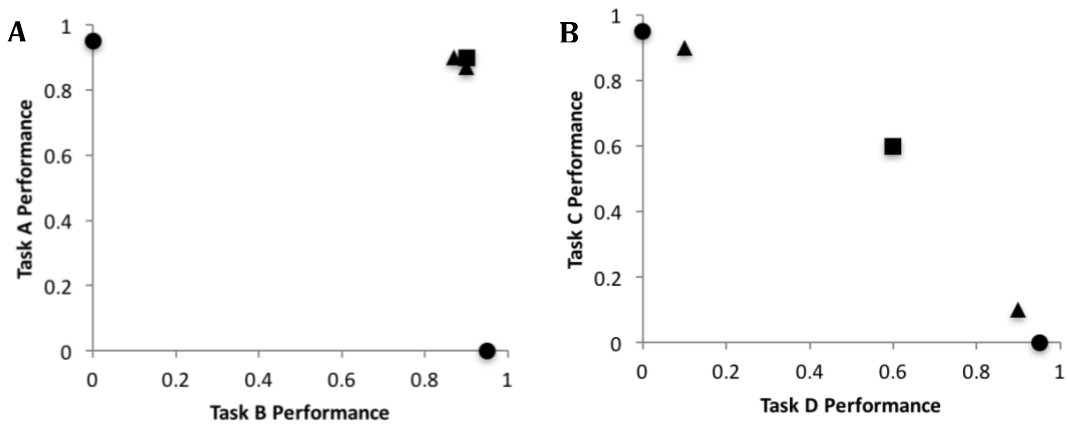
6.3 DISCUSSION

As in Experiment 3, performance on both the memory and saccade task were unimpeded under dual task conditions. Instead, participants performed equally well on the saccade task under dual task conditions and single task conditions. This finding contrasts with the results of Experiments 1, 2, and 4 and, in conjunction with Experiment 3, provides evidence to suggest that a VWM task impairs saccade task performance because they rely on common resources.

CHAPTER 7: EXPERIMENTS 6A & 6B

The results of Experiments 1, 2, and 4 suggest perceptual stability may rely on VWM: When participants attempt to detect disruptions of stability while maintaining a VWM load, their performance suffered. This was not the case when participants' AWM was loaded. A more robust test of the relationship between perceptual stability and VWM is to generate an Attention Operating Characteristic (AOC) curve for our WM and saccade tasks. AOC analyses are generally considered to be the gold standard for assessing dual-task performance because they allow one to assess how performance changes when participants attempt to prioritize one task over the other.

To generate an AOC function for our WM and saccade tasks, participants completed several blocks of the same dual tasks used in Experiments 4 and 5 with different instructions. Within each session, participants were asked to prioritize their performance on the WM task, prioritize their saccade task performance, and to weight the two tasks equally in three separate blocks of trials. The results of these different conditions can be compared to each other, and to the participant's single task performance on each task, to determine the extent to which the two tasks interfere with each other (or not) due to their reliance on shared resources. Figure 17A is a representation of an imaginary subject's performance in an AOC study in which the two tasks do not rely on a shared resource—when the participant weights both tasks equally, performance does not suffer on either task compared to when the participant weights performance on Task A over Task B (and vice versa). In contrast, Figure 17B depicts another imaginary subject's performance on two tasks that do rely on the same resource—performance suffers for both tasks when the participant weights each task equally compared to when they are focused on one task or the other. If perceptual stability across saccades relies on VWM resources, as was suggested by Experiments 1,2, and 4, our participants' performance should look more like the subject in Figure 17B. If, however, saccade targets are placed into VWM in an obligatory fashion, participants would be largely unable to prioritize their performance on the working memory task resulting in an AOC curve similar to that shown in Figure 17C, where Task F is automatically prioritized over Task E. Given the results of Experiments 3 and 5, we anticipate the AOC curve generated for our AWM and saccade tasks will look more like Figure 17A where we see little impairment on either task under dual task conditions.



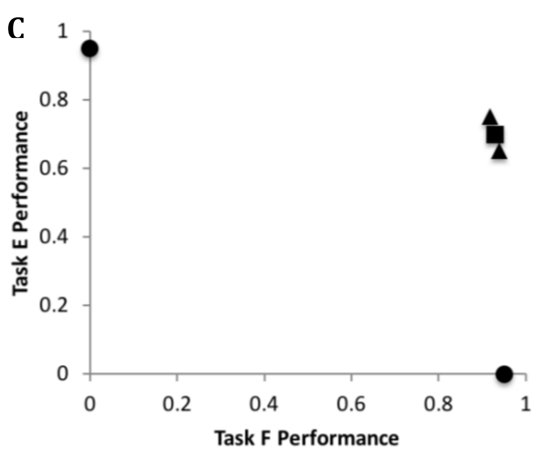


Figure 17. Circular markers indicate single task conditions, triangular markers indicate dual task conditions prioritizing one task over the other, and square markers indicate dual task conditions where each task is given equal priority. **A**. AOC curve for two tasks that do not rely on the same resource. **B.** AOC curve for two tasks that rely on the same resource. **C.** AOC curve for two tasks that rely on the same resource, and for which one task (*F*) is automatically prioritized over the other (*E*).

For these experiments, we used the same task conditions as in Experiment 4: the saccade target displacement discrimination task and the VWM task with no articulatory suppression for Experiment 6A, and the same task conditions as Experiment 5 for Experiment 6B. Participants were given instructions to emphasize their performance on one or both tasks under dual task conditions. The same group of people participated in the two experiments.

7.1 METHOD

7.1.1 Participants

A power analysis was conducted using the effect sizes found in Experiment 1 to determine the sample size necessary to detect the same effects at 80% power for this experiment. Thus, nine experimentally naïve University of Illinois at Urbana-Champaign students and the author participated in a 10-session study (10 total subjects). One subject dropped out after their first session and was replaced. Five of the ten sessions used the visual task (Experiment 6A) and five used the auditory task (Experiment 6B). Each experiments' sessions were blocked and the order the subjects completed the two experiment blocks was counterbalanced across participants. Sessions lasted approximately one hour. Each experimental block was completed over the course of 1-2 weeks.

7.1.2 Apparatus, Stimuli, and Procedure

During each session, participants participated in five task conditions: WM task alone, saccade task alone, dual task equal priority, dual task prioritize WM task, and dual task prioritize saccade task. The order of these tasks was randomized across participants and across sessions. The WM alone condition had 50 trials per session, while the saccade task alone and the dual task conditions had 60 trials per session. This resulted in 250 WM alone trials per subject and 300 trials for the saccade task and each dual task for each subject. The apparatus was the same as in Experiments 4 and 5. A 5-point calibration procedure was completed prior to the start of the saccade task alone and the three dual task condition blocks. Participants initiated each trial for all conditions by pressing the space bar while fixating a central fixation dot. During the saccade and dual task blocks, an automatic drift correction was performed upon this button press.

7.1.2.1 Experiment 6A – VWM task

During VWM task alone trials, a black fixation cross was presented at the center of the screen, followed 1000 ms later by 5 color patches. Each color patch subtended 3.49° of visual angle and could be one of 9 colors: red (255,0,0), green (0,128,0), blue, (0,0,255), yellow (255,255,0), lavender (204,102,255), light green (0,255,128), light blue (0,255,255), orange (255,144,27), and pink (255,0,255). The color patches remained on screen for 200 ms, followed by a blank screen for 1500 ms. Then, the 5 color patches reappeared until participants made a response. On 50% of trials, one of the color patches changed color upon reappearing. The new color was randomly selected from the 4 colors that went unused in the first set of color patches. Participants indicated whether they detected a change in the color patches by pressing one of two response keys.

7.1.2.2 Experiment 6B – AWM task

As in Experiment 5, in the AWM task alone trials began with a black fixation cross at the center of the display. Seven randomly selected consonants from the set [B, C, D, F, G, H, J, K, L, M, N, P, Q, R, S, T, V, W, X, Z] were read in a male voice over speakers at a rate of 1 letter every 500ms. After a 1500ms delay, one letter was played back to participants. On

50% of trials, this letter was a randomly selected consonant that did not appear in the original memory set. Participants indicated whether the test letter was one of the original 7 letters or not.

7.1.2.3 Experiments 6A and 6B

Saccade task alone trials began with a black fixation cross subtending 0.8° by 0.8° presented at the center of the screen. After 500 ms, the fixation cross moved 6° or 8° to the left or right of fixation. Participants were asked to move their eyes to the new location of the cross. While their eyes moved, the screen was blanked for 250ms, after which the cross reappeared 0°, 1° or 2° to the left, or 1° or 2° to the right of its pre-blank position. Participants responded with one of two keys to indicate whether they thought the cross had moved forwards (away from fixation), or backwards (closer to fixation). Different sets of keys were used to respond to the saccade task and the VWM task.

As in the previous experiments, the three dual task conditions combined these two tasks: participants first saw the VWM task array (Experiment 6A) or heard the stream of letters (Experiment 6B), then performed the saccade task, and finally were tested on the WM task. The only difference between the three conditions were the instructions given to the participants. Each participant received the following instructions both on-screen and verbally by the experimenter. For the dual task equal priority condition, participants were asked to perform equally well on both the saccade and WM task. During the dual task prioritize WM condition, participants were asked to maximize their performance on the WM task, regardless of the effect it might have on their performance on the saccade task. The reverse was the case under dual task prioritize saccade conditions: participants were asked to maximize their performance on the saccade task, regardless of the effect that may have on their WM task performance. Finally, we manipulated response order to ensure that the order participants responded to the tasks did not have an effect on task performance. Half of participants responded to the saccade task immediately after making their eye movement, then responded to the WM task. The other half of participants responded to the saccade task after responding to the WM task. For these participants, the memory task array reappeared at the center of the screen (Experiment 6A) or the test letter was played (Experiment 6B) approximately 1 second after the reappearance of the saccade target. Participants responded to the memory task, then reported the direction of the saccade target displacement. This manipulation was used to ensure that participants were not prioritizing one task over the other simply because of the order in which we asked them to respond.

7.2 RESULTS AND DISCUSSION

7.2.1 Data handling Experiment 6A (VWM)

Data were trimmed as in Experiments 1-5—trials were excluded if participants failed to move their eyes towards the saccade target, if they moved their eyes too short of a distance to reach the saccade target, if the experimental display did not blank before participants completed their saccade, or if participants moved their eyes from fixation exceptionally quickly (<100ms) or exceptionally slowly (>500ms). The number of trials excluded for each subject varied, but each subject was relatively consistent in the number of trials lost across task conditions. Approximately 8.3% of trials were excluded overall (8.76% of saccade only trials; 8.8% of dual task, equal priority trials; 6.97% of dual task saccade priority trials; 8.76% of dual task memory priority trials).

7.2.2 Data handling Experiment 6B (AWM)

Data were trimmed as in Experiment 6A. The number of trials excluded for each subject varied, but each subject was relatively consistent in the number of trials lost across task conditions. Approximately 9.0% of trials were excluded overall (8.03% of saccade only trials; 10.1% of dual task, equal priority trials; 8.67% of dual task saccade priority trials; 11.2% of dual task memory priority trials).

7.2.3 Saccade Task Performance

7.2.3.1 Experiment 6A (VWM)

Average saccade latencies are listed in Table 9. A one-way repeated measures ANOVA on saccade latencies for the four task conditions in Experiment 6A was significant, $F(3,27)=10.311$, $p<0.001$, $f=1.07$, $p_{BIC}>0.99$. Participants moved their eyes towards the saccade target faster under single task conditions than under dual task conditions, and slower when they prioritized the memory task under dual task conditions. These differences in saccade latency are consistent with participants successfully prioritizing the tasks as instructed.

Table 9

Mean saccade latency for Experiments 6A and 6B (standard deviations in parentheses)

Experiment	Single Task	Dual Task – Equal	Dual Task – Saccade	Dual Task – Memory
6A (VWM)	158.09 (24.04)	182.87 (26.44)	175.20 (24.51)	187.86 (28.24)
6B (AWM)	162.92 (27.52)	167.85 (25.36)	165.46 (23.79)	167.37 (24.94)

To assess the extent to which the VWM task interfered with correct discrimination of the saccade target's movements, we next looked at participants' accuracy rates. Mean saccade task accuracies are displayed in Table 10. A one-way repeated measures ANOVA on saccade task accuracy was not significant, $F(3,27)=1.291$, $p=0.298$, $f=0.377$, $p_{BIC}=0.04$, suggesting participants were not significantly impaired on the saccade task by having to perform a simultaneous VWM task. While the differences are not significant, the overall means for each task condition are qualitatively consistent with the results of Experiments 1, 2, and 4, and with participants successfully prioritizing each task as instructed: Participants performed best under single task conditions (mean=0.914, SD=0.57), equally well on the equal-priority (mean=0.906, SD=0.051) and saccade-priority (mean=0.906, SD=0.047) conditions, and worst on the VWM-priority condition (mean=0.887, SD=0.600).

While we found significant differences in saccade-task performance in Experiments 1,2, and 4, and therefore anticipated finding differences in saccade-task performance here, the forward/backward saccade displacement detection task used in this Experiment (and in Experiment 4) appeared to be considerably easier than the move/no-move task used in Experiments 1 and 2, so a potential ceiling effect may have made it difficult to find significant differences in saccade task performance here. It is also worth noting that the dual-task costs in Experiments 1, 2, and 4 were larger on the VWM task than on the saccade task, consistent with the hypothesis that saccade targets are automatically prioritized over the contents of VWM (e.g., Shao et al., 2010); this might have the effect of minimizing dual-task costs on saccade target displacement detection.

Table 10

Mean saccade task accuracy for Experiments 6A and 6B (standard deviation in parentheses)

Experiment	Single Task	Dual Task – Equal	Dual Task – Saccade	Dual Task – Memory
6A (VWM)	0.91 (0.06)	0.91 (0.05)	0.91 (0.05)	0.89 (0.06)
6B (AWM)	0.90 (0.07)	0.87 (0.07)	0.86 (0.10)	0.86 (0.10)

7.2.3.2 Experiment 6B (AWM)

Mean saccade latencies are listed in Table 9. As for Experiment 6A, a one-way repeated measures ANOVA was conducted on saccade latencies across the four task conditions. There was no significant effect of task condition on saccade latency, $F(3,27)=1.898$, $p=0.154$, $f=0.459$, $p_{BIC}=0.10$. This result contrasts with the results of Experiment 6A: participants did not move their eyes to the saccade target significantly more slowly under dual task conditions compared to single task conditions. This suggests that the AWM task did not significantly interfere with participants programming their first eye movements away from fixation. In Experiment 6A, participants moved their eyes significantly slower under dual task conditions compared to single task conditions.

