Ready, Set, Rotate: The Relationship Between Working Memory Capacity and Mental Rotation Speed

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Abstract

Higher working memory capacity has been linked to greater accuracy and speed on mental rotation tasks (Hyun & Luck, 2007; Kaufman, 2007; Pardo-Vasquez & Fernandez-Rey, 2012). In general, participants are slower to respond to mental rotation stimuli that are rotated at more extreme angles from each other or from "normal" orientation. The present study added to the research in this area by examining how this angular deviation reaction time effect varied as a function of working memory capacity (as measured by operation span [OSPAN]) across both 2D and 3D mental rotation tasks. Participants completed a computerized OSPAN task, to determine their working memory capacity, as well as computerized 2D and 3D mental rotation tasks. Inconsistent with previous research (e.g., Hyun & Luck, 2007; Pardo-Vasquez & Fernandez-Rey, 2012), higher working memory capacity participants were not faster than those with lower working memory capacity. However, only lower working memory capacity participants exhibited the typical angular deviation reaction time effect. The current results imply that working memory is utilized for mental rotation, and situations of higher processing demand do not impede the mental rotation speed of those with higher capacities to the extent of those with lower capacities. These results could imply that people with higher working memory capacity approach mental rotation tasks differently than those with lower working memory capacity.

Keywords: working memory, mental rotation, reaction time, operation span

Many of the complex cognitive tasks we complete every day would not be possible without working memory. Working memory is a part of conscious memory, which is utilized to hold on to some information while working with separate information to solve a problem or complete a task (Baddeley & Hitch, 1974). Daneman and Carpenter (1980) defined working memory as a cognitive system responsible for the simultaneous storage and manipulation of information. For example, a task as simple as reading requires working memory. One must hold onto previously encoded information (i.e., storage of information) to make sense of the sentence one is currently trying to read and comprehend (i.e., manipulation of information). Because of working memory's cognitive resource limits and rapid loss of information, it has a limited capacity, and many studies reveal that individuals vary with regard to their working memory capacity (WMC - also called memory span or complex span) (Baddeley & Hitch, 1974; Conway & Engle, 1994; Conway & Engle, 1996; Daneman & Carpenter, 1980; Daneman & Carpenter, 1983; Engle, Kane, & Tuholski, 1999; Turner & Engle, 1989).

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There are many ways to measure one's WMC. However, according to Pardo-Vazquez and Fernandez-Rey (2012), a type of complex span task called the operation span task (OSPAN; Turner & Engle, 1989) has become one of the most pervasive techniques for measuring and examining individual differences in WMC (Beaman, 2004; Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Brumback, Low, Gratton, & Fabiani, 2005; De Neys, D'Tdewalle, Schaeken, & Vos, 2002; Kane & Engle, 2000; Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004). The typical OSPAN task is non-spatial in nature and involves working on some information (i.e., arithmetic) while trying to remember other information (i.e., words; Turner & Engle, 1989).

Because the OSPAN task requires switching between mental calculation and rehearsal, such tasks are thought to capture the dynamic, executive nature of working memory. Furthermore, OSPAN tasks correlate better with more complex cognitive task performance than other measures of short-term memory (such as Digit Span or Memory Span by Miller, 1956). Specifically, working memory, as measured by complex span or OSPAN, is associated with performance on reading comprehension, learning, reasoning, and problem solving (for review see Engle, 2002). In all of these cognitive tasks, individual differences in WMC have been implicated in cognitive performance differences. For example, McVay and Kane (2012) and Turner and Engle (1989) found a positive correlation between WMC (measured by OSPAN score) and reading comprehension. Higher working memory span scores (assessed via various types of OSPAN tasks) have also been positively correlated with higher SAT scores (Mrazek, Smallwood, Franklin, Chin, Baird, & Schooler, 2012), and higher fluid intelligence (Fry & Hale, 1996). OSPAN scores also predict performance on several attentional tasks (e.g., Attentional Blink; Arnell, Stokes, MacLean, & Gicante, 2010) and performance in tasks that involve top-down constraint of the focus of visual attention (Heitz & Engle, 2007). From this research, we can conclude that differences in WMC predict cognitive performance and working memory ability is involved in a wide variety of important cognitive functions.

There is also a growing body of evidence that working memory is involved in the important cognitive process of mental rotation, which is the ability to imagine an object rotating about a spatial axis so it can be visualized from different angles (Shepard & Metzler, 1971; von Károlyi, 2013). Many everyday tasks would not be possible without the ability to mentally rotate. For example, without the ability to visualize things from different angles when driving or following a map, one might become lost and confused. As empirical evidence of its importance, more advanced mental rotation ability is strongly correlated with better performance in several academic areas and career fields, especially the STEM-related fields (i.e., science, technology, engineering, and mathematics) (see von Károlyi, 2013; Wai, Lubinski, & Benbow, 2009).

Mental rotation ability has been assessed through performance on many different types of tasks (see von Károlyi, 2013), which have been shown to be reliable assessments of individual differences in mental rotation ability (see Hirschfeld, Thielsch, & Zernikow, 2013; Vandenberg & Kuse, 1978). In a typical mental rotation task (proposed by Shepard & Metzler, 1971, and Cooper & Shepard, 1973; also see Vandenberg & Kuse, 1978), participants must decide as quickly and as accurately as possible whether a picture of an object is a normal image or a mirror image (e.g., Hyun & Luck, 2007; Pardo-Vasquez & Fernandez-Rey, 2012).

Other mental rotation tasks require one to compare a picture of a target object to one or more selection options and then choose the one selection option that matches the target, as it would be viewed from various angles of orientation (e.g., Lehmann, Quaiser-Pohl, & Jansen, 2014). For example, participants may be presented with two visual stimuli (e.g., letters or cubed objects) that are either the same or are different (e.g., mirror image; see Figures 1 and 2). The two stimuli can be two-dimensional (2D) objects as shown in Figure 1, where the rotation is in plane and requires only 2D visualization. These objects can also be three-dimensional (3D) as shown in Figure 2, where the rotation is in depth and requires 3D visualization. Regardless of their 2D or 3D nature, the two stimuli are presented at different angles of rotation from one another (ranging from 0° to 330°). This difference in angle of rotation is referred to as *angular deviation*. Participants are told to determine as quickly and accurately as possible whether the two stimuli are the same object ("normal image") or are mirror images of each other (i.e., enantiomorphs). To successfully complete this task, participants use one of the objects as a stationary, original position object and mentally rotate the other object in their mind until is it at the same angle of orientation as the original. The typical finding is that participants are less accurate at deciding whether the image(s) are normal (i.e., the same) or mirrored when there is greater *angular deviation* (Hyun & Luck, 2007; Jansen, Schmelter, Quaiser-Pohl, Neuburger, & Heil, 2013; Liesefeld, Fu, & Zimmer, 2015; Pardo-Vasquez & Fernandez-Rey, 2012; Shepard & Metzler, 1971). Another typical finding is that the time it takes (i.e., speed or reaction time [RT]) to decide if the pairs match or not is linearly proportional to the *angular deviation*, or the angle of rotation from the original position (hereafter referred to as the *angular deviation reaction time effect*; Cooper & Shepard, 1973; Hyun & Luck, 2007; Jansen et al., 2013; Liesefeld et al., 2015; Pardo-Vasquez & Fernandez-Rey, 2012; Shepard & Metzler, 1971). In other words, participants exhibit slower reaction times (RT) on mental rotation tasks when the stimuli presented are rotated at more extreme angles from each other or from "normal" orientation. A key purpose of the present study was to further demonstrate the *angular deviation reaction time effect* and its relationship to WMC, thereby expanding on the existing research on the link between WMC and mental rotation ability.

Figure 1.
Example of stimuli in the 2-D mental rotation task.

Figure 2.
Example of stimuli in the 3-D mental rotation task.

Several researchers have reported relationships between WMC and performance on 2D rotation tasks (i.e., where the objects are rotated in plane) in children (Lehmann et al., 2014) and in adults (Hyun & Luck, 2007; Pardo-Vasquez & Fernandez-Rey, 2012). For example, Lehmann and colleagues (2014) examined the relationship between mental rotation accuracy and working memory performance in children ages 3 to 6. They found a positive correlation between accuracy on the Picture Rotation Test (a 2D mental rotation test; Quaiser-Pohl, Rohe, & Amberger, 2010) and four different working memory capacity tests (i.e., Corsi Block Tapping Test - Forward and Backward by Corsi, 1973, Digit Span – Forward and Backward by Petermann & Petermann, 2008). Although Lehmann and colleagues' (2014) results provide support for the link between WMC and 2D mental rotation ability, their measures assessed visuospatial short-term memory (e.g., Corsi Block Tapping Test) and verbal short-term memory (e.g., Digit Span Task) instead of non-spatial, executive working memory, like what is measured by the OSPAN task. Furthermore, there is evidence that the OSPAN task predicts some aspects of attentional function (Trick, Mutreja, & Hunt, 2012). Therefore, it is unclear from Lehmann and colleagues' (2014) results whether the relationship between WMC and mental rotation ability generalizes to non-spatial, executive working memory measures, such as OSPAN.