A one-way repeated measures ANOVA on saccade task accuracies was not significant, $F(3,27)=2.055$, $p=0.130$, $f=0.478$, $p_{BIC}=0.12$. This result is consistent with Experiments 3 and 5, where we found no differences in saccade performance when participants simultaneously performed an AWM task. Participants performed best under single task conditions, with little difference between the dual-task conditions.

7.2.3.3 Experiments 6A vs. 6B

To assess the extent to which the VWM and AWM tasks interfered with correct discrimination of the saccade target's movements, we next compared participants' accuracy rates under dual-task conditions across Experiments 6A and 6B. A 2 (memory condition) X 3 (dual-task condition) repeated measures ANOVA with response order as a between subjects factor revealed a significant main effect of memory condition, $F(1,8)=6.600$, $p=0.033$, $f=0.908$, $p_{BIC}=0.86$, and a main effect of the between subjects factor, response order, that approached significance, $F(1,8)=5.286$, $p=0.051$, $f=0.813$, $p_{BIC}=0.80$. In addition, memory condition significantly interacted with response order, $F(1,8)=5.436$, $p=0.048$, $f=0.825$, $p_{BIC}=0.81$. Contrary to our predictions, participants performed worse on the saccade task when they maintained an AWM load (mean=0.86, SD=0.066) compared to when they maintained a VWM load (mean=0.90, SD=0.047). In addition, participants were significantly worse overall on the saccade task when they reported the saccade target displacement after reporting their response to the memory task. However, as indicated by the interaction with response order, saccade task performance was most negatively impacted when participants responded to the saccade task second and maintained an AWM load (Table 11; Figure 20), while response order had relatively little effect on saccade task performance while participants maintained a VWM load (Table 11; Figure 19).

There are a few possible explanations for this result. First we should note the low number of participants in each response order cell—one subject who struggled or excelled on the saccade task in either group may have had a disproportionate effect on the overall group performance. It is also possible that this pattern of results was driven by a sort of modality switch cost. When participants maintained an AWM load and responded to the saccade task second, they had to shift their attention from the auditory stream of letters to the visual saccade task, back to the auditory test letter, then (arguably) back to the visual modality to report the displacement of the saccade target. Another possibility is that by engaging participants in an auditory task and incentivizing performance on that task by requesting the AWM response first, participants may have disengaged from the saccade task. For example, Buetti and Lleras (2016) showed that engagement in an auditory task leads to less distraction by visual events. Finally, it is also possible participants translated their response to the saccade task into a verbal code (e.g., "forwards"), which was then disrupted by the letter memory task. While this effect complicates our ability to compare Experiments 6A and 6B, it is important that the saccade task performance while participants maintained a VWM load was not particularly affected by response order, suggesting that our findings in Experiments 1, 2, and 4 were not driven by the order in which we asked participants to respond to the tasks.

Importantly, a repeated measures ANOVA with memory task (VWM or AWM) and task priorities (single, dual equal priority, dual saccade priority, dual memory priority) as within subjects factors and experiment order (6A first, 6B first) as a between-subjects factor, did not show a significant main effect of experiment order, $F(1,8)=0.154$, $p=0.705$, $f=0.139$, nor did it interact with memory load, $F(1,8)=0.064$, $p=0.807$, $f=0.089$. These null results suggest participants did not get better at the saccade task over the course of the experiment, so any differences in saccade task performance in 6A and 6B are not due to practice effects.

Table 11

Mean saccade and memory task performance by response order (standard deviations in parentheses)

	Saccade Task		Memory Task	
Response Order	Expt 6A (VWM)	Expt 6B (AWM)	Expt 6A (VWM)	Expt 6B (AWM)
Saccade First (N=6)	0.913 (0.05)	0.91 (0.06)	0.692 (0.08)	0.824 (0.07)
Memory First (N=4)	0.88 (0.05)	0.80 (0.06)	0.718 (0.08)	0.842 (0.07)

Surprisingly, we found no effect of task priority on saccade task performance, $F(2,16)=2.059$, $p=0.160$, $f=0.508$, $p_{BIC}=0.33$, though we were not well powered to find this effect. The means for each priority condition suggest participants were somewhat successful in prioritizing the saccade task with a VWM load (saccade task performance was best under saccade task priority conditions and worst under memory task priority), while less-so with an AWM load (saccade task performance was best on the equal priority condition and slightly worse for the other two conditions; Table 10).

7.2.4 Memory Task Performance

7.2.4.1 Experiment 6A (VWM)

A one-way repeated measures ANOVA on VWM task performance across the four task priority conditions revealed a significant main effect of task priority condition, $F(3,24)=9.891$, $p<0.001$, $f=1.11$, $p_{BIC}>0.99$. Pairwise comparisons of the four task conditions (Table 12) using Bonferroni adjusted α revealed that accuracy in the single task condition (mean=0.763, SD=0.0912) was significantly higher than accuracy in each of the dual-task conditions: equal-priority condition (mean=0.714, SD=0.076); saccade-priority condition (mean=0.685, SD=0.104); memory-priority condition (mean=0.716, SD=0.89). Response order was again used as a between-subjects factor, but there was neither a main effect, $F(1,8)=0.311$, $p=0.593$, $f=0.20$, $p_{BIC}=0.28$, nor an interaction with task priority, $F(3,24)=0.217$, $p=0.884$, $f=0.16$, $p_{BIC}=0.01$.

Table 12

Mean memory task accuracy for Experiments 6A and 6B (standard deviation in parentheses)

Experiment	Single Task	Dual Task – Equal	Dual Task – Saccade	Dual Task – Memory
6A (VWM)	0.76 (0.09)	0.71 (0.07)	0.68 (0.10)	0.71 (0.08)
6B (AWM)	0.85 (0.04)	0.84 (0.06)	0.81 (0.08)	0.84 (0.07)

As in Experiments 1, 2, and 4, we calculated Pashler's K for each subject. A one-way repeated measures ANOVA on the average K for each task priority revealed a significant effect of task condition, $F(3,24)=4.905$, $p=0.008$, $f=2.05$, $p_{BIC}>0.99$. Pairwise comparisons revealed that this effect was driven by the difference between single task (mean=3.022, SD=0.920) and saccade-priority (mean=2.308, SD=0.753) conditions. When participants prioritized the saccade task, they lost an average of ~0.714 items from VWM compared to single task performance. The average K for equal priority (mean=2.640, SD=0.623) and memory priority (mean=2.602, SD=0.493) were not significantly different than the average K for single task performance.

These results suggest that participants were somewhat successful in manipulating the priority they placed on the VWM and saccade tasks. Participants performed worse on the memory task when they prioritized the saccade task compared to the single task and when they prioritized the saccade and VWM tasks equally compared to the single task. This is consistent with the results of Experiments 1, 2, and 4.

7.2.4.2 Experiment 6B (AWM)

In contrast to Experiment 6A, a one-way repeated measures ANOVA on AWM dual-task performance across the four priority conditions with response order as a between subject variable revealed no significant effects. Participants' performance on the AWM task was not significantly affected by their task priorities, $F(3,24)=1.301$, $p=0.297$, $f=0.403$, $p_{BIC}=0.05$, nor by response order, $F(1,8)=0.057$, $p=0.817$, $f=0.08$, $p_{BIC}=0.01$. Task condition and response order did not interact, $F(3,24)=0.453$, $p=0.717$, $f=0.239$, $p_{BIC}=0.01$. While we do not have clear evidence that our participants successfully manipulated their priorities in our three dual task conditions because none of the individual task conditions differed significantly from the saccade task, it appears that participants did not need to prioritize the AWM task over the saccade task to perform well on it (Table 12).

As in Experiments 3 and 5, we calculated Cowan's K for each participant. A one-way repeated measures ANOVA on the average K value for each task priority condition was also not significant, $F(3,24)=0.508$, $p=0.681$, $f=0.25$, $p_{BIC}=0.01$.

These results are consistent with Experiments 3 and 5—participants' ability to perform an AWM task was not impaired by a simultaneous saccade task. These results also contrast directly with the results of Experiment 6A, where we found participants VWM task performance was impaired when participants prioritized the saccade task.

7.2.5 AOC Results

As described in the introduction for Experiments 6A and B, an AOC curve visualizes the extent to which two tasks rely on shared resources. Therefore, we generated both overall (Figure 18) and individual subject (see Appendix) AOC plots for both tasks (Experiment 6A and 6B) by plotting memory task accuracy against saccade task accuracy. The response order for each subject is indicated above their AOC plots.

While the differences in single and dual task performance are not numerically large, it is clear from the overall VWM AOC function that performance on the memory task consistently suffered under dual task conditions, even when it was prioritized over the saccade task. However, performance on the saccade task did not suffer unless participants were prioritizing the memory task. In contrast, the overall AWM AOC function shows a slight performance decrement on the saccade task for all dual task conditions. As noted earlier, this seems largely due to performance on the saccade task being poor when participants had to respond to the auditory memory probe before they made their saccade displacement response (see Table 11). There was no effect of the AWM load on saccade task performance when participants responded to the saccade task first and the memory task second. Thus, the detrimental effect of the AWM load on saccade task performance in this experiment may have been due to response demands rather than to interference in memory per se. For example, participants who responded to the memory task first may have tried to maintain their response to the saccade task with a verbal code (i.e., “forward” or “backward”) which may have been disrupted by the verbal memory test. In contrast to the VWM task, there was no significant drop in AWM task performance under any of the dual task conditions.

In the individual subject AOC plots, the data are substantially noisier, but an overall trend is apparent: in the VWM AOC plots for most subjects VWM task performance (and sometimes saccade task performance) drops compared to single task performance. Meanwhile, the AWM AOC plots show less consistency. Some of this noise in the AWM AOC plots may be driven by the effect of response order on saccade task performance in Experiment 6B. For example, Subject 3, who had to respond to the saccade task after responding to the AWM task, showed markedly poorer performance on the saccade task under dual task conditions than other subjects.

Differences in individual AOC plots may also have been driven by individual differences in WM capacity and attention control. In the case of VWM task performance, it is possible a subject with a larger than average VWM capacity would not have difficulty performing both the saccade task and the VWM task concurrently, even if both tasks rely on VWM. A participant with smaller VWM capacity might struggle to complete both tasks well. Similarly, VWM capacity is thought to be related to attention control mechanisms, (Heitz & Engle, 2007; Unsworth, Schrock, & Engle, 2004). A participant with a larger VWM capacity would again be at an advantage in this dual task paradigm. Unfortunately, we did not measure our subjects' VWM capacities and so we cannot assess whether these scenarios may have played out in this dataset.