Hyun and Luck (2007) found similar relationships between WMC and mental rotation ability and clarified which specific type of working memory (object or spatial) was employed in the completion of mental rotation tasks. They also found that the relationship between WMC and mental rotation accuracy generalized to mental rotation speed. They determined which type of working memory was involved in mental rotation by investigating how a 2D mental rotation load influenced performance on an object working memory task and a spatial working memory task (a dual-task approach similar to Vogel, Woodman, & Luck, 2001). They found that there was bidirectional interference between the tasks only with performance on the object working memory task, and this interference effect increased as the angular deviation increased. From these results, they concluded that 2D mental rotation ability is associated with object working memory.

Hyun and Luck's (2007) previously described results suggest that object working memory is involved in mental rotation. However, the working memory tasks they used to measure working memory performance were not the complex span or OSPAN tasks that capture the more complex and executive nature of working memory. In contrast, Pardo-Vasquez and Fernandez-Rey (2012) did utilize an automated version of the OSPAN task in their study. Automated versions of the OSPAN correlate well with other measures of WMC and have both good internal consistency ($\alpha = .78$) and test-retest reliability ($r = .83$; see Pardo-Vasquez & Fernandez-Rey, 2008; Unsworth, Heitz, Schrock, & Engle, 2005). They found that higher OSPAN correlated with speed and accuracy on a 2D mental rotation task. Specifically, compared to “low” WMC individuals, those with “high” WMC were faster and more accurate on the 2D mental rotation task. However, they only found these differences for the angular deviations of 60°, 120°, and 180°, where processing demands were higher, but not for the 0° angular deviation condition, where processing demands were lower. Their results imply that there may be a relationship between WMC and mental rotation accuracy and speed (i.e., RT) on a 2D mental rotation task, but that this relationship is moderated by the extremity of *angular deviation* or the processing demands of the task.

The results of the previously described study (Pardo-Vasquez & Fernandez-Rey, 2012) provide evidence for the link between working memory capacity, as measured by OSPAN, and mental rotation speed and accuracy. However, their results must be interpreted with caution for several reasons. First, to determine the effect of processing demand on mental rotation performance differences between lower and higher WMC groups, they combined the data from individual angular deviations into smaller and larger angular deviation conditions. Specifically, their “lower” processing condition only included the 0° angular deviation trial, where there was no need to mentally rotate at all, and their “higher” processing condition included the 60°, 120°, and 180° angular deviation trials. As a result, their processing conditions contained an unequal number of angular deviation conditions and their lower processing condition did not require any mental rotation at all. Therefore, their operational definition of lower and higher processing demand was actually a comparison of no processing demand with higher processing demand. Furthermore, they did not examine how differences in WMC were related to decision speed (i.e., RT) differences across the angular deviation conditions. In other words, no implications can be drawn regarding the presence or absence of the *angular deviation reaction time effect* within each of the WMC groups. A second reason their results should be interpreted with caution is that they had a non-English, Spanish-speaking sample and used Spanish verbal stimuli. Thus, it is unclear whether the relationship between WMC and mental rotation speed generalizes to English-speaking participants with English verbal stimuli. Finally, they only examined the correlation between WMC and 2D mental rotation speed and accuracy. Mental rotation tasks that require 3D representations typically take longer than those that only require 2D visualization (Hoyek, Collet, Fargier, & Guillot, 2012; Jansen et al., 2013; Shepard & Metzler, 1988; Stumpf & Eliot, 1999). Therefore, it is unclear from this study alone whether the relationship between WMC and mental rotation speed varies as a function of angular deviation and generalizes to performance on 3D tasks in an English-speaking sample.

A review of the literature revealed that one research study on the relationship between WMC and mental rotation accuracy did include both 2D and 3D mental rotation tasks. Specifically, Kaufman (2007) found positive correlations between measures of verbal and spatial working memory and accurate performance on 2D and 3D mental rotation (i.e., DAT [Space Relations Test by Psychological Corporation, 1995], and the MRT [a Mental Rotations Test by Vandenberg & Kuse, 1978]). However, it is important to note that their sample only included adolescents between ages 16 and 18 in the secondary education level. Additionally, Kaufman (2007) focused on mental rotation accuracy results and did not report any mental rotation speed results. Therefore, conclusions related to the role of WMC in the *angular deviation reaction time effect* are not possible. Furthermore, the memory span tasks utilized were either verbal or spatial in nature and thus more short-term memory measures instead of working memory measures. The one task that did measure executive memory function (i.e., the Verification-Block Span [see Shah & Miyake, 1996]) is very different from the OSPAN task because it requires simultaneous storage of spatial information (i.e., memorize series of block locations) while processing verbal information (i.e., decide whether a sentence is sensible or not). Therefore, the processes induced by their executive working memory task were very different from the OSPAN, which involves simultaneous storage of verbal information while working on solving complex arithmetic. Therefore, like other researchers (Lehmann et al., 2014; Hyun & Luck, 2007), Kaufman (2007) also did not use the results of the OSPAN task to operationally define WMC. To summarize, although Kaufman’s (2007) results also provide support for the link between WMC and mental rotation accuracy, conclusions regarding generalizability to 2D and 3D mental rotation speed in college-aged adults using the OSPAN task are evasive.

Taken together, the result of the previously reviewed studies on mental rotation and WMC imply that those with higher WMC may be faster and more accurate at 2D and 3D mental rotation. Furthermore, the correlation between WMC and mental rotation ability has been shown to generalize to other types of working memory such as object working memory (storage of non-spatial features of an object, e.g. color and form) and spatial working memory (storage of spatial attributes of an object, e.g. location in the visual field; Hyun & Luck, 2007). However, there are some shortcomings in the methodologies of the previously described studies that limit conclusions drawn from them. To summarize, some only used 2D mental rotation tasks (Hyun & Luck, 2007; Lehmann and colleagues, 2014; Pardo-Vazquez & Fernandez-Rey, 2012), and some only tested adolescents or children (Kaufman, 2007; Lehmann and colleagues, 2014) or Spanish-speaking samples (Pardo-Vazquez & Fernandez-Rey, 2012). Additionally, others failed to include mental rotation speed measures (Kaufman, 2007; Lehmann and colleagues, 2014), precluding examination of how WMC interacts with the *angular deviation reaction time effect*. Pardo-Vazquez and Fernandez-Rey (2012) did combine angles into smaller and larger angular deviation conditions to create conditions of lower and higher processing demand. However, Pardo-Vazquez and Fernandez-Rey's (2012) processing conditions contained an unequal number of angular deviation conditions. Specifically, their "lower" processing condition only included the 0° angular deviation trial, where there was no need to mentally rotate at all, and their "higher" processing condition included the 60°, 120°, and 180° angular deviation trials. Instead, we created the lower and higher processing conditions using the same number of trials from two smaller angular deviations (30° and 60°), where there was actually a need to mentally rotate, and two larger angular deviations (150° and 180°), respectively. Thus, we combined the RTs for the 30° and 60° angular deviation trials to create a "smaller angular deviation" condition (i.e., lower processing demand), and we combined the RTs for the 150° and 180° angles to create a "larger angular deviation" condition (i.e., higher processing demand).

Additionally, all of the previously described studies only included three to four angular deviation conditions (Hyun & Luck, 2007; Kaufman, 2007; Lehmann and colleagues, 2014; Pardo-Vazquez & Fernandez-Rey, 2012), instead of the many more *angular deviation* manipulations possible. Including more angular deviation conditions allows one to more closely examine how mental rotation speed varies as a function of angular deviation or the magnitude of the working memory processing demands. Finally, none of the previous researchers examined how differences in WMC were related to mental rotation speed differences across the angular deviation conditions. In other words, it is unclear from previous research how the *angular deviation reaction time effect* might vary between the WMC groups. In summary, to date, there is no research study on the relationship between WMC (as measured by OSPAN) and 2D and 3D mental rotation speed in an English-speaking sample utilizing seven angular deviations altogether in one experiment.

Purpose of the Current Study

The purpose of the present study was to simultaneously investigate the relationship between non-spatial, executive WMC (via OSPAN) and 2D and 3D mental rotation speed (reaction time [RT]) across seven angular deviations in an English-speaking sample. The present study added to the research in this area by more closely examining how the *angular deviation reaction time effect* varied as a function of WMC (as measured by OSPAN) across both 2D and 3D mental rotation tasks. It is also important to note that unlike other previous researchers, we employed computerized versions of both the OSPAN task (similar to Pardo-Vasquez & Fernandez-Rey, 2012) and the mental rotation tasks (for validation information see Voyer, Butler, Cordero, Brake, Silberswieg, Stern, & Imperato-McGinley, 2006).