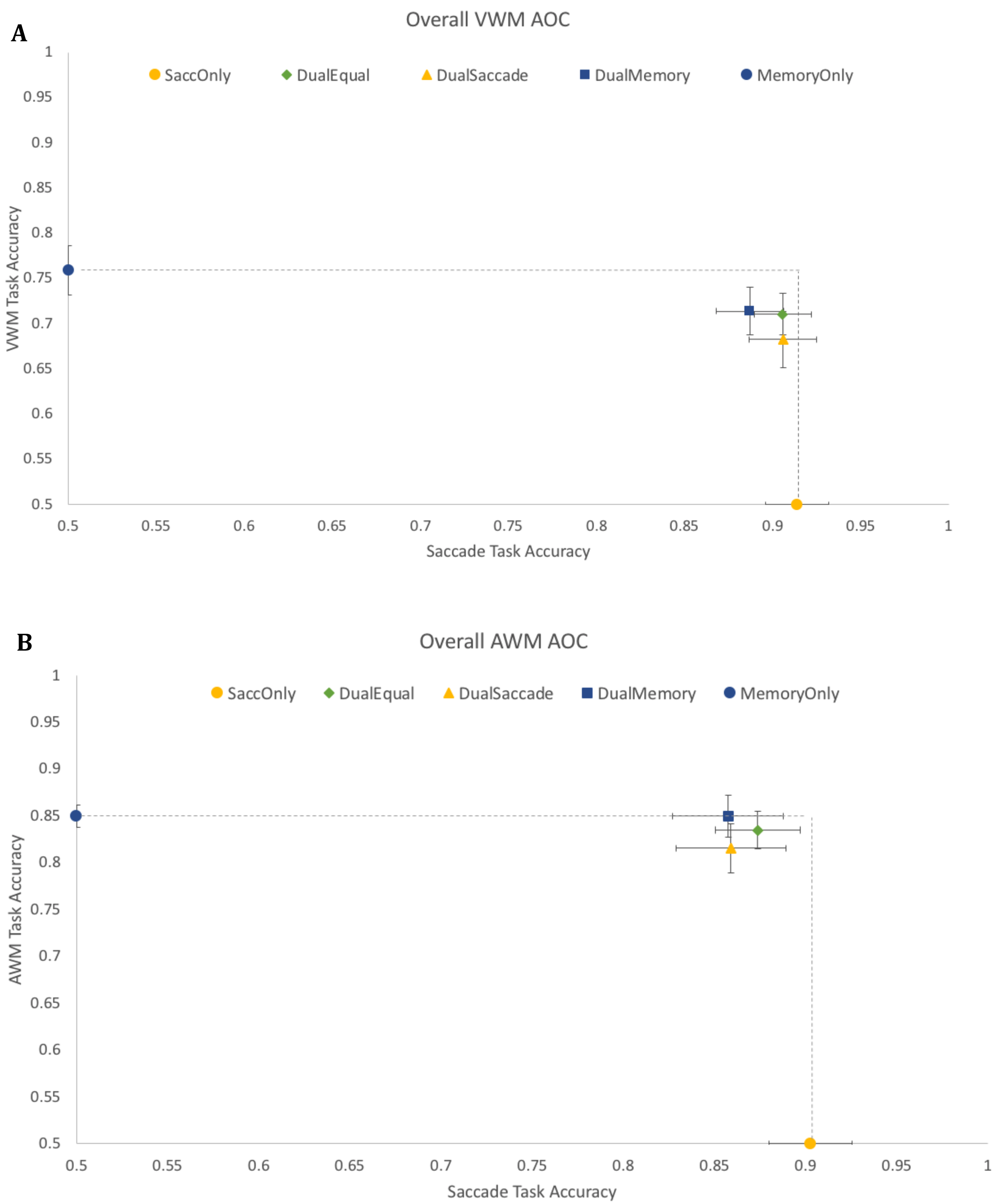
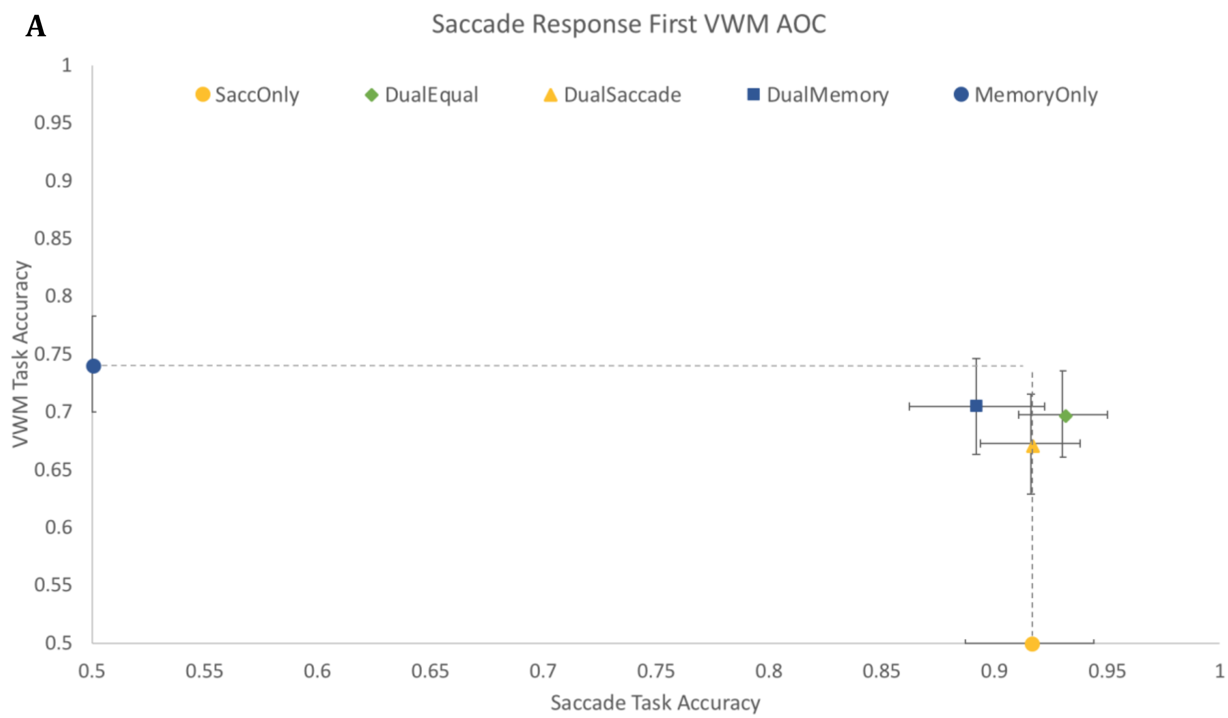


Figure 18. Overall AOC plots for Experiment 6A (A) and Experiment 6B (B). Saccade task performance is plotted on the X, memory task performance on the Y. Single task performance for each task is plotted on the corresponding axis.

A



B

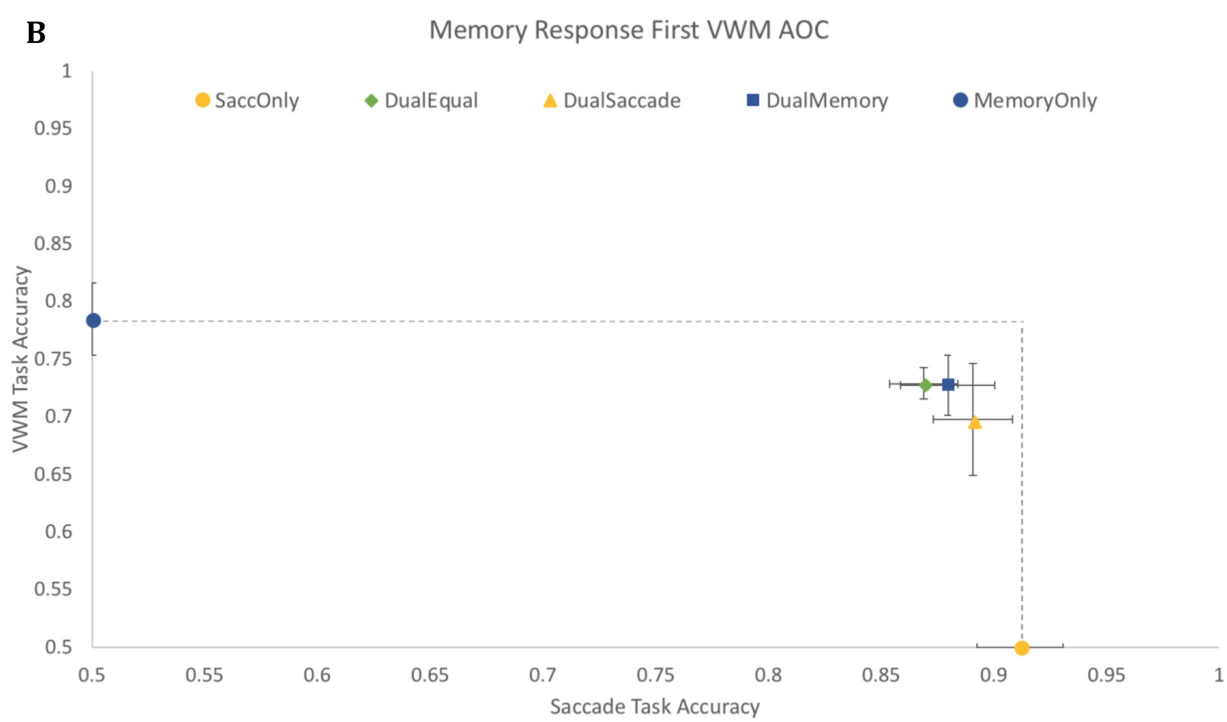
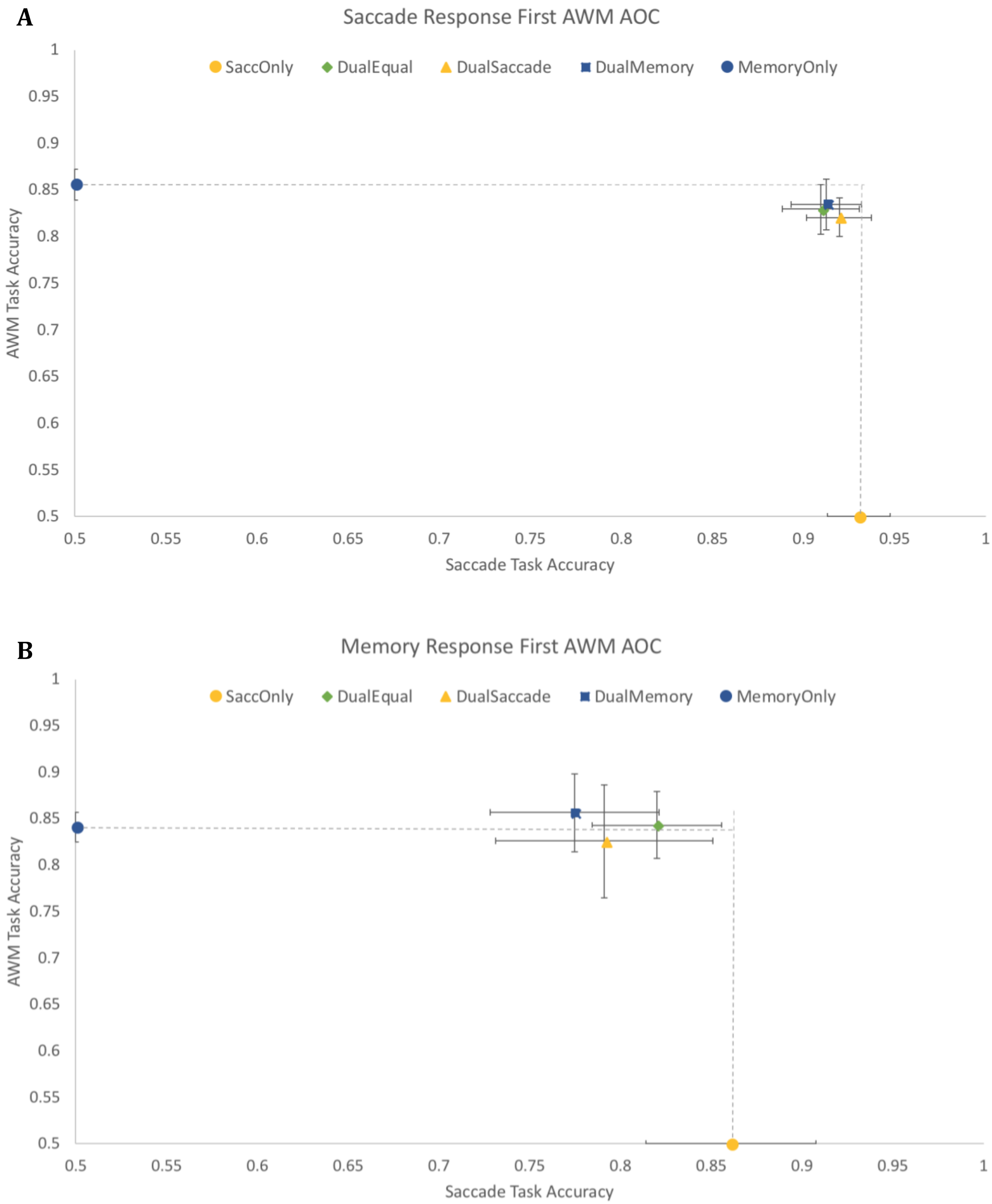


Figure 19. VWM AOC Plots for subjects who responded to the saccade task first (A) and the memory task first (B). The between-subjects effect of response order was not significant for either task.

A



B

Figure 20. AWM AOC Plots by participants response order. Participants who responded to the saccade task first (A) performed significantly better on the saccade task than participants who responded to the memory task first (B).

7.3 DISCUSSION

Experiments 6A and 6B complement the findings of Experiments 1-5. Participants performed significantly worse on a VWM task under dual task conditions than under single task conditions. This was not the case with an AWM task. Unlike prior experiments, we did not find a significant difference in saccade task performance when participants simultaneously performed a VWM task. In Experiment 4, the difference between saccade task performance under single and dual task conditions was only about 3% — a difference we may not have been sufficiently well-powered to detect in Experiment 6A. Regardless, in four experiments, we find consistent evidence of the saccade task interfering with VWM, suggesting a role for VWM in detecting and discriminating saccade target displacements. This claim is bolstered by the lack of interference between the saccade task and the AWM tasks in Experiments 3, 5, and 6B.

While the overall AOC plots were consistent with Experiments 1-5 (AOC-like plots for Experiments 1-5 are shown in the second appendix), individual subject plots varied in the extent to which they fit the pattern predicted by the prior experiments. Some subjects fit the predicted pattern perfectly, some subjects were not impaired by either WM task, and some subjects performed better on one or both of the tasks under dual task conditions. This variation may have been due to differences in participants' memory capacities, attention control abilities, and engagement, as well as noise created due to the response order manipulation. These possibilities were discussed in Section 7.3.4.

CHAPTER 8: GENERAL DISCUSSION

This sequence of six experiments provides direct evidence that VWM is involved in maintaining perceptual stability across saccades. Experiments 1, 2 and 4, using different VWM tasks and saccade tasks, showed that when their VWM was loaded, participants were less likely to notice displacements of their saccade target and were less able to discriminate the direction of that displacement compared to when they did not have a VWM load. Participants were also more likely to make errors on a visual memory task when they simultaneously had to detect displacements of their saccade target. In contrast, Experiments 3 and 5 showed that when participants had to remember verbal information while detecting saccade target displacements, their ability to detect saccade target displacements and to successfully perform the verbal memory task were unimpeded. In Experiment 3, we actually found improved performance on the saccade task under dual task conditions. This pattern of results suggests that participants rely on VWM resources to remember information about their saccade target object across a saccade and that they use this information in the perception of stability. Experiment 6 suggested that manipulations of participants' task priorities had relatively small effects on performance, indicating that the differences between VWM and AWM load effects in Experiments 1-5 were not due to differences in participants' dual-task priorities.

Our findings are consistent with theories that assume that VWM is recruited to establish object correspondence across saccades (e.g., Bays & Husain, 2008; Demeyer et al., 2010; Hollingworth et al., 2008; Irwin & Robinson, 2014, 2015; McConkie & Currie, 1996; Tas et al., 2012): VWM maintains features of the saccade target object before the saccade so that, after the saccade, we can search for those features near foveal vision. If the saccade target object features are detected near foveal vision, object correspondence is established and perceptual stability is maintained. Our results show that loading VWM interferes with the object correspondence process, presumably because a VWM load makes it harder for people to remember properties of the saccade target.

Our results are similar to those of Hollingworth et al. (2008), who showed that VWM plays an important role in gaze correction across saccades. As described in the Introduction, these authors found that a concurrent VWM load interfered with corrections of gaze to a memory-defined target, whereas a verbal working memory load did not. Thus, VWM appears to support several aspects of processing across saccades.