Hypothesis 1: Replication of the Angular Deviation Reaction Time Effect

Based on previous research (Cooper & Shepard, 1973; Hyun & Luck, 2007; Jansen et al., 2013; Liesefeld et al., 2015; Pardo-Vasquez & Fernandez-Rey, 2012; Shepard & Metzler, 1971), it was hypothesized that we would replicate the standard *angular deviation reaction time effect*. Participants were predicted to exhibit an increase in reaction time (i.e., slower speed) as the angular deviation increased.

Hypothesis 2: Replication of the Greater Difficulty of the 3D Compared to the 2D Task

Given the complexity of the 3D task and the results of previous research (Hoyek et al., 2012; Jansen et al., 2013; Shepard & Metzler, 1988; Stumpf & Eliot, 1999), we hypothesized a replication of slower reaction times on the 3D task compared to the 2D task.

Hypothesis 3: Relationship between 2D Mental Rotation Reaction Time and Working Memory Capacity

Based on the previous research reporting a negative relationship between WMC and mental rotation RT on 2D mental rotation tasks (e.g., Hyun & Luck, 2007; Pardo-Vasquez & Fernandez-Rey, 2012), it was hypothesized that there would be a negative correlation between OSPAN scores and mental rotation RT on the 2D mental rotation task. Thus, participants with higher WMC would be faster (i.e., have shorter RTs) at determining whether the 2D stimuli were mirror images of each other or not.

Hypothesis 4: Relationship between 3D Mental Rotation Reaction Time and Working Memory Capacity

Given the comparatively limited research on the relationship between verbal WMC and performance on 3D mental rotation tasks in adults (e.g., Kaufman, 2007), we formed a non-directional hypothesis regarding the relationship between 3D mental rotation RT and WMC. The 3D task is more difficult and complex than the 2D task (Hoyek et al., 2012; Jansen et al., 2013; Shepard & Metzler, 1988; Stumpf & Eliot, 1999), and this increased level of difficulty could contribute to floor levels of performance on the 3D task, thus making it difficult to determine any relationship between mental rotation RT and WMC.

Hypothesis 5: Reaction Time as a Function of Mental Rotation Processing Demands and Working Memory Capacity

Another purpose of this study was to replicate the previously found interaction between the angular deviation and the WMC grouping variable. In other words, we examined how the relationship between WMC and mental rotation RT varied as a function of the difficulty of the mental rotation angular deviation trials (i.e., compared RT performance between higher and lower WMC participants on the smaller angular deviation trials and on the larger angular deviation trials). Based on research by Pardo-Vasquez and Fernandez-Rey (2012), we hypothesized that the higher WMC group would exhibit faster RTs than the lower WMC group on the greater angular deviation trials but not on the smaller angular deviation trials. In other words, when the processing demands of the task were higher, it was hypothesized that there would be a RT advantage of having a higher WMC. Higher WMC was not predicted to benefit RT when the processing demands were lower.

Hypothesis 6: Angular Deviation Reaction Time Effect as a Function of Working Memory Capacity

Finally, we hypothesized that because of limits to their ability to deal with higher processing demands, lower WMC participants would exhibit the typical *angular deviation reaction time effect*. Specifically we hypothesized that it would take lower WMC participants longer to make their mental rotation decisions on the larger angular deviation trials, where processing demands were higher, compared to the smaller angular deviation trials, where processing demands were lower. However, higher WMC participants, perhaps because of their enhanced ability to deal with higher processing demands, were predicted to not exhibit the typical *angular deviation reaction time effect*. Specifically, we predicted that higher WMC participants would not exhibit any significant decision time differences between smaller and larger angular deviation trials.

Method

Design

The study formed a 2 x 2 x 7 mixed subjects factorial design with mental rotation task (2D objects rotated in plane, 3D objects rotated in depth) and seven rotation angular deviation conditions (0°, 30°, 60°, 90°, 120°, 150°, and 180°) as the within-subjects factors, working memory capacity (WMC; lower, higher) as the grouping variable, and mental rotation reaction time (RT) as the dependent measure.

Participants

A total of 22 undergraduate psychology students served as participants in this study in exchange for credit in their cognitive psychology class. There were 20 females and two males. The average age of the participants in the sample was 19.76 years old, average GPA was 3.53, average self-reported SAT score was 1136.50 (excluding the written portion), and average self-reported ACT score was 25.11. Additionally, 86% of the participants were Psychology majors. Participation in the study was part of students' normal required coursework, however the Institutional Review Board approved the research and all participants provided informed consent.

Tasks, Stimuli, and Materials

Operation Span Task (OSPAN). Participants completed an automated version of the OSPAN task via the Operation Span ZAPS lab (wwnorton.com), and scores on this task were used as a measure of WMC. It is important to note that automated versions of *OSPAN* tasks, such as the one utilized in the current study, correlate well with other measures of WMC and have good internal consistency (α = .78; Unsworth, Heitz, Schrock, & Engle, 2005). The *OSPAN* stimuli (see Appendix A), included 40 mathematical equations and 40, one-to-two syllable, English words. The object of the *OSPAN* task was to work on some information in memory (i.e., determine the accuracy of mathematical equations), while also maintaining some other information in memory (i.e., remember words in the correct order). Participants were told to accurately determine the correctness of the mathematical equations and to remember as many words in the correct order for a later memory test (i.e., intentional learning instructions). This automated operation span (*OSPAN*) task followed a sequential presentation paradigm. First, participants were shown a math problem (e.g., (10 + 15) / 5 = 6) on the screen in front of them, and they had to indicate whether the mathematical equation was correct or incorrect by clicking one of two buttons ("thumbs down" = incorrect, "thumbs up" = correct) on the computer screen. After determining the accuracy of the equation, they were then shown a single word on the computer screen (e.g., milk) for 2 seconds. Then another set (mathematical equation appeared followed by a word) was presented. Participants practiced two trials before completing 10 experimental *OSPAN* trials. The 10 experimental trials varied in set size (i.e., the number of math problem / words). Set sizes ranged from three to nine so that each of the 10 experimental trials consisted of a minimum of three to as many as nine, stimuli pairs consisting of a mathematical equation and a word. The order of the set sizes was randomized so that participants could not predict the number of words they would have to memorize. After each trial, participants completed a recognition memory task; they were shown all the words in the previously shown set and they had to select the words in the previous set in the order that they were shown. In order to ensure that participants did in fact pay attention to and solve the mathematical equations, we required an 85% accuracy rate on the equations for inclusion of the participants' data in the study. The range of possible *OSPAN* scores is 0 to 40, where higher scores indicate higher working memory capacity.

Perceptions of Memory Scale (PMS) and Demographic Questionnaire. Participants completed the *Perceptions of Memory Scale* (see Appendix B) consisting of five statements designed by the authors of the present study to assess self-perceptions of memory efficacy for numbers, events, exam material as well as ease of multi-tasking and beliefs about the accuracy of the OSPAN score as a representation of one's WMC. Participants rated each statement on a 5-point rating scale, where 1 = "strongly disagree" and 5 = "strongly agree." Participants also completed a demographics questionnaire designed to assess age, gender, college year, major and minor, college admissions standardized test scores and percentile, and GPA.

2D and 3D Mental Rotation Tasks. Participants completed a two-dimensional (2D) mental rotation task and a three-dimensional (3D) mental rotation task on the ZAPS website (wwnorton.com). In the 2D task, participants were shown pairs of letters (see Figure 1) that were either the same ("normal version") or mirror images of each other. The two letters in the 2D task were rotated in plane from each other at 12 angular deviations (0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°). In the 3D mental rotation task, participants were shown two 3D figures that were either the same ("normal version") or mirror images of each other (see Figure 2). The two 3D figures were rotated in depth from each other at the same 12 angular deviations as the 2D task. For both the 2D and 3D tasks, participants had to determine as quickly and as accurately as possible whether the two stimuli presented were identical, or if they were mirror images of each other. There were 5 to 9 trials per angular deviation in each of the 2D and 3D tasks. Although there were an uneven numbers of trials between the different angular deviations, the reference data (i.e., the general outcome of the experiment) from the ZAPs website indicates that participants' data follow the typical *angular deviation reaction time effect* (i.e., longer RTs correspond with larger angular deviations).

It is important to note that for conceptual and statistical purposes (as in Pardo-Vasquez & Fernandez-Rey, 2012) the angles were paired based on the size of the angular deviations (not on the direction of angular deviation from "starting point"). For example, because 60° and 300° are the result of rotating the stimulus 60° to the right and to the left, respectively, they were averaged and analyzed as a "60°" angular deviation condition. Similarly, the data from the angular deviation trials of 330° and 30° were averaged because they represent the same angular deviations between the two stimuli (i.e., both indicate an angular deviation of 30°). In the current study, 12 angular deviation trials (0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°) were paired into seven angular deviation conditions, corresponding to long and short ways around (i.e., clockwise and counterclockwise rotations in the vertical plane or horizontal depth). Therefore, we combined the data into the following seven angular deviation categories: a. 0°, b. 30° (included 30° and 330°), c. 60° (included 60° and 300°), d. 90° (included 90° and 270°), e. 120° (included

120° and 240°), f. 150° (included 150° and 210°), and g. 180°.

Procedure

First, participants completed the *OSPAN* task. Two weeks later, participants returned and completed the mental rotation tasks, the demographics questionnaire, and the *Perceptions of Memory Scale* (participants' self-reported perceptions of their memory abilities). We did not counterbalance the completion of the *OSPAN* and the mental rotation tasks because there is no literature to support asymmetric transfer from the *OSPAN* task to the mental rotation tasks. Furthermore, because the *OSPAN* and mental rotation tasks were separated by a two-week time span, any transfer from the *OSPAN* task to the mental rotation tasks were minimized or eliminated. Following completion of the demographics and *Perceptions of Memory Scale*, participants were randomly assigned to complete either the 2D or the 3D task first. Thus, the order of mental rotation task completion was counterbalanced between participants.

Results

Operational Definition of Higher and Lower Working Memory Capacity (WMC) Groups. WMC was operationally defined by scores on the Operation Span ZAPS lab (wwnorton.com). The average *OSPAN* score for the entire sample was 31.73, with a range of 18 to 40. The working memory grouping variable was created by defining "higher" WMC individuals as those who scored in the top 33.33% of *OSPAN* scores in the sample, while the "lower" WMC individuals scored in the bottom 33.33%. The *OSPAN* scores of higher WMC group (n = 8) ranged from 36 to 40, with an average *OSPAN* score of 39.00 (SD = 1.60). The *OSPAN* scores of lower WMC group (n = 14) ranged from 18 to 34, with an average of 27.57 (SD = 5.84). The average *OSPAN* scores in the higher and lower working memory groups were consistent with one standard deviation above and below the overall average *OSPAN* score of 31.73. An independent samples t-test revealed that there was a significant difference in average *OSPAN* scores between the higher WMC group and the lower WMC group, $t(20) = 5.37$, $p = .001$.

As shown in Table 1, a series of independent sample t-tests revealed no significant differences between the lower WMC group and the higher WMC group on any of the following demographic characteristics: age, GPA, standardized test score percentile, self-rated memory for numbers, their self-rated memory for events, and self-rated memory for exam material, as well as their self-rated ability to multi-task, $ps > .21$. There was also no significant difference between the higher *OSPAN* participants and the lower *OSPAN* participants in their beliefs regarding the accuracy of their *OSPAN* scores with respect to their WMC, $p = .16$.

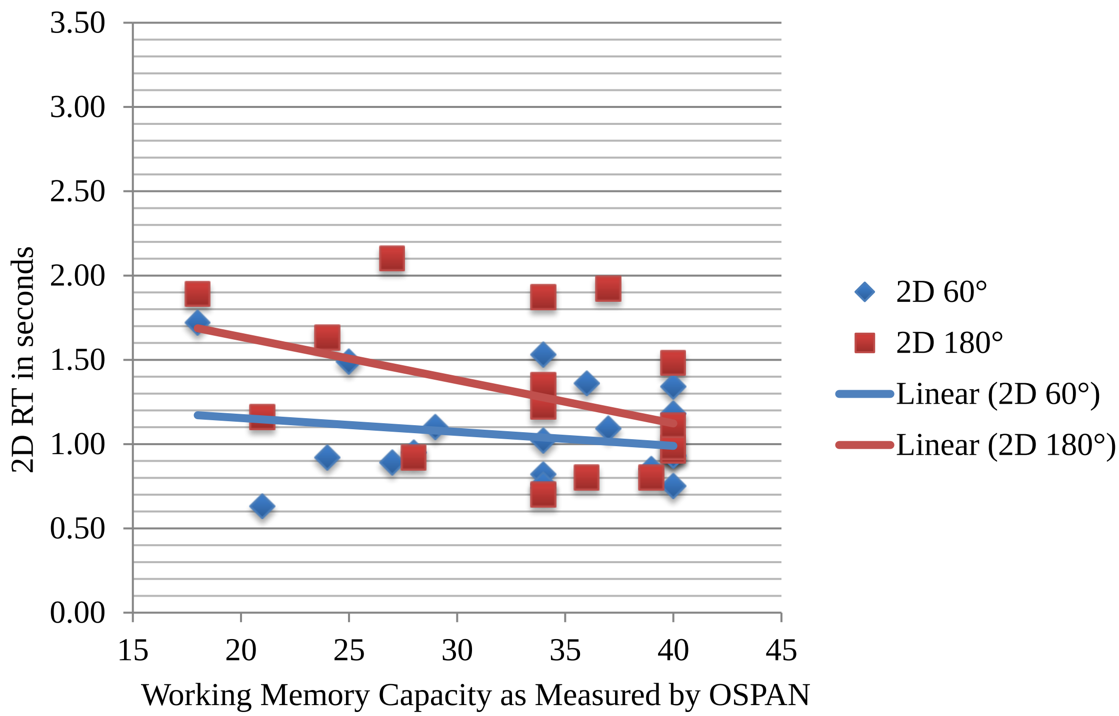
Table 1. Demographic Comparisons Between the Higher and Lower Working Memory Capacity Groups.

Demographic Variable	OSPAN Group	Mean (SD)	t stat
Age	Higher Lower	19.50 (1.41) 20.33 (1.23)	t (15) = 1.30, p =.21
GPA	Higher Lower	3.65 (0.28) 3.46 (0.43)	t (15) = 1.04, p =.30
Standardized Test Percentile	Higher Lower	80.13 (9.21) 79.97 (12.63)	t (15) = .03, p =.98
Self-Rated Memory for Numbers	Higher Lower	3.25 (0.71) 3.33 (0.71)	t (15) = .24, p =.81
Self-Rated Memory for Events	Higher Lower	4.00 (0.54) 3.78 (0.67)	t (15) = .75, p =.46
Self-Rated Memory for Exam Material	Higher Lower	3.13 (0.84) 3.33 (1.00)	t (15) = .46, p =.65
Self-Rated Multitasking Ability	Higher Lower	3.00 (1.07) 2.78 (0.97)	t (15) = .45, p =.66
Beliefs that the OSPAN score accurately measures WM	Higher Lower	3.38 (0.52) 2.89 (0.78)	t (15) = 1.49, p =.16

Counterbalancing of Order of Mental Rotation Tasks Check. Because the order of the two mental rotation tasks were counterbalanced, it was important to check for an order effect. Counterbalancing order of type of mental rotation task did not have a significant effect in this study, $F < 1$, therefore the order variable was excluded from the report of the results.