Several other recent studies are consistent with the conclusion that VWM supports the perception of stability across saccades. For example, visual factors that affect the quality of the representation of the saccade target in memory, such as contrast (Matsumiya, Sato, & Shioiri, 2016), preview duration (Zimmermann, Morrone, & Burr, 2013), and size (Zimmermann, 2016) have been shown to affect displacement perception across saccades. In addition, Irwin and Robinson (2015) found that the detection of stimulus displacement across saccades was capacity-limited and largely (but not exclusively) focused on the saccade target. It has also been demonstrated that a saccade disrupts VWM task performance when transcranial magnetic stimulation (TMS) is applied to parietal or early visual cortex presumably because TMS prevents the neurons maintaining the visual representation of the memory from undergoing remapping, thereby disrupting memory for that object (Prime et al, 2008; Malik, Dessing, & Crawford, 2015).

Recently, Tas, Luck, and Hollingworth (2016) proposed that VWM obligatorily encodes information about the saccade target regardless of its current load, overwriting information as necessary. Their subjects performed worse on a VWM task when they had to make a saccade to a saccade target compared to when they were required to make a covert shift of attention to the target or made a saccade to an empty region of space (see also, Shao, Shui, Zheng, Lu, & Shen, 2010). This explanation is consistent with the loss of memory task item information we found under dual task conditions in Experiments 1, 2, and 4, as reflected by the ~0.6-0.9 item decreases in K values.

Although it is possible that the source of interference we have observed between saccade target displacement detection and a VWM load is due to the saccade target being obligatorily encoded into VWM, it is also possible that the two tasks interfere by drawing attentional resources away from each other rather than by creating a capacity-consuming memory representation of the saccade target. In other words, although our results show that the two tasks rely on an overlapping resource to some extent, they do not necessarily demonstrate that this resource is a capacity limited memory store. An additional complication is that there is considerable debate about whether VWM should be conceptualized as a discrete item-based store (e.g., Adam, Vogel, & Awh, 2017; Cowan, 2001; Luck & Vogel, 1997; Zhang & Luck, 2008) or as consisting instead of a continuous resource that can be distributed over memory representations in a graded fashion (e.g., Bays & Husain, 2008; van den Berg, Shin, Chou, George, & Ma, 2012; Wilken & Ma, 2004). Regardless of its underlying structure, our findings show interference between a VWM load and saccade displacement detection, thereby implying a role for VWM resources in the perception of stability across saccades. The lack of interference between the AWM load and the saccade task is consistent with research that has shown that information in AWM can be rehearsed using domain-specific resources in addition to central attentional ones (e.g., Ricker & Cowan, 2010; Ricker, Cowan, & Morey, 2010).

It is also important to note in this study we do not distinguish between the feature or object-based and spatial subcomponents of visual working memory. Saccade Target Object Theory predicts interference in the object subsystem of VWM, but from our data it is possible that the interference found in Experiments 1, 2, 4, and 6 is in the spatial subsystem. All of the visual tasks used in this study have both a spatial and feature component (the color patches have unique locations) while the verbal tasks had no spatial component (letters were presented in a stream at fixation or through speakers). Future studies should investigate the relative contributions of spatial and feature VWM and spatial AWM to saccade target displacement detection.

One limitation of the first 5 experiments is that we had no control over how participants prioritized the displacement perception task and the working memory task under dual-task conditions. It was reassuring that each task interfered with the other in Experiments 1,2, and 4 and that neither task interfered with the other in Experiments 3 and 5. In general it seemed that the displacement perception task interfered with the VWM task more than the VWM task interfered with the displacement perception task, which may suggest that displacement perception received higher priority. This was supported to some extent by Experiment 6, which explicitly manipulated participants' priorities in an AOC design and showed that the displacement perception task interfered more with the VWM task than the reverse, regardless of the priority manipulation. Variations in individual participant's AOC curves and the significant negative correlation between VWM performance and displacement perception performance reported in the discussion of

Experiment 5 suggests that individual subjects may differ in their ability and/or willingness to give more priority to one task than to the other, however. Future studies should examine more closely the extent to which individual differences in VWM capacity affect subjects' sensitivity to transsaccadic changes and the relative contributions of feature- or object-based and spatial VWM to perceptual stability.

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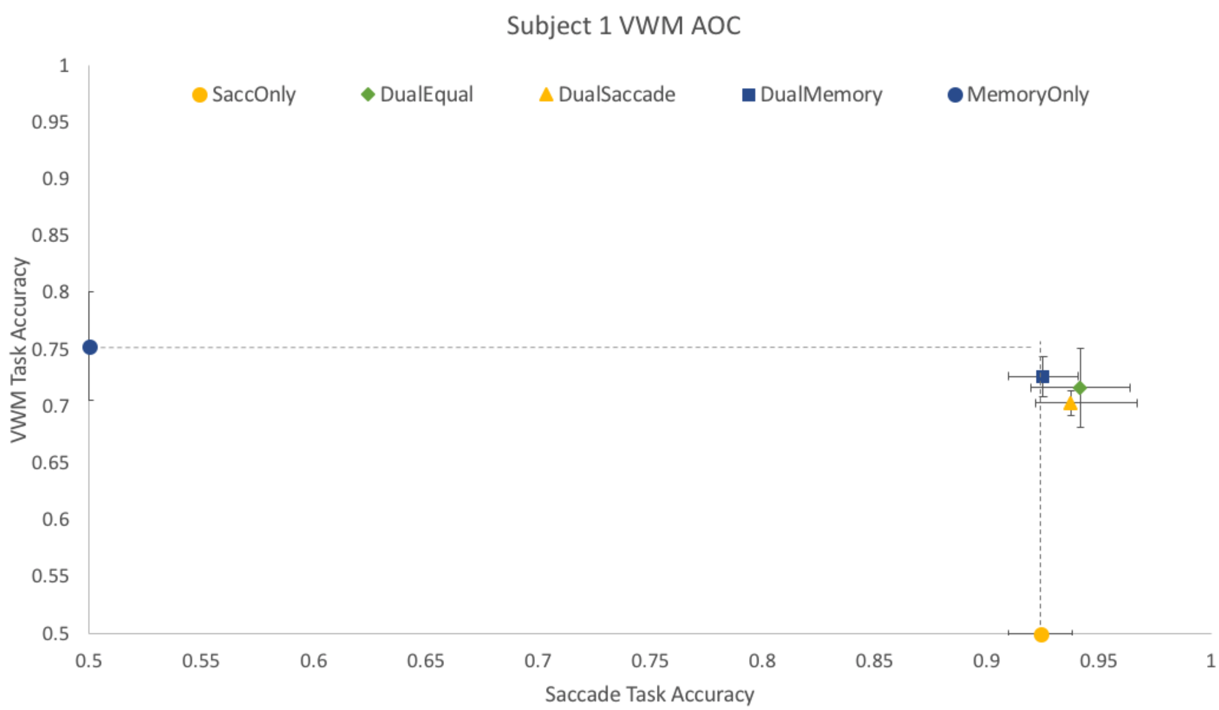
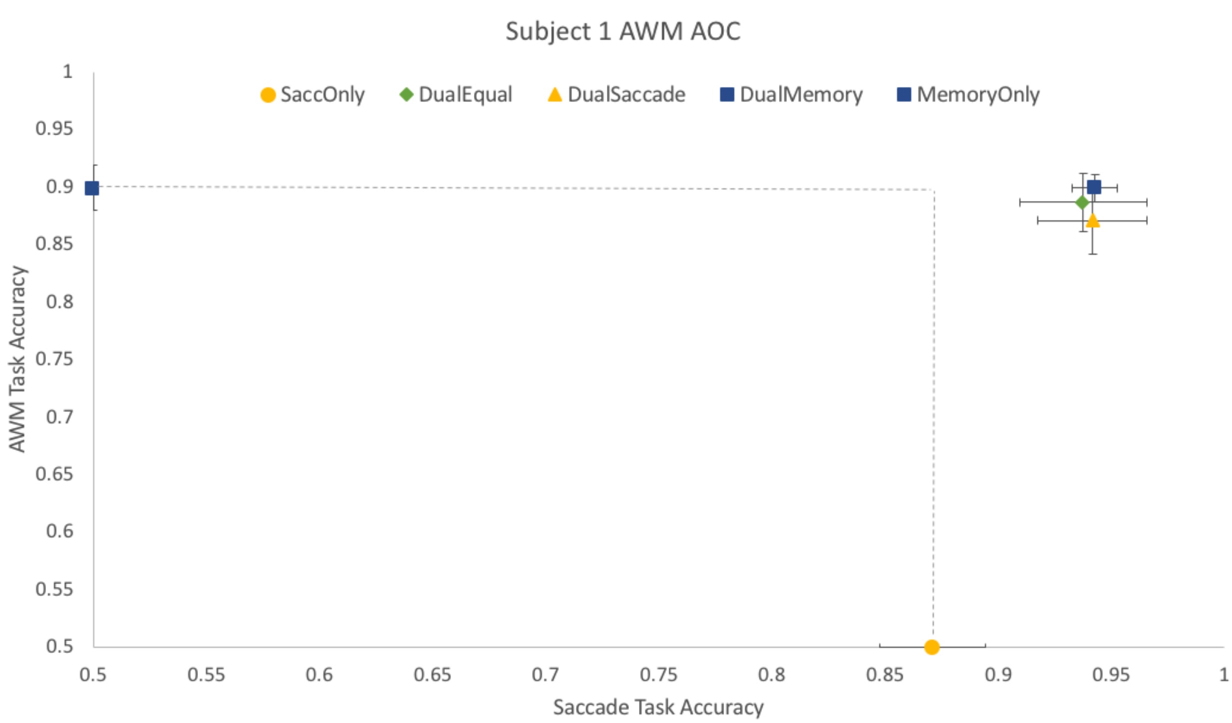
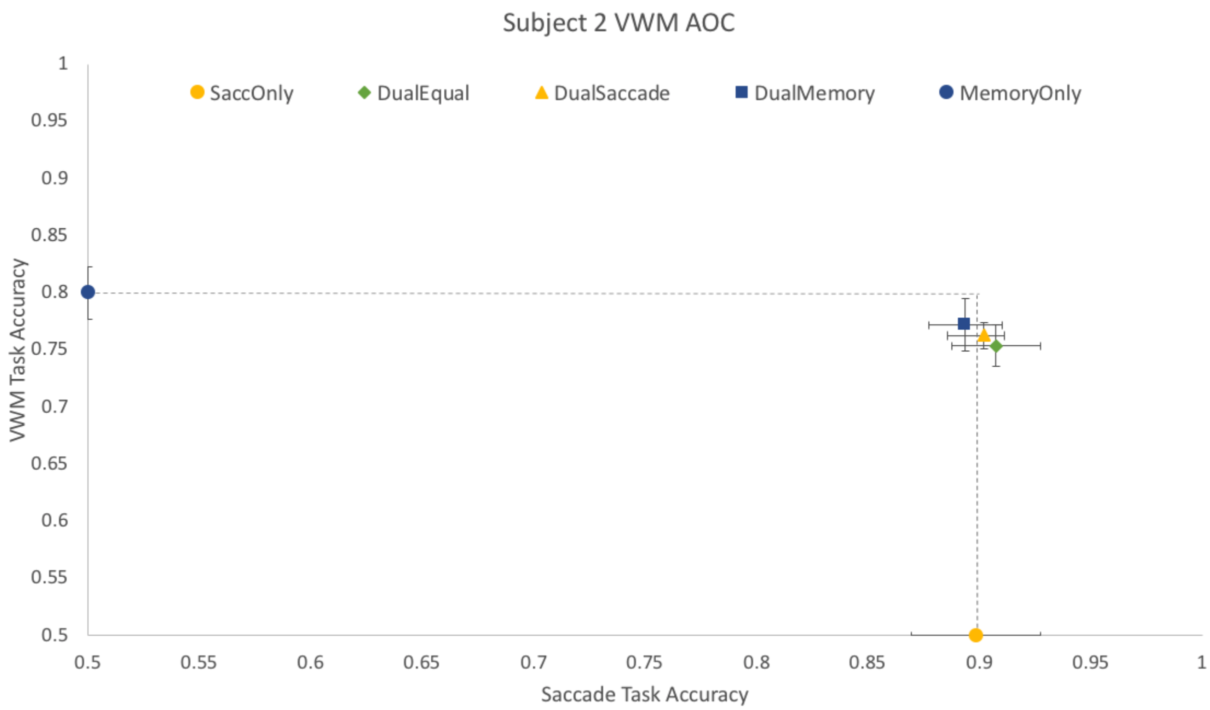
APPENDIX A: INDIVIDUAL SUBJECT AOC PLOTS

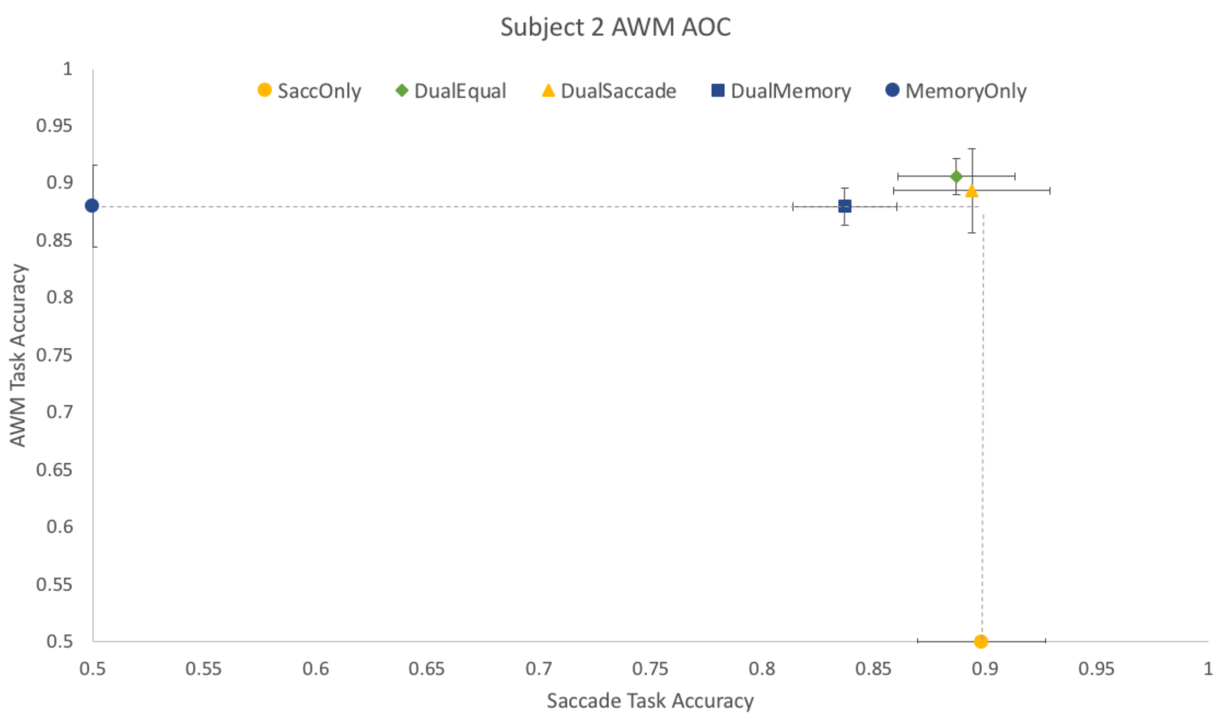
Subject 1 AOC Plots
Response Order: Saccade task first