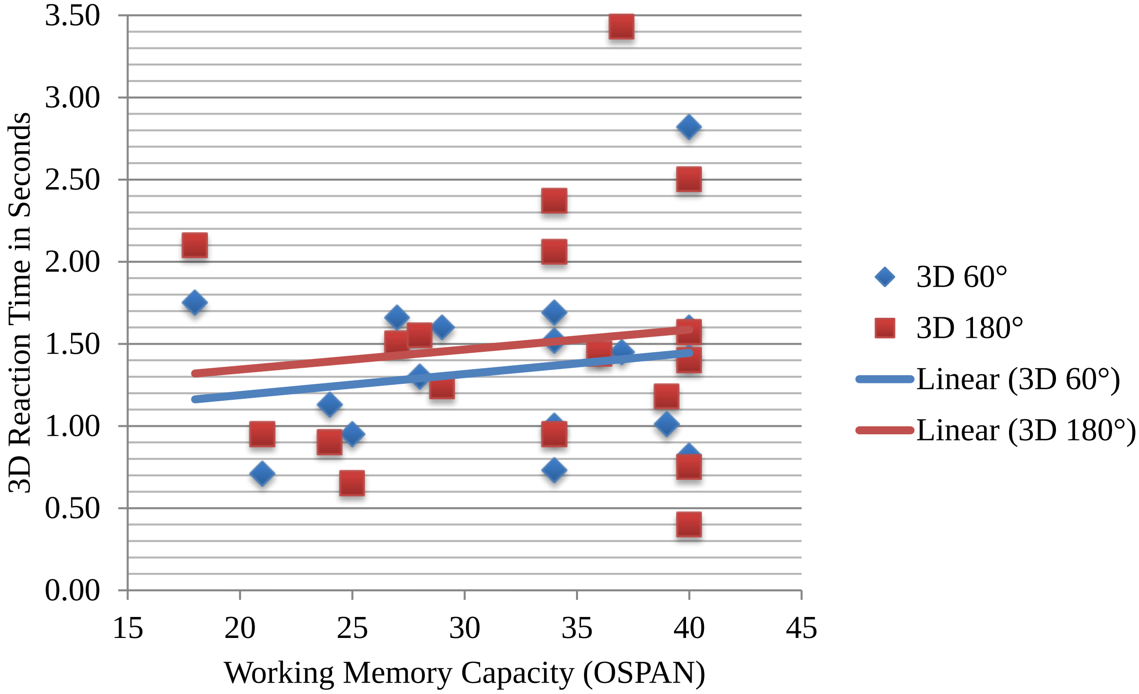
Correlational Analyses. Simple correlations were conducted between WMC (OSPAN score) and RT at the 0°, 60°, and 180° angular deviation conditions in the 2D and 3D mental rotation tasks. The 60° and 180° angular deviations were chosen because previous researchers found significant differences at these angular deviations (Pardo-Vasquez & Fernandez-Rey, 2012). As shown in Figure 3, there was a non-significant, positive correlation between 2D RT and WMC in the 0° angular deviation condition ($r = .19$, $p = .44$). There was a trend of increasing negative correlations between 2D RT and WMC as the angular deviations increased from the 60° angular deviation to the 180° angular deviation. However, the negative correlation between speed and WMC in the 60° angular deviation was not significant ($r = -.19$, $p = .42$) and the negative correlation in the 180° angular deviation condition only approached significance ($r = -.37$, $p = .10$).

Figure 3.
Relationship between working memory capacity (WMC) and 2D mental rotation reaction time (RT) in the 2D 60° and 180° angular deviation conditions.



Inconsistent with the trending increase in negative correlations between 2D RT and WMC from smaller to larger angular deviations (see Figure 4), correlations between 3D RT and WMC were positive, but non-significant in the 0° ($r = .16$, $p = .50$), 60° ($r = .17$, $p = .47$), and 180° angular deviation conditions ($p = .28$, $r = .23$).

Figure 4.
Relationship between working memory capacity (WMC) and 3D mental rotation reaction time (RT) in the 3D 60° and 180° angular deviation conditions.



In order to remain consistent with statistical procedures employed by Pardo-Vasquez and Fernandez-Rey (2012), we conducted a 4 x 2 x 2 repeated measures factorial ANOVA with rotation angular deviation (0°, 60°, 120°, 180°) and mental rotation task (2D, 3D) as the within-subjects factors, WMC (lower, higher) as the grouping variable, and RT (in seconds) on the mental rotation task as the dependent measure. The means, standard deviations, and pairwise comparisons for the four angular deviation conditions (0°, 60°, 120°, 180°) across the WMC groups and mental rotation tasks are shown in Table 2. There was a main effect of angular deviation on RT, $F(3, 60) = 28.38$, $p = .001$, $\eta_p^2 = .59$. Overall, as shown in Table 1, participants were slower at making mental rotation decisions when the angular deviations were larger than when they were smaller. Paired sample t-tests revealed that overall, there was a significant increase in RT between the 0° condition ($M = .76$, $SD = .15$) and the 60° condition ($M = 1.17$, $SD = .36$), $t(21) = -7.72$, $p = .001$, $d = -1.49$, as well as between the 60° to the 180° condition ($M = 1.36$, $SD = .43$), $t(21) = -3.10$, $p = .005$, $d = -.48$. All other pairwise comparisons between the angular deviations were not significant, *ps* > .15. This significant RT advantage for smaller angular deviation trials over larger trials was found for both lower and higher WMC participants as the interaction between the WMC grouping variable and the angular deviation was not significant, $F < 1$. Thus, both lower and higher WMC participants reacted faster on the smaller angular deviation conditions than on the larger conditions.

Table 2. Mean RTs (standard deviations) as a function of angular deviation (0°, 60°, 120°, 180°), mental rotation task type (2D, 3D), and WMC group (lower, higher).

Mental Rotation Task	Angular Deviation	Working Memory Capacity Group	*Mean* RT (*SD*) *in seconds*	*t stat*
2D	0°	Lower WM	0.65 (.18)	-1.21, *p* = .24
		Higher WM	0.73 (.10)	
	60°	Lower WM	1.02 (.34)	-0.27, *p* = .79
		Higher WM	1.05 (.23)	
	120°	Lower WM	1.07 (.44)	-0.97, *p* = .34
		Higher WM	1.25 (.36)	
	180°	Lower WM	1.28 (.46)	0.66, *p* = .51
		Higher WM	1.16 (.38)	
3D	0°	Lower WM	0.82 (.20)	-1.15, *p* = .26
		Higher WM	0.91 (.15)	
	60°	Lower WM	1.22 (.42)	-1.23, *p* = .23
		Higher WM	1.49 (.60)	
	120°	Lower WM	1.43 (.56)	-0.59, *p* = .57
		Higher WM	1.55 (.30)	
	180°	Lower WM	1.37 (.62)	-1.01, *p* = .32
		Higher WM	1.67 (.79)	

There was also a significant main effect of type of mental rotation task on RT, $F(1, 20) = 14.40$, $p = .001$, $\eta_p^2 = .42$. Overall, participants exhibited slower RTs on the 3D mental rotation task ($M = 1.28$, $SD = .46$) compared to the 2D mental rotation task ($M = 1.02$, $SD = .32$). This significant RT advantage for 2D over 3D was found for both lower and higher WMC participants as the interaction between type of mental rotation task and WMC group was not significant, $F(1, 20) = 1.11$, $p = .31$, $\eta_p^2 = .05$. Subsequent independent samples t-tests revealed that when the data was collapsed across the angular deviations conditions, there were no significant differences in 2D RT between the lower WMC group ($M = 1.00$, $SD = .30$) and higher WMC group ($M = 1.05$, $SD = .17$), $t(20) = -.37$, $p = .72$, $d = -.21$. There were also no significant differences in 3D RT between the lower WMC group ($M = 1.21$, $SD = .39$) and higher WMC group ($M = 1.41$, $SD = .33$), $t(20) = -1.22$, $p = .24$, $d = -.55$. Paired samples t-tests confirmed that lower WMC participants had slower 3D reaction times ($M = 1.28$, $SD = .37$) than 2D ($M = 1.02$, $SD = .26$), $t(21) = -3.64$, $p = .002$, $d = .81$, and higher WMC participants also had slower 3D RTs ($M = 1.41$, $SD = .33$) than 2D RTs ($M = 1.05$, $SD = .17$), $t(7) = -2.86$, $p = .02$, $d = 1.37$. Thus, both lower and higher WMC participants exhibited slower RTs on the 3D task compared to the 2D task.

There was no significant relationship between the WMC grouping variable and RT, $F < 1$. Overall, lower WMC participants were not significantly slower (or faster; $M = 1.11$, $SD = .40$) than higher WMC participants ($M = 1.23$, $SD = .36$), $d = -.32$. The interaction between the WMC grouping variable and angular deviation was not significant, $F < 1$, indicating that the lack of relationship between WMC and mental rotation RT did not vary as a function of the processing demands of the mental rotation trials. Subsequent independent samples t-tests revealed that when the data was collapsed across the type of mental rotation task, there were no RT differences between the lower and higher WMC group at any of the four angular deviations, $ps > .20$.

There was also no three-way interaction between WMC, angular deviation, and type of mental rotation task, $F(3, 60) = 1.20$, $p = .31$, $\eta_p^2 = .06$. As shown in Table 2, independent samples t-tests revealed that there were no significant differences in RT between the lower and higher WMC participants in any of the angular deviation by mental rotation task conditions, $ps > .24$. A series of paired samples t-tests were conducted to compare 2D and 3D RTs across the angular deviation conditions for each WMC group. These pairwise comparisons revealed that the lower WMC participants exhibited a significant increase in 2D and the 3D RT between the 0° and the 60° angular deviation conditions, $t(13) = -6.02$, $p = .001$, $d = 1.39$, and $t(13) = -5.51$, $p = .001$, $d = 1.24$, respectively. The lower WMC participants exhibited a significant increase in 2D and 3D RT between the 0° and 180° angular deviation conditions, $t(13) = -6.65$, $p = .001$, $d = -1.87$, and $t(13) = -3.90$, $p = .002$, $d = -1.19$, respectively. Finally, the lower WMC group also had a significant increase in RT from the 60° to 180° angular deviation conditions in the 2D condition, $t(13) = -2.56$, $p = .02$, $d = -.67$, but not in the 3D condition, $t(13) = -1.11$, $p = .29$, $d = -.28$. All other pairwise comparisons within the lower WMC group were not significant, $ps > .08$. To summarize, lower WMC participants exhibited slower

RTs on the 3D task compared to the 2D task. In the 2D task, lower WMC participants also exhibited slower RTs on the 60° and 180° angular deviation conditions compared to the 0° condition, and the slower RTs on the 180° condition compared to the 60° condition. In the 3D task, lower WMC participants only exhibited significantly slower RTs and on the 60° and 180° angular deviation conditions compared to the 0° condition.

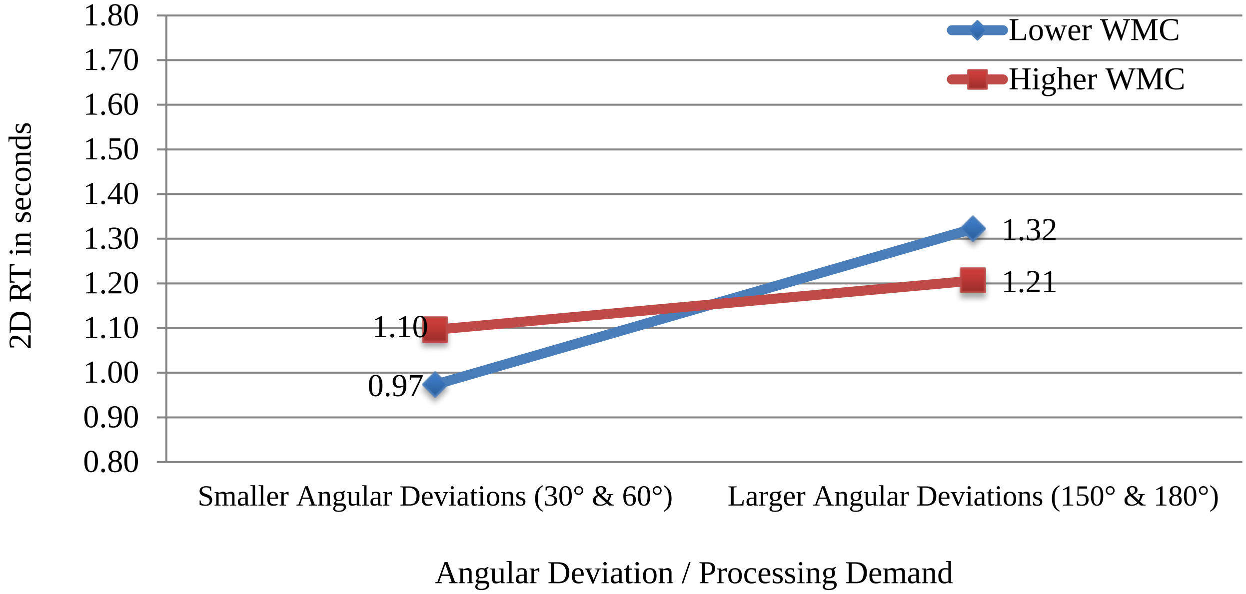
Paired sample t-test on the higher WMC participants revealed a similar pattern of results. Higher WMC participants exhibited a significant increase in 2D and 3D RT between the 0° and the 60° angular deviation conditions, $t(7) = -5.88$, $p = .001$, $d = -1.86$, and $t(7) = -3.16$, $p = .02$, $d = -1.32$, respectively. They also had a significant increase in 2D and 3D RT between the 0° and 180° conditions, $t(7) = -3.17$, $p = .02$, $d = -1.55$, and $t(7) = -2.86$, $p = .02$, $d = -1.34$, respectively. All other pairwise comparisons within the higher WMC group were not significant, $ps > .17$. To summarize, higher WMC participants exhibited slower RTs on the 3D task compared to the 2D task. Higher WMC participants also exhibited slower 2D and 3D RTs on the 60° and 180° angular deviation conditions compared to the 0° condition. Taken altogether, the results of the 3-way ANOVA between WMC, mental rotation task, and angular deviation revealed that all participants, regardless of variations in WMC, exhibited slower RTs on the 3D task and on two of the larger angular deviations (60° and 180°) compared to the 0° angular deviation condition.

To determine the effect of angular deviation processing demands (lower, higher) on RT data between the lower and higher working memory groups, we completed subsequent, planned comparisons between "smaller" and "larger" angular deviation conditions. Like Pardo-Vazquez and Fernandez-Rey (2012), we combined angular deviations into smaller and larger angular deviation conditions to create conditions of lower and higher processing demand. However, Pardo-Vazquez and Fernandez-Rey's (2012) processing conditions contained an unequal number of angular deviation conditions. Specifically, their "lower" processing condition only included the 0° angle trial, where there was no need to mentally rotate at all, and their "higher" processing condition included the 60°, 120°, and 180° angular deviation trials. Instead, we created the lower and higher processing conditions using the same number of trials from two smaller angular deviations (30° and 60°), where there was actually a need to mentally rotate, and two larger angular deviations (150° and 180°), respectively. Thus, we combined the RTs for the 30° and 60° angular deviations to create a "smaller angular deviation" RT condition, and we combined the RTs for the 150° and 180° angular deviations to create a "larger angular deviation" RT condition. Using these two categories of lower and higher processing demand conditions, we conducted a 2 x 2 x 2 mixed subjects factorial ANOVA with angular deviation/processing demand (smaller/lower, larger/higher) and mental rotation task figure type (2D, 3D) as the within-subjects factors, WMC (lower, higher) as the grouping variable, and RT (in seconds) as the dependent measure.

There was a significant main effect of angular deviation on RT, $F(1, 18) = 7.67$, $p = .001$. As shown in Figure 5, as angular deviation and processing demands increased, the combined 2D and 3D RT increased (1.07s $\rightarrow$ 1.31s). Thus, we replicated the *angular deviation reaction time effect* (i.e., participants were slower to react to larger angular deviations compared to smaller). As the combined 2D and 3D angular deviation increased and processing demands increased, participants were slower at making their mental rotation decisions. The interaction between WMC (higher, lower) and angular deviation (smaller, larger) was not significant, $F < 1$. However, subsequent planned comparisons revealed that the difference in RT between smaller and larger angular deviations was greater for those who had lower WMCs. Specifically, participants with lower WMCs were significantly slower (28 ms) in the larger angular deviation conditions when processing demands were higher ($M = 1.28$, $SD = .44$) compared to the smaller angular deviation conditions when processing demands were lower ($M = 1.00$, $SD = .24$), $t(11) = - 2.66$, $p = .02$. However, higher WMC participants were not significantly slower (only 15 ms) in the larger angular deviation conditions ($M = 1.35$, $SD = .26$) compared to the smaller conditions ($M = 1.20$, $SD = .27$), $t(7) = - 1.42$, $p = .20$.

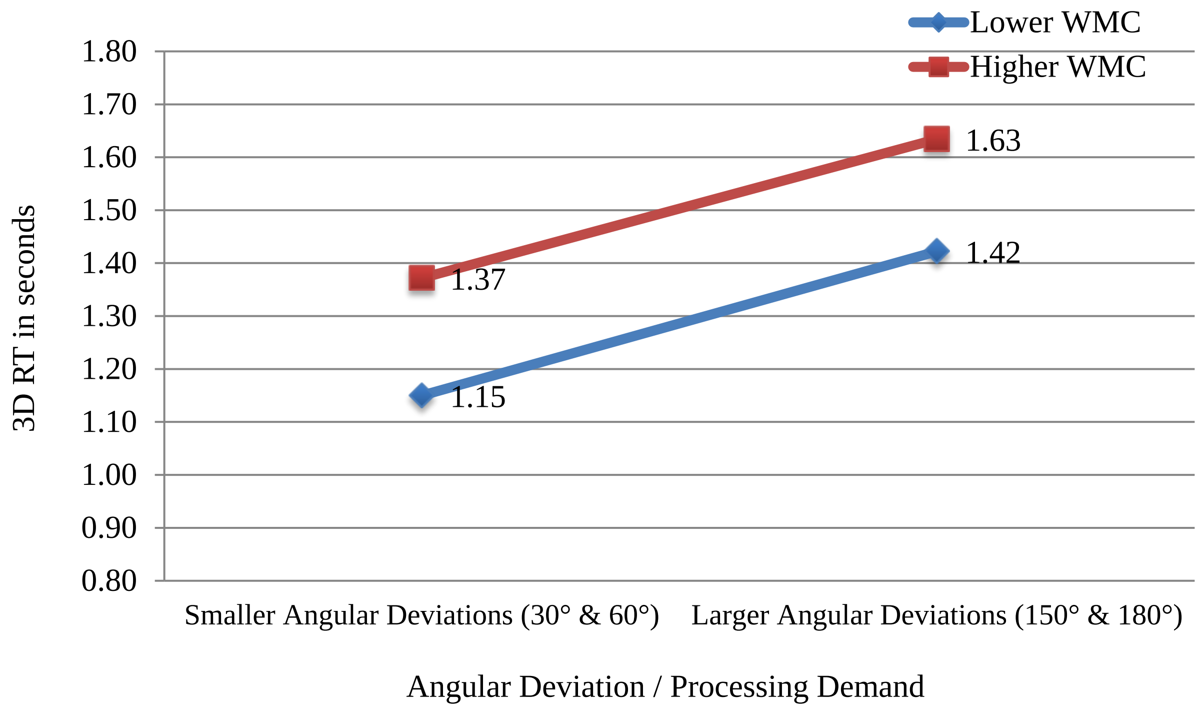
A 2 x 2 repeated measures factorial ANOVA was conducted with 2D angular deviation (smaller, larger) as the within-subjects factor, WMC (lower, higher) as the grouping variable, and RT (in seconds) on the 2D mental rotation task as the dependent measure. There was a significant main effect of 2D angular deviation (smaller, larger) on RT, $F(1, 18) = 13.83$, $p = .002$. As shown in Figure 5, as angular deviation increased, RT increased (1.04*s* $\rightarrow$ 1.26*s*), indicating that as the processing demands increased, participants took longer to make their 2D mental rotation decisions. The interaction between WMC (lower, higher) and 2D angular deviation (smaller, larger) approached significance, $F(1, 18) = 3.75$, $p = .07$. Planned comparisons revealed that there was no significant difference in RT between lower and higher WMC participants at the smaller or the larger 2D angular deviations, p's > .21. However, lower WMC participants exhibited a significant increase in RT from smaller to larger angular deviations (i.e., a significant 2D *angular deviation reaction time effect*), $t(11) = -4.59$, $p = .001$. In contrast, higher WMC participants did not exhibit a significant increase in RT from smaller to larger angular deviations on the 2D task (i.e., a non-significant *angular deviation reaction time effect*), $t(7) = -1.11$, $p = .31$.