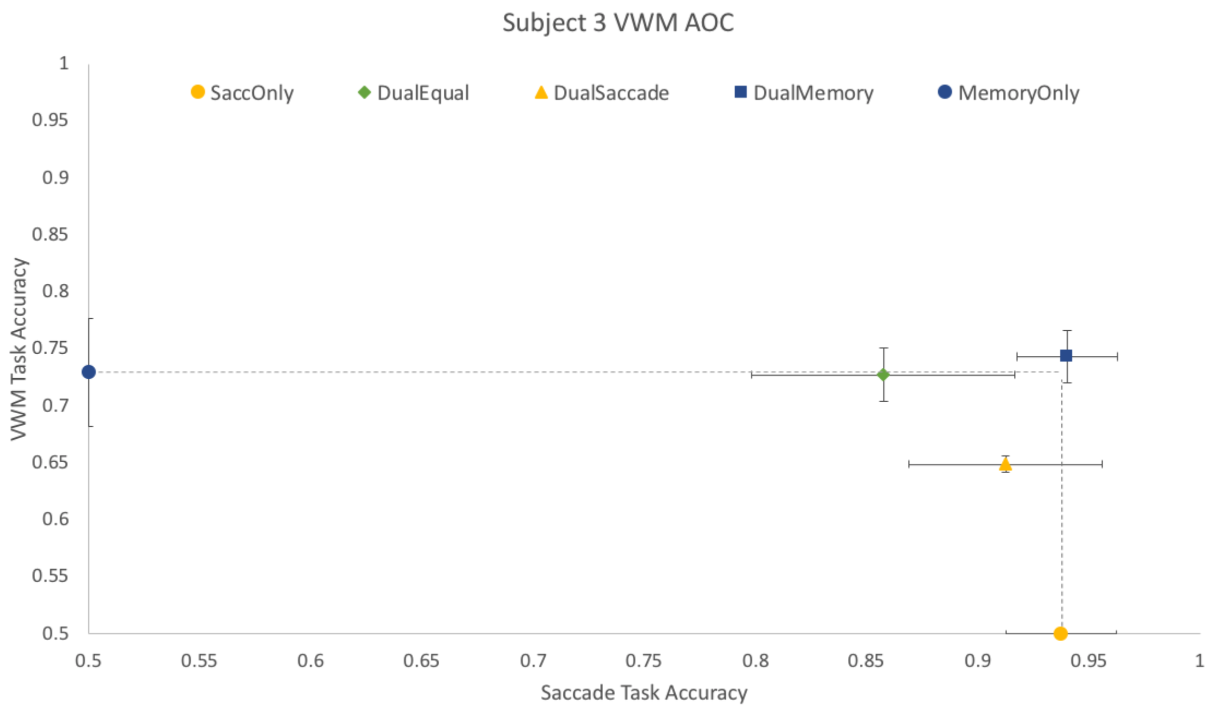


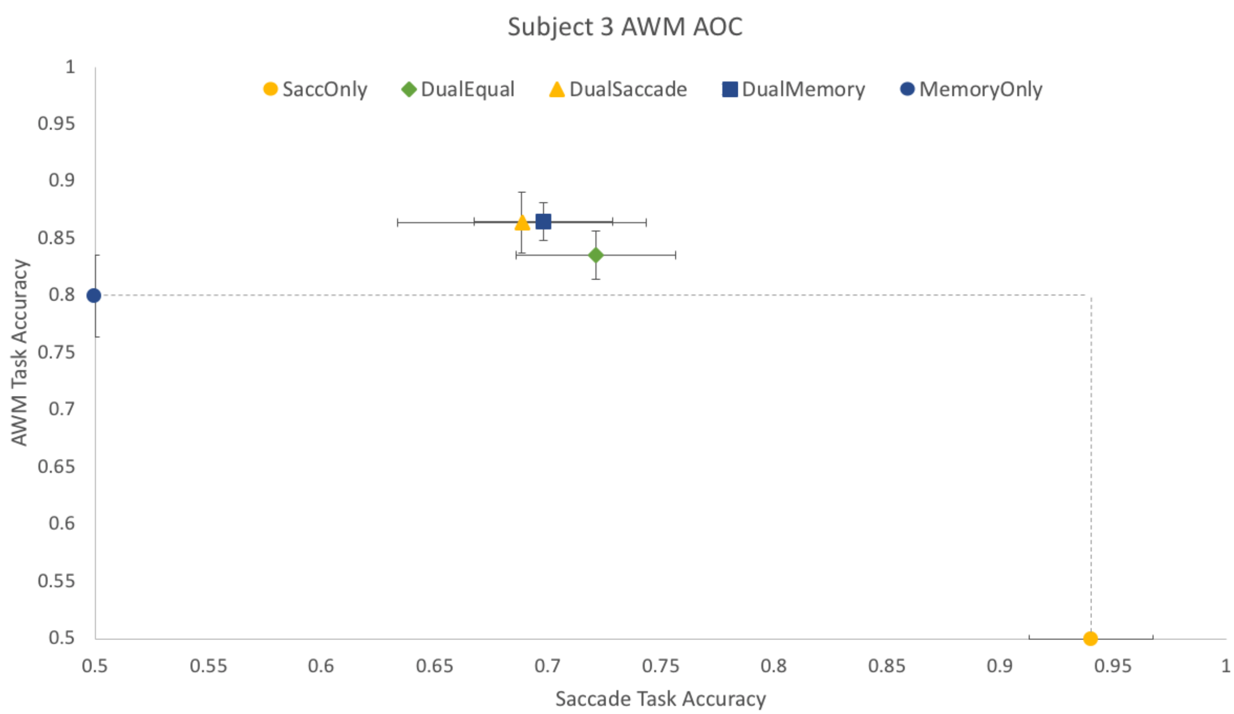
Subject 2 AOC Plots
Response Order: Memory task first



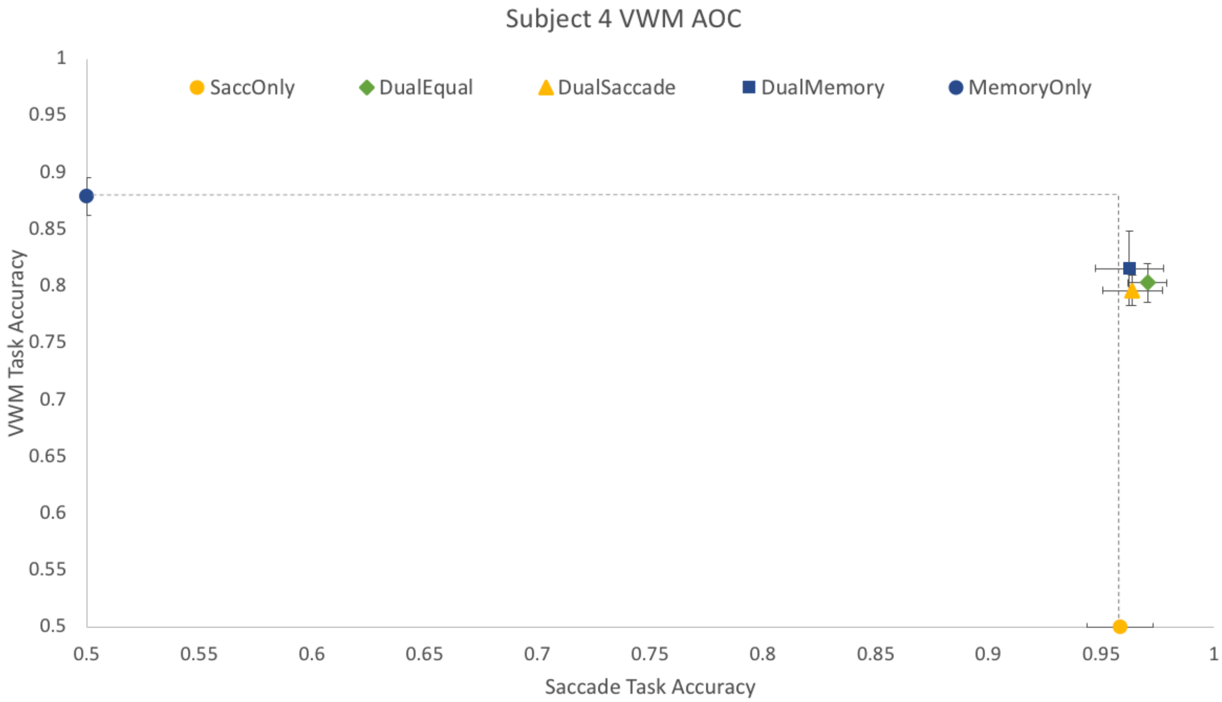


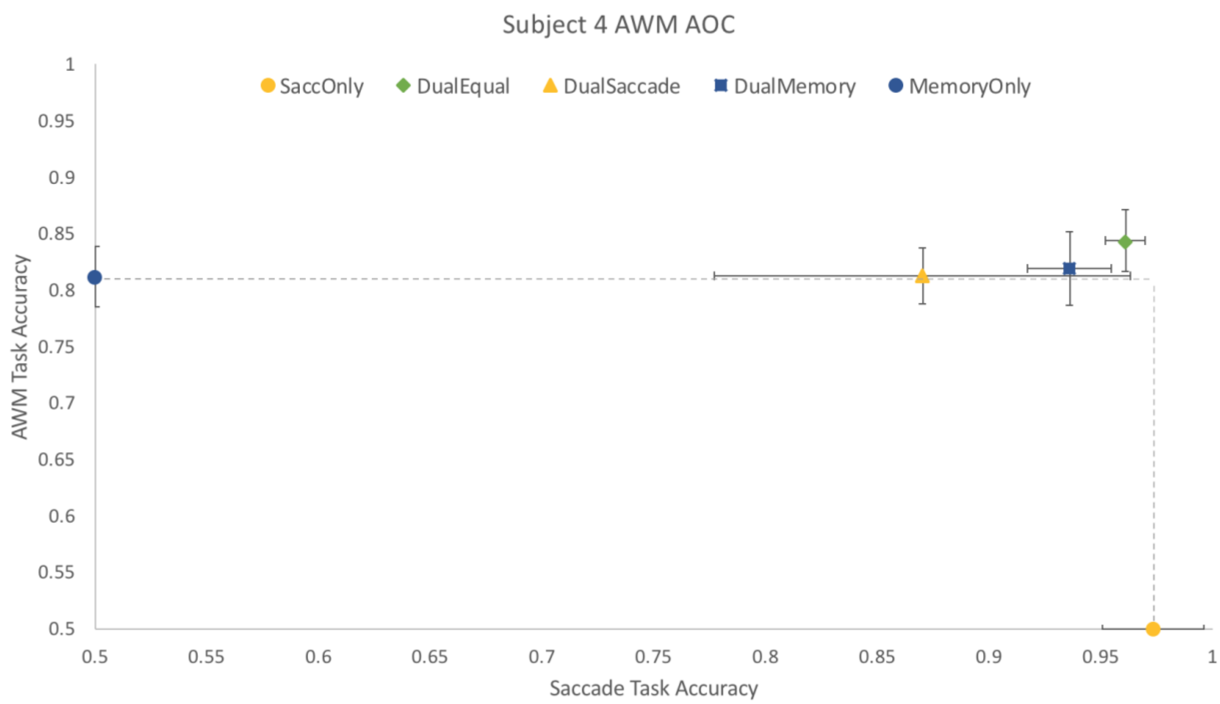
Subject 3 AOC Plots
Response Order: Memory task first