Figure 5.
Reaction time (RT) in the 2D mental rotation task as a function of angular deviation / processing demand (smaller/lower, larger/higher) and working memory capacity (WMC).



Another 2 x 2 repeated measures factorial ANOVA was conducted with 3D angular deviation (smaller, larger) as the within-subjects factor, WMC (lower, higher) as the grouping variable, and RT (in seconds) on the 3D mental rotation task as the dependent measure. There was a significant main effect of 3D angular deviation (smaller, larger) on RT, $F(1, 18) = 7.17$, $p = .015$. As shown in Figure 6, as the angular deviation increased, RT increased (1.26*s* → 1.53*s*), thus replicating the *angular deviation reaction time effect* (i.e., participants were slower to react to larger angular deviations compared to smaller). The interaction between WMC and 3D angular deviation was not significant, $F < 1$. Planned comparisons revealed that there was no significant difference in RT between lower and higher WMC participants at the smaller or the larger 3D angular deviations, *p*'s > .12. However, lower WMC participants exhibited an increase in RT from smaller to larger angular deviations that approached significance, $t(11) = -2.16$, $p = .054$. In contrast, higher WMC participants did not exhibit a significant increase in RT from smaller to larger angular deviations on the 3D mental rotation task, $t(7) = -1.69$, $p = .135$.

Figure 6.
Reaction time (RT) in the 3D mental rotation task as a function of angular deviation/processing demand (smaller/lower, larger/higher) and working memory capacity (WMC).



Discussion

The purpose of the present study was to simultaneously investigate the relationship between non-spatial, executive working memory capacity (via OSPAN) and 2D and 3D mental rotation speed across several angular deviations in an English-speaking sample. Based on previous research on the *angular deviation reaction time effect* (Cooper & Shepard, 1973; Hyun & Luck, 2007; Jansen et al., 2013; Liesefeld et al., 2015; Pardo-Vasquez & Fernandez-Rey, 2012; Shepard & Metzler, 1971) and on the greater difficulty of 3D mental rotation tasks compared to 2D (Hoyek et al., 2012; Jansen et al., 2013; Shepard & Metzler, 1988; Stumpf & Eliot, 1999), we hypothesized that participants would exhibit slower RTs on the larger angular deviation trials (i.e., the *angular deviation reaction time effect*) compared to the smaller angular deviation trials and slower RTs on the 3D tasks compared to the 2D. Consistent with our first hypothesis, both higher and lower WMC participants were slower at making mental rotation decisions when the angular deviations were larger than when they were smaller. This replication of the *angular deviation reaction time effect* supports previous research showing a consistent and strong relationship between the physical angular deviation and a person's mental rotation speed (Cooper & Shepard, 1973; Hyun & Luck, 2007; Jansen et al., 2013; Liesefeld et al., 2015; Pardo-Vasquez & Fernandez-Rey, 2012; Shepard & Metzler, 1971).

We also found support for our second hypothesis: Both higher and lower WMC participants exhibited slower speeds on the 3D mental rotation task compared to the 2D task. This finding is consistent with previous research on the greater difficulty of mental rotation tasks that require 3D mental representations than those that only require 2D representations (Hoyek et al., 2012; Jansen et al., 2013; Shepard & Metzler, 1988; Stumpf & Eliot, 1999).

In support of our third hypothesis regarding the relationship between 2D mental rotation RT and WMC and partially consistent with previous research (Hyun & Luck, 2007; Pardo-Vasquez and Fernandez-Rey, 2012), we found a small, negative correlation between WMC and 2D mental rotation RT in the 60° and 180° angle conditions, suggesting that lower WMC individuals had slower RTs than higher WMC participants. Furthermore, this difference in RT between those with higher and those with lower WMC was more pronounced in the larger angular deviation conditions. Specifically, as the angular deviation increased from 60° to 180°, the negative correlation between OSPAN score and RT increased from -.19 to -.37, indicating that in the larger angular deviation conditions, the negative relationship between WMC and mental rotation RT was even stronger. However, because only one of these negative correlations (180°) only approached significance (due to smaller sample size), this finding of an increasing negative correlation between 2D speed and WMC should be interpreted with caution. Future studies should include larger sample sizes in order to increase power to detect significant correlations.

While we did find limited evidence to support a RT advantage of higher WMC on the 2D mental rotation task, we found no significant, negative relationship between WMC and RT on the 3D mental rotation task. This lack of correlation between WMC and 3D mental rotation speed is very different from what we found in the 2D condition. However, we propose that this lack of negative relationship was due to a floor effect (i.e., slower RTs) stemming from the greater difficulty of the 3D task over the 2D (Hoyek et al., 2012; Jansen et al., 2013; Shepard & Metzler, 1988; Stumpf & Eliot, 1999). Thus, the difficulty of the 3D task (and much slower RTs for all participants on this task) may have obscured our ability to detect any relationship between WMC and 3D mental rotation RT.

Pardo-Vasquez and Fernandez-Rey (2012) only found differences in RT between higher and lower WMC participants when processing demands were higher (i.e., on the larger angular deviation trials). Therefore, we also compared RT performance between higher and lower WMC participants on the smaller angular deviation trials (where processing demands were lower) and on the larger angular deviation trials (where processing demands were higher). Inconsistent with our fifth hypothesis and the results of Pardo-Vasquez and Fernandez-Rey (2012), we failed to find any differences in RT between the lower WMC group and the higher WMC group on any of the angular deviation trials. Therefore, having a higher WMC did not coincide with a mental rotation speed benefit, even when processing demands of the task were greater. It is possible that the two WMC groups in the current experiment adopted different mental rotation tasks strategies, and these different strategies contributed to our failure to find a mental rotation speed benefit for those with higher WMC. For example, participants were told to complete the tasks as quickly and as accurately as possible. Given the tradeoff between accuracy and mental rotation speed, a mental rotation strategy focused more on accuracy may have resulted in slower RTs. Higher WMC participants may have opted to focus on maintaining a higher level of accuracy on the task, thus increasing their normal RTs overall and obscuring any RT benefit for this group. Consistent with this interpretation, higher WMC participants exhibited slower RTs on many of the trials, especially trials in the 3D task. Given the possible influence of strategy dominance, future research should include RT measures as well as accuracy measures and questions designed to assess the dominant strategies employed by the participants.