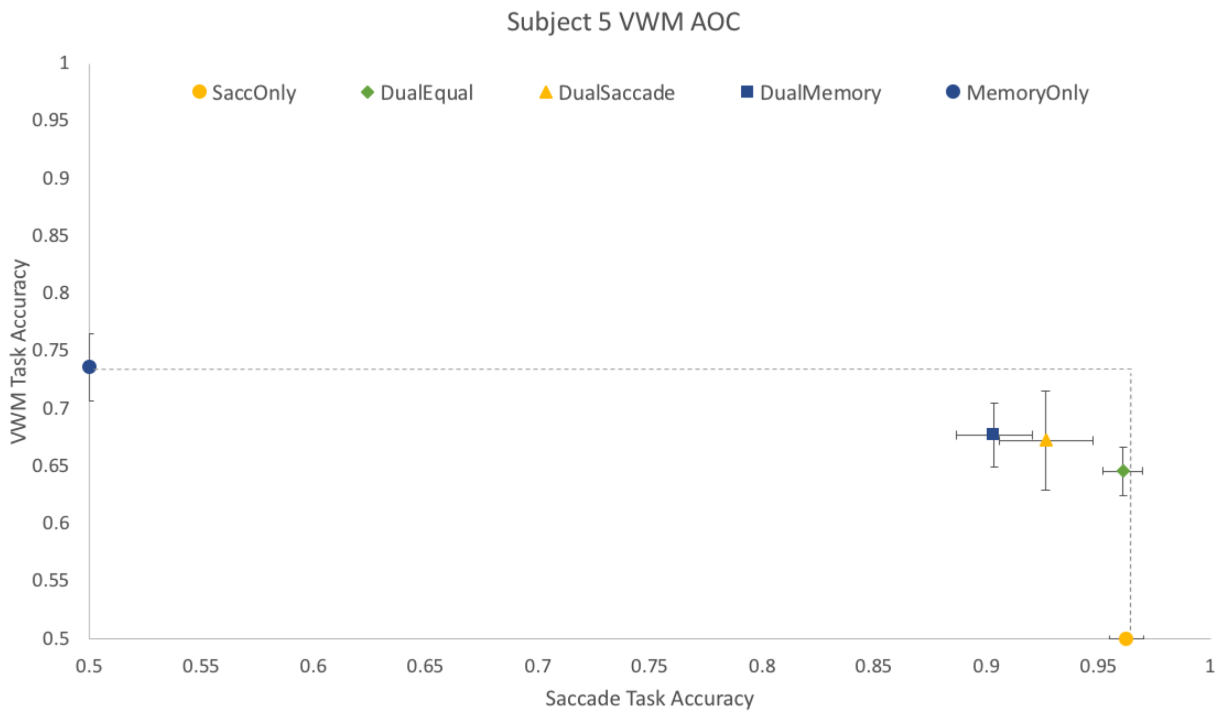


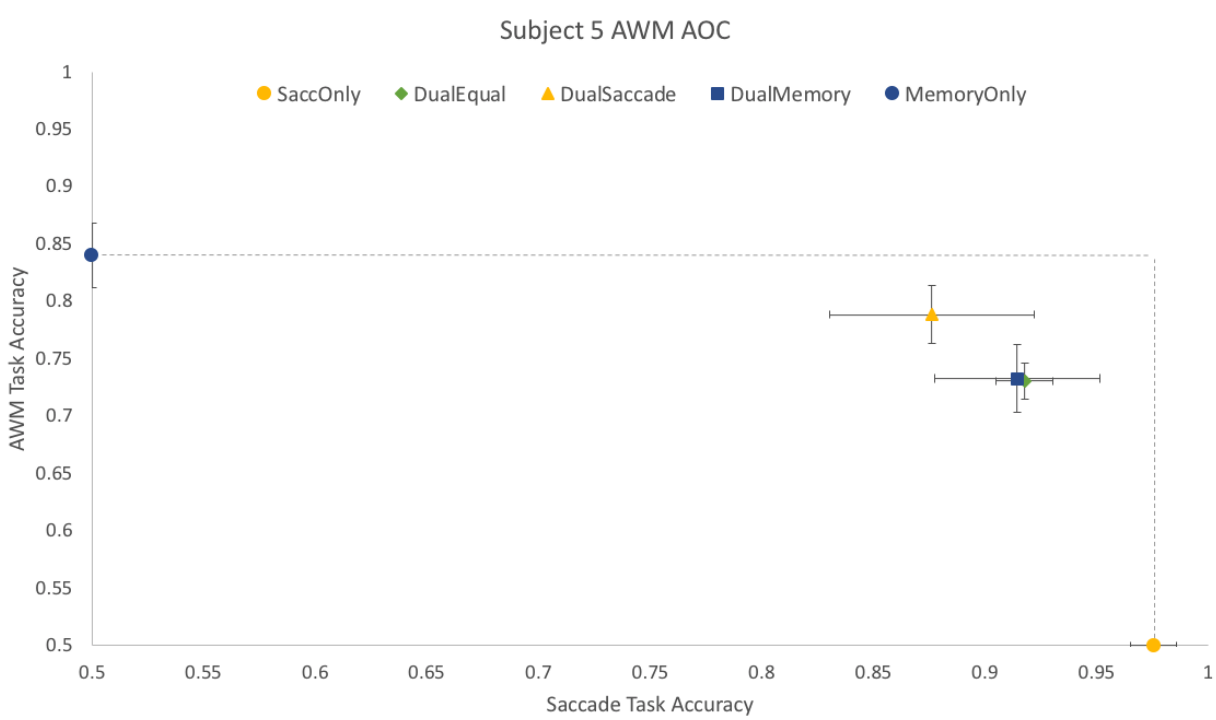
Subject 4 AOC Plots
Response Order: Saccade task first



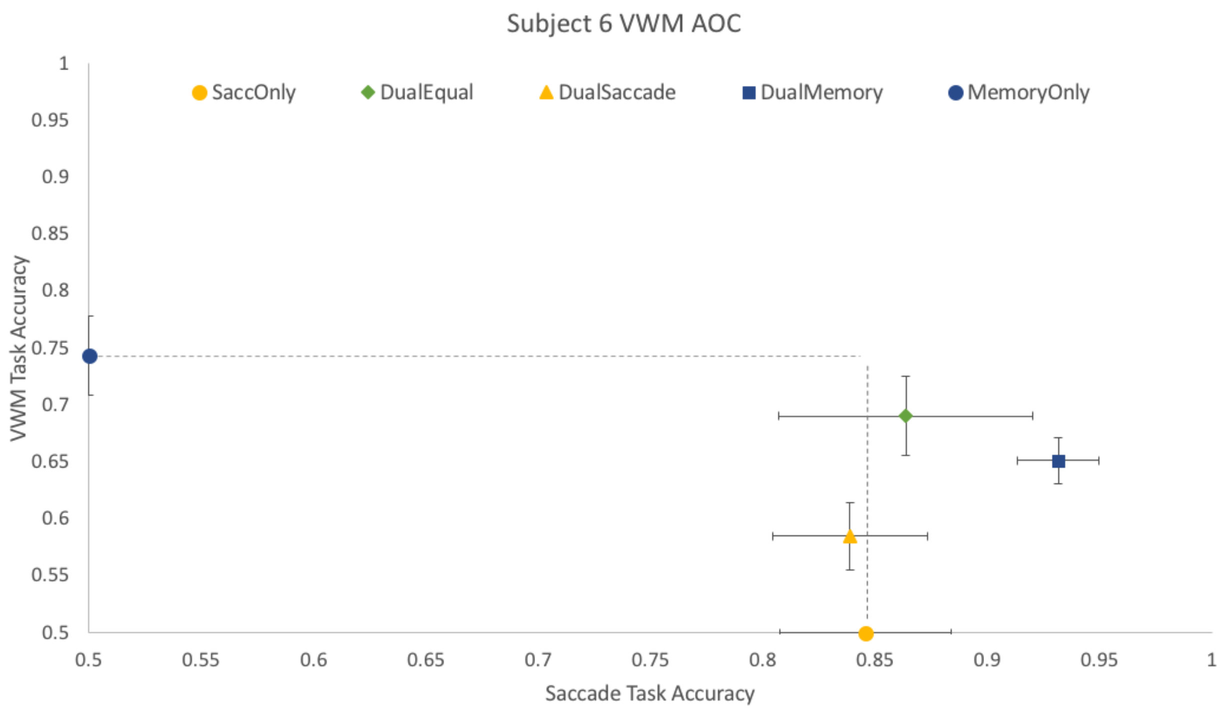


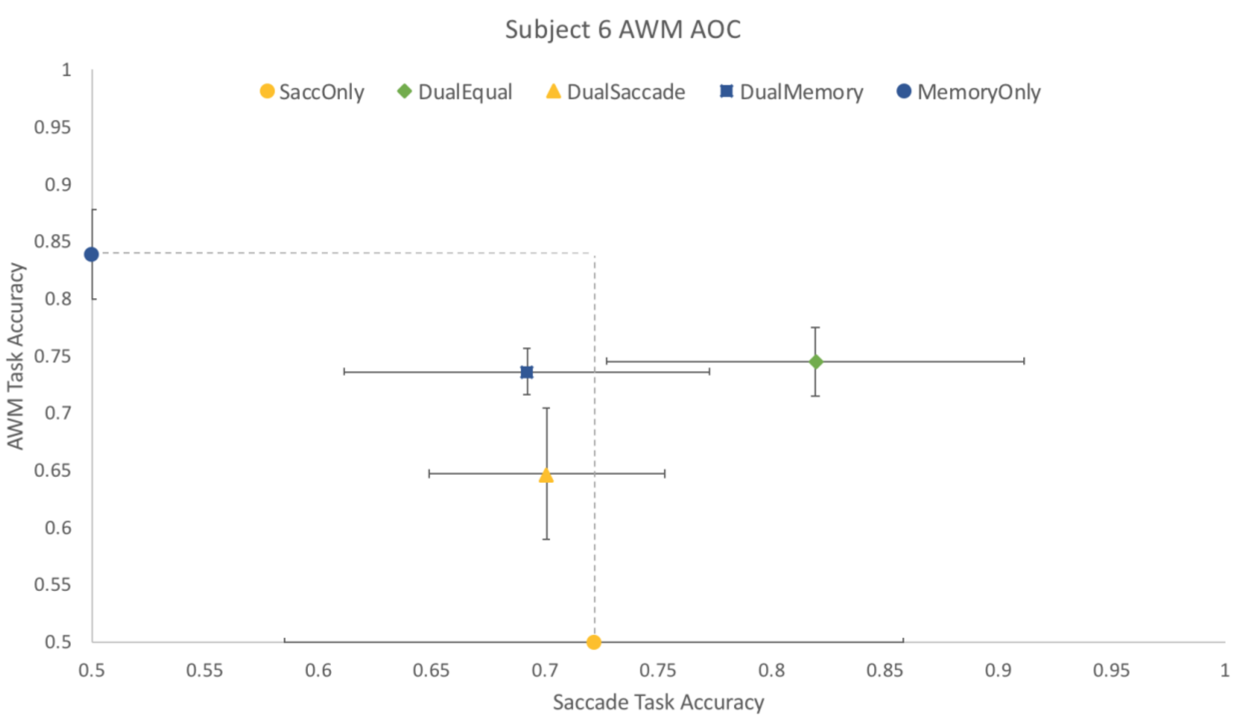
Subject 5 AOC Plots
Response Order: Saccade task first



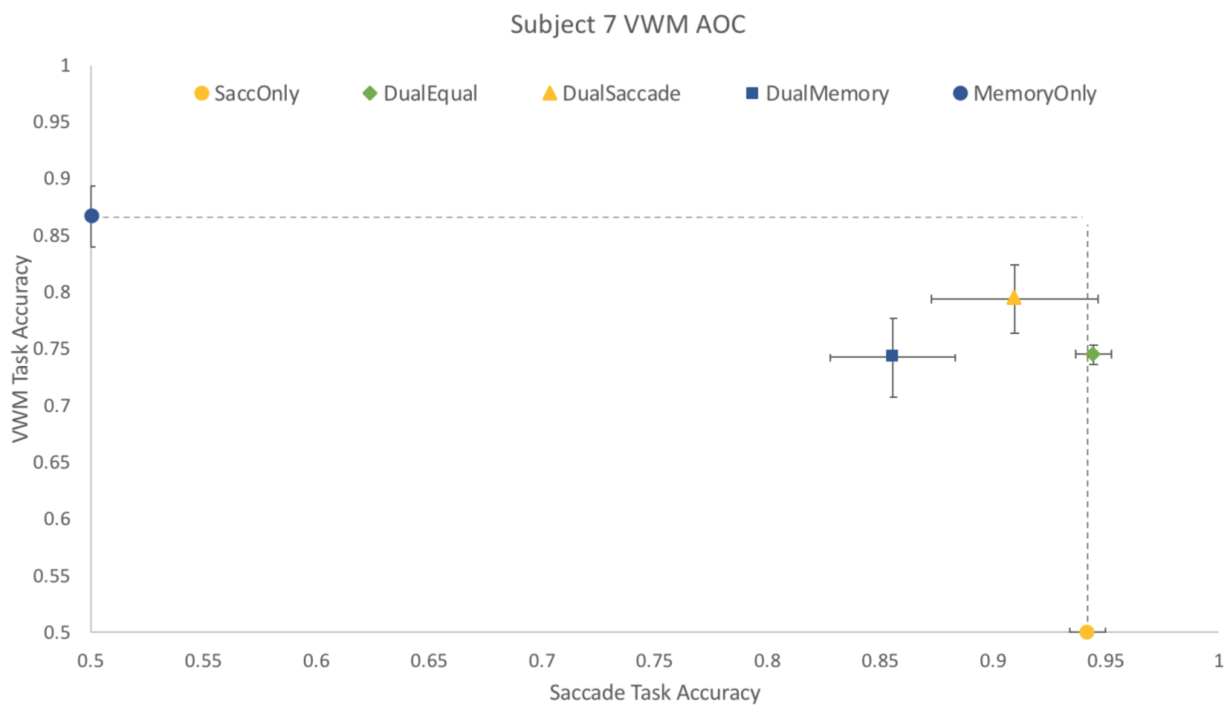


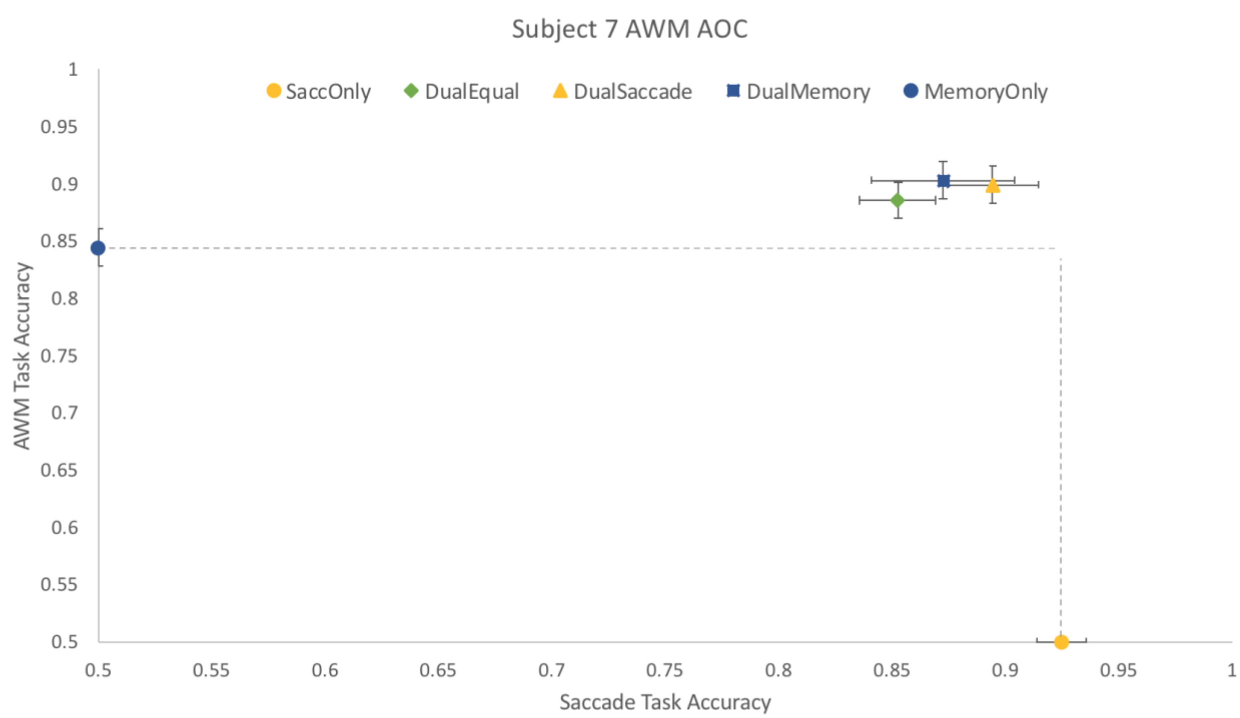
Subject 6 AOC Plots
Response Order: Memory task first



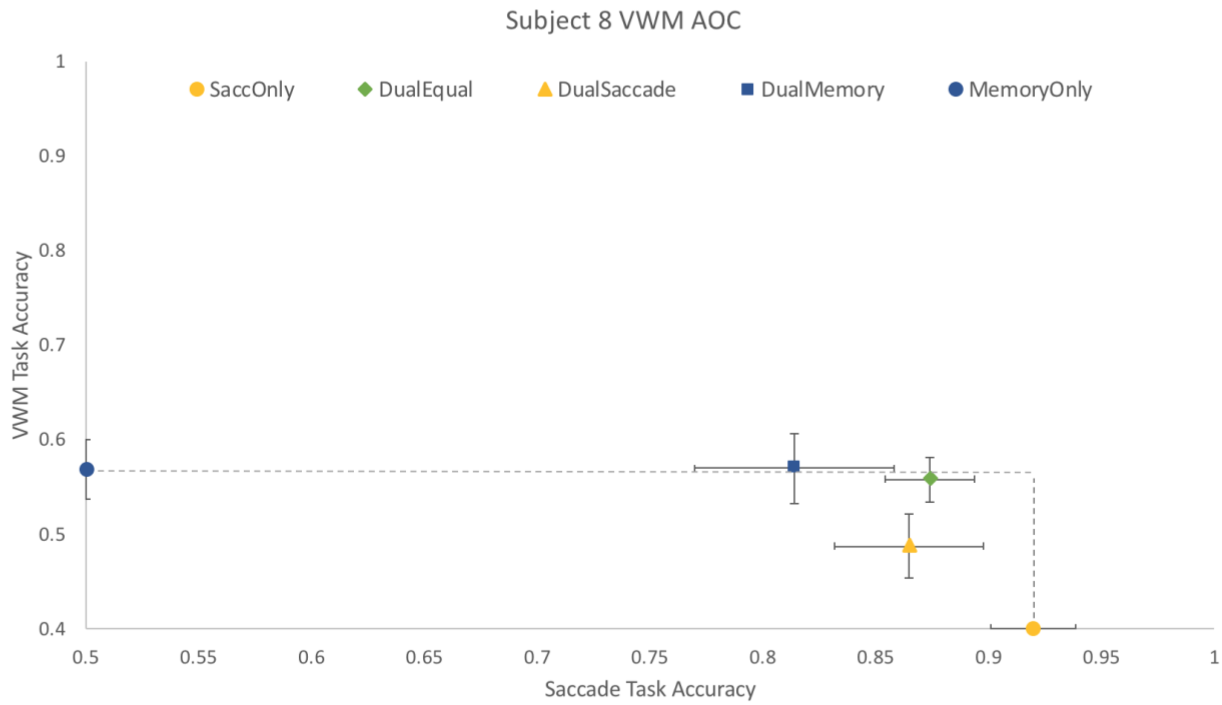


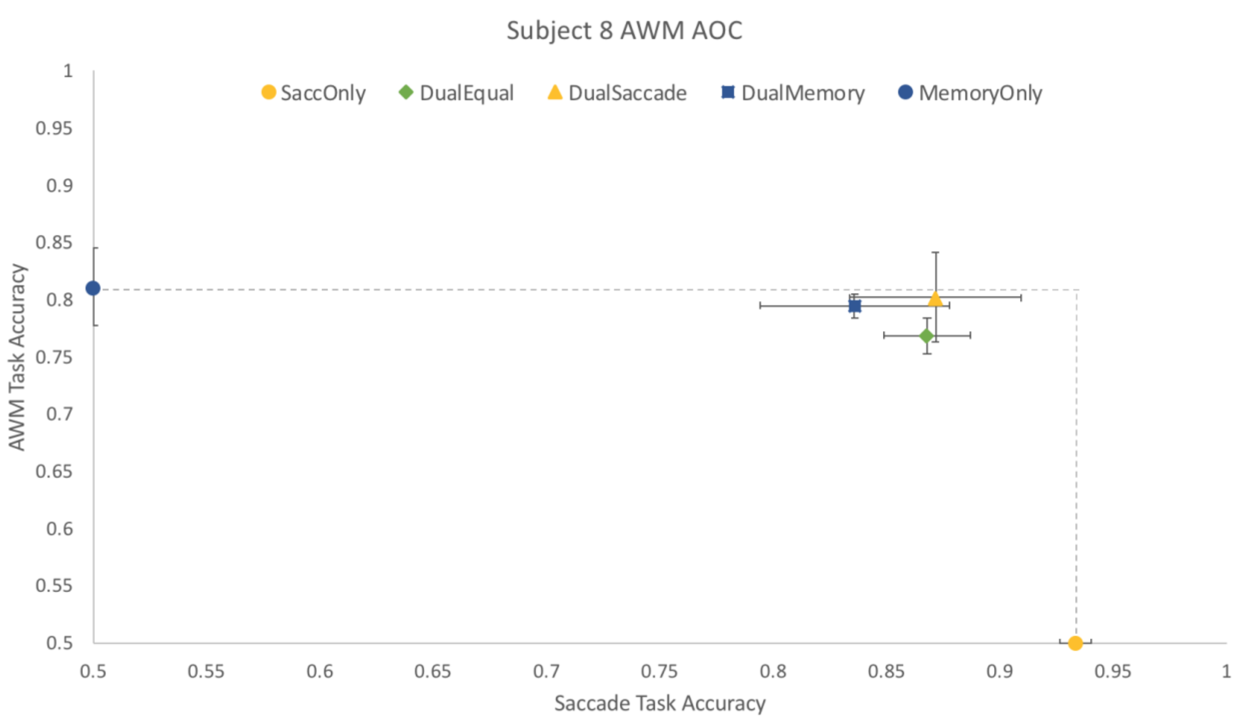
Subject 7 AOC Plots
Response Order: Memory task first



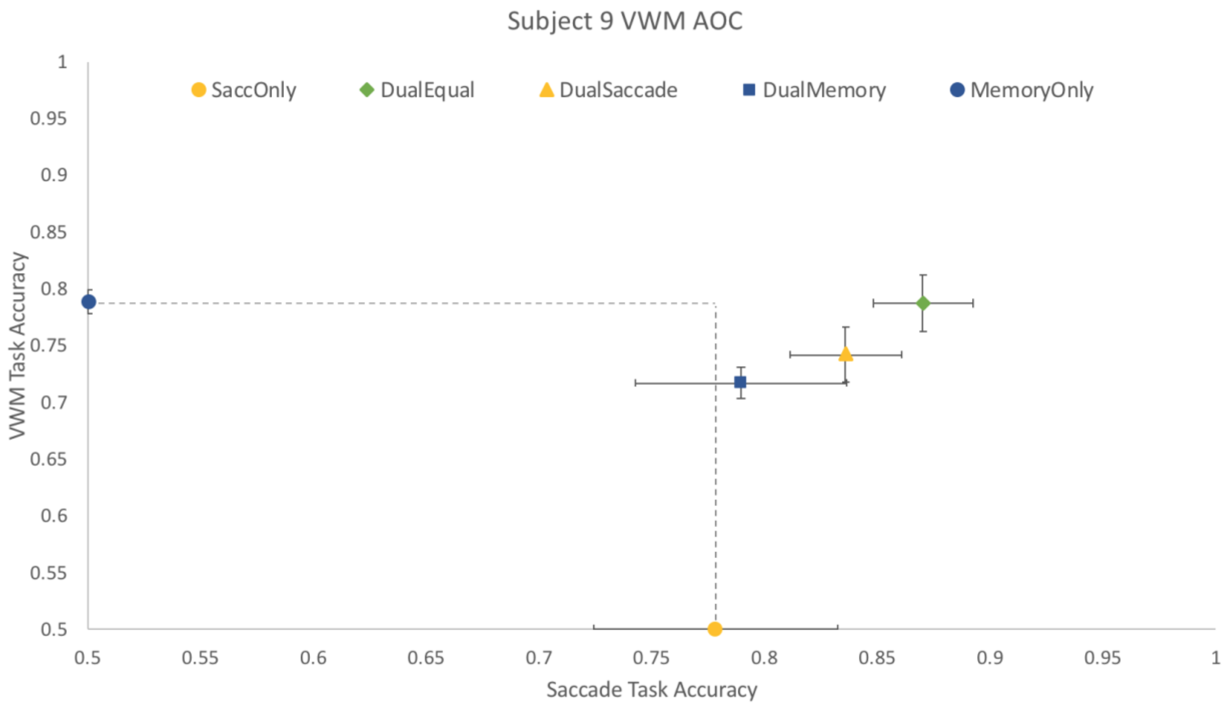


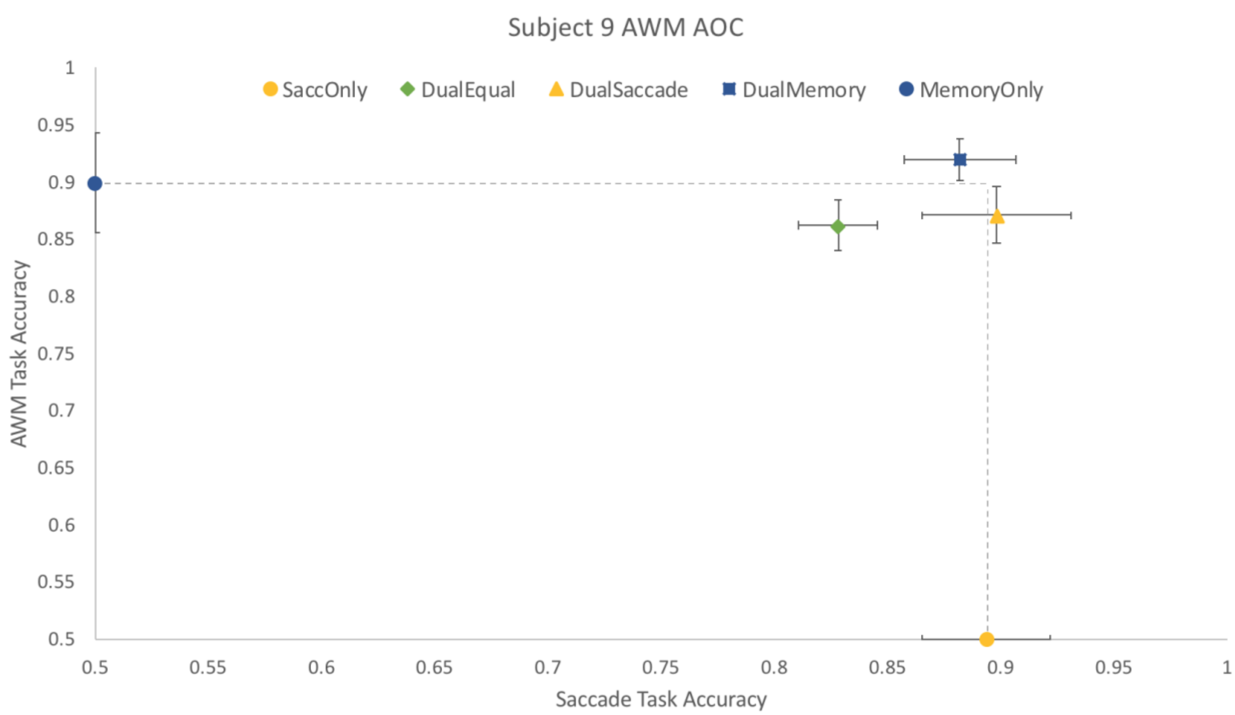
Subject 8 AOC Plots
Response Order: Saccade task first
*NOTE: VWM Y-AXIS starts at 0.4