Overall, we replicated the *angular deviation reaction time effect* (i.e., the increase in RT as the angular deviation between the objects increased) found in previous studies (Cooper & Shepard, 1973; Hyun & Luck, 2007; Jansen et al., 2013; Liesefeld et al., 2015; Pardo-Vasquez & Fernandez-Rey, 2012; Shepard & Metzler, 1971). Interestingly, participants with lower WMC displayed the standard *angular deviation reaction time effect*, while those with higher WMC did not. Consistent with our sixth and final hypothesis, lower WMC participants responded significantly faster on smaller angular deviation trials than on larger angular deviation trials, but the degree of angular deviation did not seem to impact the RTs of higher WMC participants. Lower WMC participants exhibited an *angular deviation reaction time effect* that was statistically significant in the 2D task and approached significance in the 3D task. Although higher WMC participants RTs did increase from the smaller to the larger angular deviations, these increases in RT were not statistically significant on either of the mental rotation tasks. In other words, only lower WMC participants' mental rotation ability suffered when processing demands were higher. However, this conclusion should be interpreted with caution as large variance in the data of the higher WMC participants could have obscured detection of significant increases in RTs from the smaller to the larger angular deviation conditions, especially within the 3D task. Because there are no other studies that have reported this difference in *angular deviation reaction time effect* between lower and higher WMC participants, differences in RT as function of angular deviation and WMC warrant further investigation.

In addition to a large amount of variance in the data of the higher WMC group, there are several other limitations of the current study that warrant discussion. First, the smaller sample size reduced the power of our statistical analyses, making it difficult for us to find significant results in some cases. Furthermore, the sample only included two male participants. Previous studies have shown that males tend to perform better than females on mental rotation tasks (Roberts & Bell, 2003; von Karolyi, 2013; for review see Linn & Peterson, 1985), with males and females deviating nearly one standard deviation from each other on 3D tasks (Harle & Towns, 2011). Therefore, the disequilibrium between males and females could have affected our results because our sample was almost entirely composed of females.

Another possible limitation of our study that may have contributed to our failure to replicate the advantage of higher WMC in mental rotation was our use of RT as the main dependent measure of mental rotation ability. Other researchers have primarily used mental rotation accuracy (e.g., Kaufman, 2007) as the dependent measure or included both accuracy and RT as the dependent measure (e.g., Hyun & Luck, 2007; Pardo-Vazquez & Fernandez-Rey, 2012).

As mentioned previously, the inclusion of accuracy measures could elucidate the possible influence of strategy dominance.

In addition to RT being the only measure of mental rotation ability, the operational definition of the WMC groups could also be considered a weakness of the study. Unlike previous researchers, such as Pardo-Vazquez and Fernandez-Rey (2012) who operationally defined lower and higher WMC groups as the bottom and top quartile of working memory scores, we used the bottom and top one-third of OSPAN scores to create our WMC groups. Thus, our method of group selection may be viewed as less rigorous compared to previous studies. Indeed, Pardo-Vazquez and Fernandez-Rey's (2012) working memory groups had higher and lower average WMC scores than the current WMC groups. However, it is important to note that the range of their WMC test scores was larger and like Pardo-Vazquez and Fernandez-Rey (2012), we found a statistically significant difference in OSPAN scores between our lower and higher WMC groups.

There is one final methodical distinction that may have contributed to our failure to find mental rotation speed differences between the lower and higher WMC groups. Traditionally, an experimenter administers the OSPAN task in an auditory format using recall of the words as the dependent measure. However, the computer-based OSPAN task used in this experiment utilized recognition of the words (with no distractor items) as the dependent measure. Because recognition is generally easier than recall, the computer-based test used in this experiment as a measure of WMC may have been much easier than traditional OSPAN tasks or other computer-based OSPAN tasks that required recall memory instead of recognition memory. This difference in testing modality and type of memory could have influenced the accuracy of our WMC measure, perhaps by artificially inflating the WMC scores of the participants. In support of this possibility, we did not find a significant difference between the GPAs of those with higher OSPAN scores and those with lower OSPAN scores, nor did we find a significant difference between the standardized testing scores of the two groups, while past researchers have found these differences (e.g., Mrazek, et al., 2012). The lack of relationship between OSPAN and other measures that typically correlate with it suggests that the OSPAN task used in the present study may have been a less valid measure of WMC compared to other working memory measures used in previous studies (e.g., the Reading Span Task [used in Kaufman, 2007], the Corsi Block Tapping Test [used in Lehmann et al., 2014], or SGOSPAN [used in Pardo-Vasquez & Fernandez-Rey, 2012]).

Despite the previously described limitations, the current results were consistent with the majority of our hypotheses based on previous studies. We replicated the *angular deviation reaction time effect* and replicated the greater difficulty of 3D tasks compared to 2D. We also found partial (but limited) support for a relationship between WMC and mental rotation ability found in previous studies (Hyun & Luck, 2007; Kaufman, 2007; Lehmann, et al., 2014; Pardo-Vasquez & Fernandez-Rey, 2012) because there was a negative correlation between WMC and RT on the 2D task (but not on the 3D task). Although we found no support for a mental rotation RT advantage for those with higher WMC when processing demands were higher, we report a unique finding related to the *angular deviation reaction time effect* that has not been researched previously. Unlike previous researchers, we analyzed how the *angular deviation reaction time effect* varied as a function of WMC and found that higher WMC participants' ability to mentally rotate did not appear to be hindered by larger angular deviation trials in the 2D task. This distinctive finding is consistent with working memory models that include an executive attentional control mechanism (Baddeley, 1996; Engle & Kane, 2004).

There is a wide variety of potential application for this research. If differences in WMC lead to some differences in approaches to cognitive processes like mental rotation, then some aspects of standardized testing and intelligence testing might need to be rethought. Mental rotation is also used in a variety of everyday tasks, such as driving and reading maps. If differences in WMC are related to the types of cognitive approaches utilized in mental rotation tasks, then WMC might become an aspect to consider on driving tests and in license certification. Additionally, if WMC affects how people use maps and navigation systems, companies that make GPS technology may want to investigate this difference in people's approach to cognitive tasks that involve mental rotation.

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Appendix A

OSPAN Stimuli (C = Correct, I = Incorrect)

	Mathematical Operations	**Words**
1	(22 + 16) / 2 = 18 (I)	Ideal
2	(2 x 10) / 5 = 4 (C)	Quarrel
3	(11 + 7) / 9 = 1 (I)	Friday
4	(5 + 13) / 2 = 8 (I)	Crime
5	(9 x 2) / 9 = 2 (C)	Muscle
6	(11+43) / 6 = 9 (C)	Milk
7	(36 + 4) / 5 = 8 (C)	Winter
8	(52 + 11) / 7 = 8 (I)	Page
9	(53 + 11) / 9 = 7 (I)	Leader
10	(15 + 5) / 5 = 4 (C)	Door
11	(1 + 7) / 2 = 3 (I)	Rain
12	(9 + 9) / 3 = 5 (I)	Band
13	(31 + 34) / 9 = 8 (I)	Book
14	(2 + 4) / 2 = 4 (I)	School
15	(1 + 71) / 9 = 8 (C)	Broom
16	(19 + 13) / 8 = 3 (I)	Fly
17	(2 + 10) / 6 = 2 (C)	Sharp
18	(11 x 3) / 3 = 9 (I)	Guide
19	(1 + 14) / 3 = 5 (C)	Light
20	(22 + 8)/ 6 = 5 (C)	Soldier
21	(24 + 14) / 2 = 17 (I)	Reader
22	(21 + 14) / 7 = 5 (C)	Equal
23	(6 + 12) / 3 = 6 (C)	Figure
24	(7 + 21) / 7 = 4 (C)	Wagon
25	(9 + 21) / 6 = 4 (I)	Tree
26	(14 + 22) / 4 = 8 (I)	Object
27	(2 x 20) / 5 = 6 (I)	Drama
28	(9 + 45) / 6 = 9 (C)	Shore
29	(3 + 29) / 8 = 3 (I)	Bread
30	(3 + 21) / 6 = 3 (I)	Ease
31	(1 + 11) / 3 = 4 (C)	Quarter
32	(30 + 5) / 7 = 7 (I)	Factory
33	(28 + 2) / 5 = 7 (I)	Session
34	(10 x 2) / 5 = 4 (C)	Motor
35	(4 + 12) / 2 = 7 (I)	Bottom
36	(1 x 5) / 5 = 1 (C)	Pilot
37	(10 x 3) / 3 = 10 (C)	Sausage
38	(10 + 44) / 9 = 6 (C)	Cousin
39	(14 + 14) / 7 = 4 (C)	Music
40	(3 x 10) / 5 = 6 (C)	Heat

Appendix B

Perceptions of Memory Scale

Instructions: Please rate the degree to which you agree with each statement using the scale below.

1 = "*strongly disagree*"
2 = "*somewhat disagree*"
3 = "*neither agree nor disagree*"
4 = "*somewhat agree*"
5 = "*strongly agree*"

____ 1. I have a good memory for numbers.
____ 2. I have a good memory for events.
____ 3. I find it easy to remember the material I study for exams.
____ 4. I find multitasking easy.
____ 5. I think my operation span score is an accurate representation of my working memory capacity.