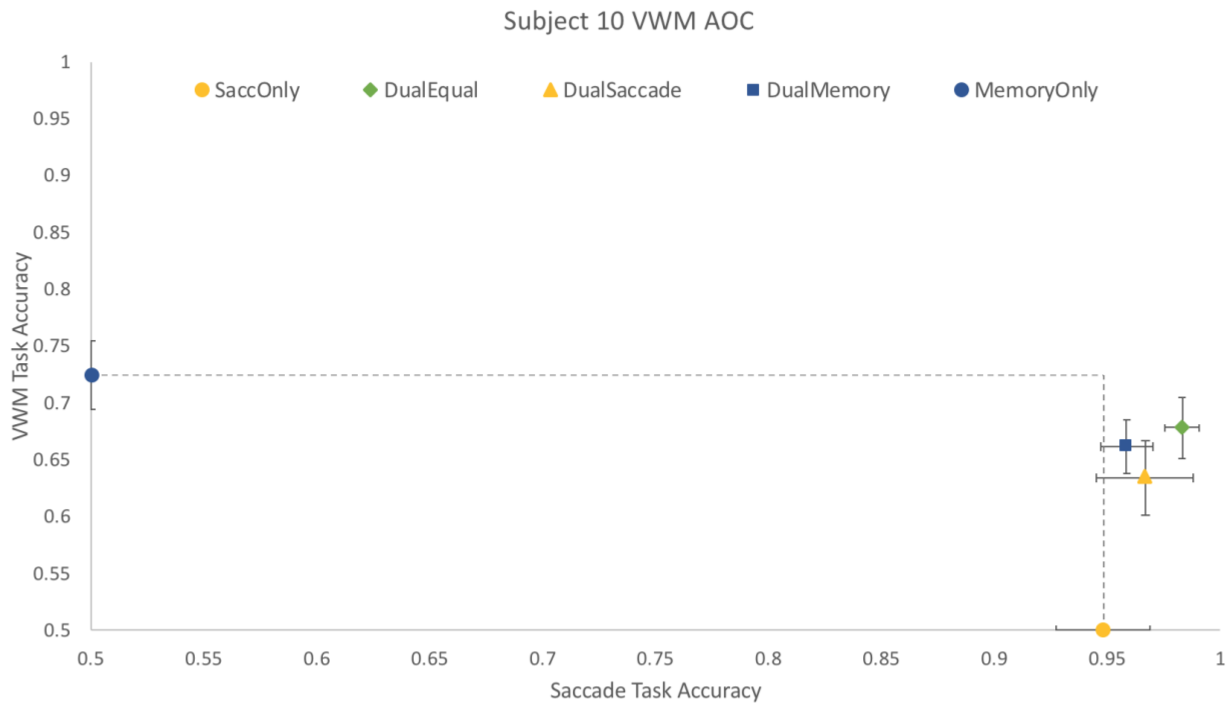


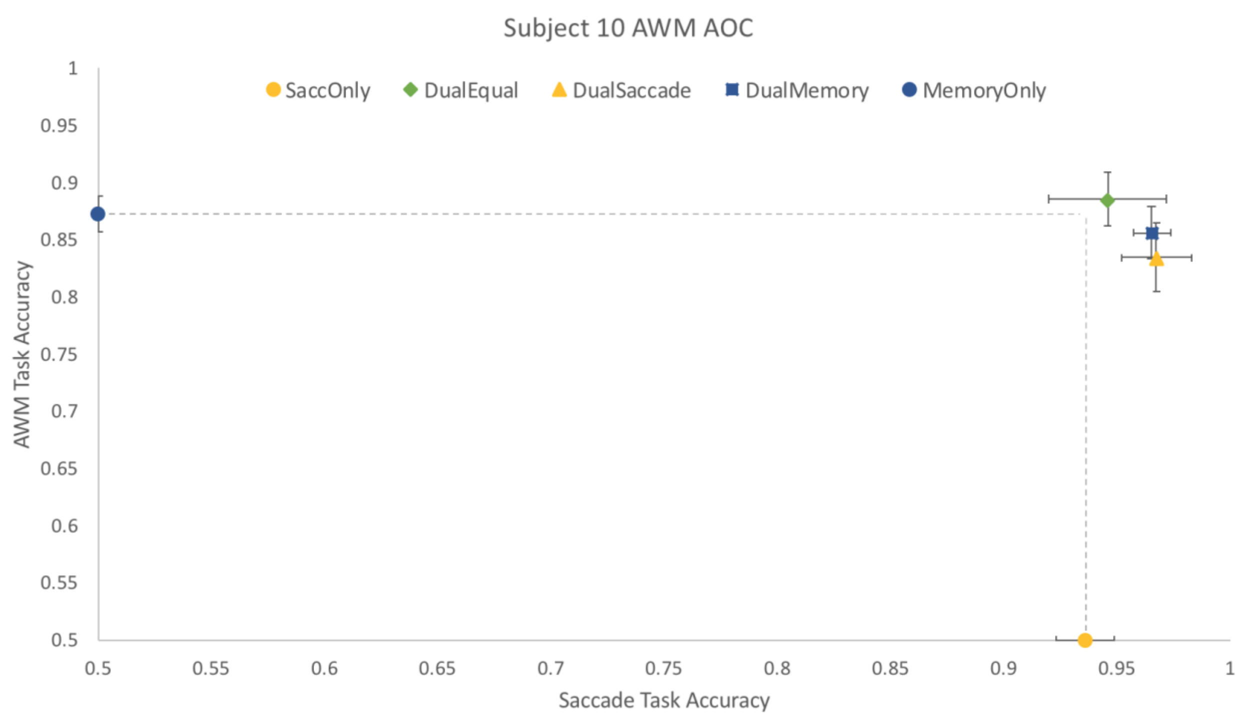
Subject 9 AOC Plots
Response Order: Saccade task first



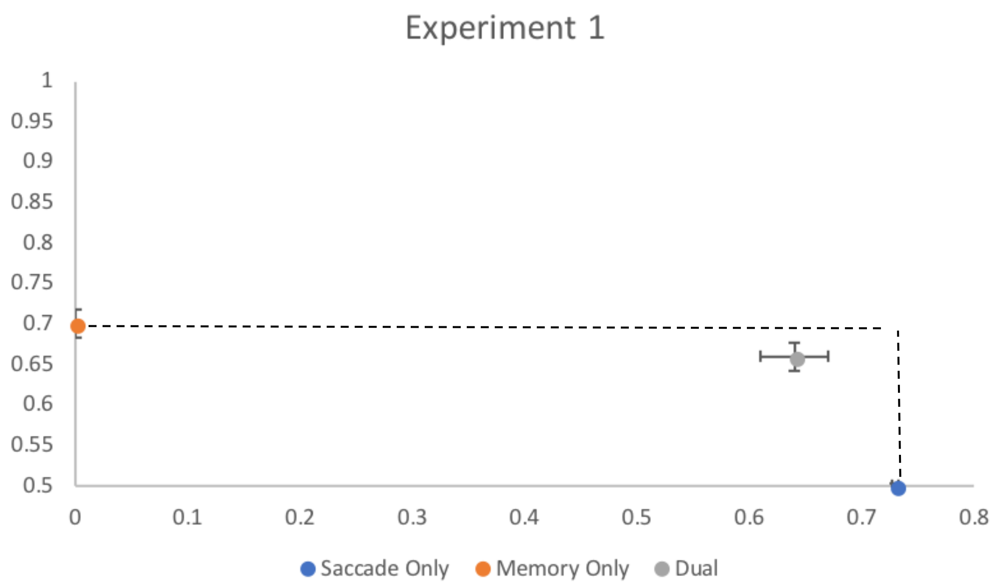


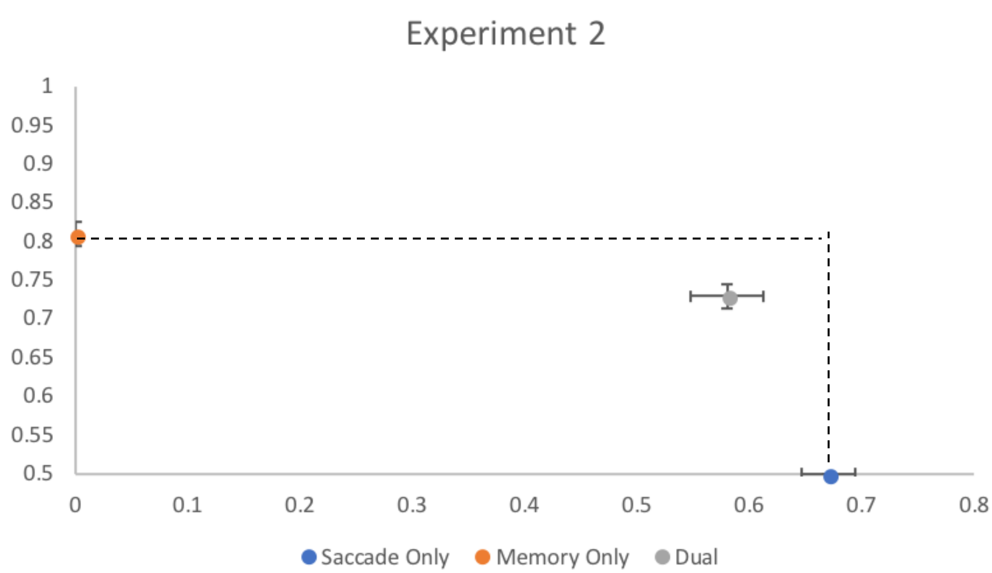
Subject 10 AOC Plots
Response Order: Saccade task first

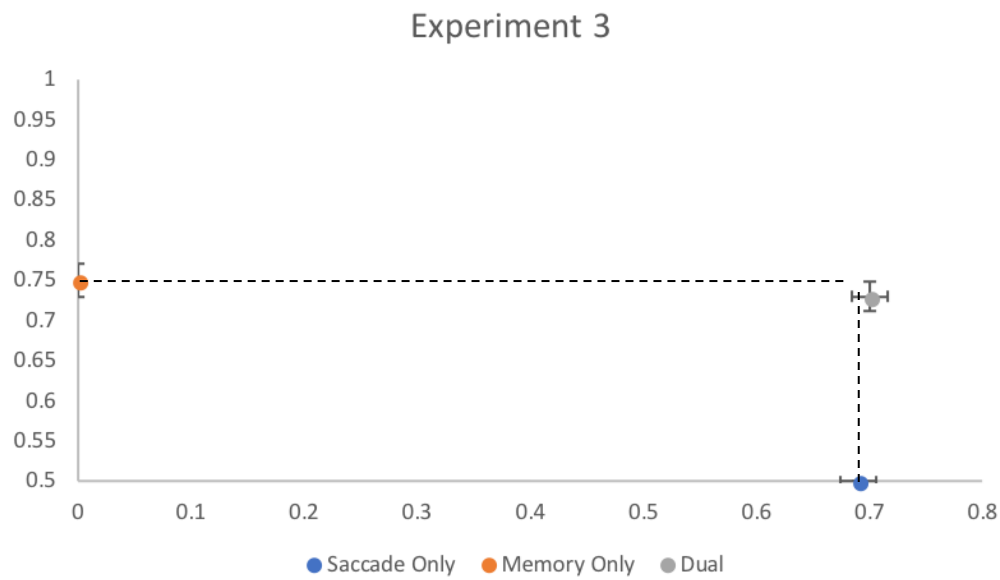


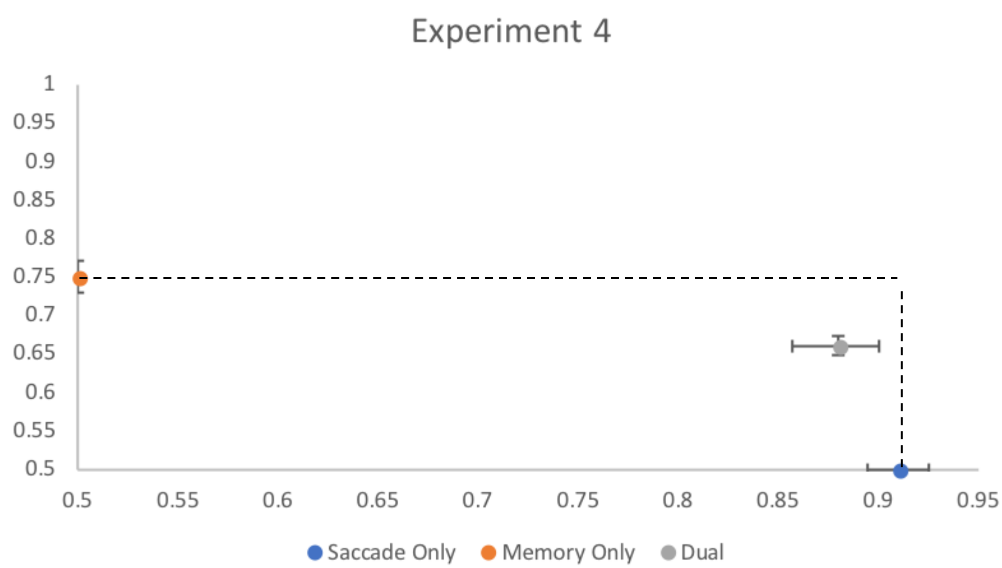


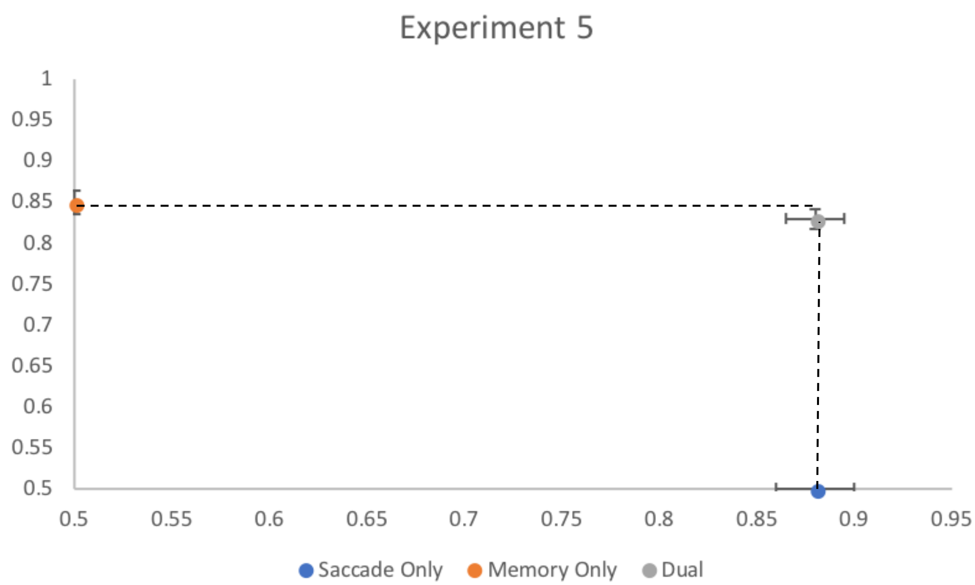
APPENDIX B: AOC-LIKE PLOTS FOR EXPERIMENTS 1-5






Experiment 3
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Saccade Only
Memory Only
Dual


Experiment 4
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
Saccade Only
Memory Only
Dual


Experiment 5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
Saccade Only
Memory Only
Dual