Spatial Working Memory in Mental Rotations: A Case for Exploring Neural Efficiency and Cognitive Strategies

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Abstract

Spatial ability, particularly the cognitive capacity for mental rotations, is a critical component of human cognition. Proficiency with mental rotation tasks is linked with education performance in various science, technology, engineering, and mathematics (STEM) disciplines, and with more general tasks such as real world wayfinding. Spatial working memory (SWM) is posited as a fundamental psychological construct associated with mental rotation ability. Through the adoption of pupillometry, this study aspired to investigate the potential role of SWM within mental rotation performance. The results of this study unexpectedly illustrate that mental effort decreased as item difficulty increased. It is posited that learning may have occurred during the initial easier tasks facilitating an increased efficiency in cognitive processing associated with SWM storage during the more difficult mental rotations tasks.

Introduction

Spatial ability is well established as a core cognitive faculty for humans (Johnson & Bouchard Jr., 2005). Proficiency in this domain has been shown to result in an increased likelihood for success in various disciplines associated with science, technology, engineering, and mathematics (STEM) (Lubinski, 2010; Wai, Lubinski, & Benbow, 2009). However, spatial ability as a construct is multidimensional, consisting of a variety of cognitive factors (Carroll, 1993). The capacity to mentally rotate abstract stimuli is a specific ability within this faculty which is widely recognized for its particular importance in human cognition.

Investigations into spatial ability and particularly mental rotations have revealed a gender difference favoring males (Linn & Petersen, 1985; Lippa, Collaer, & Peters, 2010). In attempts to understand the rationale for this difference, numerous explanatory factors have been proposed including genetics, hormones, brain structure and functions, previous experience with toys, games, activities and training, gender role identity, and confidence in spatial abilities (Doyle, Voyer, & Lesmana, 2016). By virtue of their postulation as explanatory factors for the gender difference, these factors are therefore considered as general factors involved in the cognitive action of mental rotations or in its development. Working memory capacity has also been identified as a factor inherent to mental rotations and has been shown to account for the common variance between genders (Kaufman, 2007). When considering the findings of Heil and Jansen-Osmann (2008), which illustrated males as preferring a holistic strategy and females preferring a more analytical piecemeal approach, the role of spatial working memory in mental rotations becomes increasingly interesting as the concept of mentally storing the image of an abstract stimulus through the various stages of the rotation is posited as a core process within this ability.

Cognitive Load and Spatial Working Memory in Mental Rotations

It is posited within this study that spatial working memory (SWM) is a critical psychological mechanism inherent within the process of mental rotations. SWM can be defined as “the system of psychological processes and representations that underlie our ability to remember the locations of objects in the world, for short periods of time” (Dent & Smyth, 2006, p.529). SWM is recognized as having a capacity limitation and therefore the amount of spatial information which can be contained within it is restricted (Stevanovski & Jolicœur, 2007). In the context of mental rotations, particularly where multiple rotations or steps are required, it is posited that the spatial information pertaining to a stimulus’ position will need to be stored briefly prior to subsequent rotations. In addition to this, further storage is posited to be required for remembering the target sequence of rotations, and for the comparison between the target stimulus’ state with the potential solution stimulus after various steps.

Hypothesis

Considering the postulated role of SWM in mental rotations, it is hypothesized that participants with lower levels of spatial ability will need to exert a greater amount of mental effort during a mental rotations task than people with higher levels of spatial ability. It is also hypothesized that the magnitude of this variance will increase as item difficulty increases. The work of Sorby (2009) has established that mental rotation ability can be developed, however the psychological mechanisms underpinning this development are relatively unknown. Through the investigation of these hypotheses it is envisioned that the role of SWM in mental rotations can be better understood.

Method

Approach

Pupillometry was adopted as the principle method of investigating within this study to measure pupil dilation as an indicator of mental effort in mental rotation tasks. Kahneman (1973, 2011) considers pupil dilation as probably the best index of cognitive load as it reflects the current rate of mental effort expenditure. Strengths of pupillometry include its non-invasive nature and that it provides a continuous estimate of the intensity of mental activity (Laeng, Sirois, & Gredebäck, 2012).

Participants

Participants for this study volunteered as part of their engagement in a larger study examining the effects of cognitive strategies on spatial ability performance. Initially, the cohort for the larger study (N = 85) were administered the Paper Folding test (Ekstrom, French, Harman, & Derman, 1976) as it is a valid measure of a general visualization (Vz) factor often used as a representative measure of spatial ability (Carroll, 1993). The results of this test were used to stratify the cohort into quartiles. The cohort for this study (n = 16) comprised of four participants from each quartile to ensure a range of spatial ability levels was represented. In order to control for potential variances based on biological factors, participants age, sex and handedness were controlled for (Piper et al., 2011). The study cohort consisted of all male undergraduate students, had a mean age of 20.19 with a standard deviation of 0.75 (min age = 19, max age = 21), and were all right handed.

Stimuli for Pupillometry Tasks

The stimuli for this study included the 30 items from the Purdue Spatial Visualisation Test: Visualisation of Rotations (PSVT:R) (Guay, 1977) and 30 experimental items based on those within the PSVT:R. The PSVT:R was selected as it is a psychometrically sound measure of mental rotations (Maeda, Yoon, Kim-Kang, & Imbrie, 2013) whereby the items systematically increase in difficulty as more rotations are added and the geometry becomes more complex (Branoff, 2000). All items in the PSVT:R contain abstract stimuli. The experimental items contained common real life objects in place of the abstract stimuli found in the standard PSVT:R. The familiar nature of the stimuli was the only variance in the experimental items as all rotations were designed to correspond to those within the standard test.

Implementation

All testing was conducted individually with participants. Test items were displayed on a monitor and pupil dilation was recoded using the Tobii T60 system. The Tobii T60 system tracks both eyes, has a sampling rate of 60 Hz and a spatial resolution of 0.2°. Participants were seated with their heads resting on a chinrest 65 cm in front of the monitor. Participants were evenly distributed between one of two test conditions (Figure 1) with two participants from each quartile being assigned to each. Following an explanation of the test instructions participants completed two sample items from each type of stimulus to ensure that the data from initial items wasn't skewed by the novelty of the experience. Both tests were preceded by a 10000 ms fixation period. There was no time limit placed on participants when answering any test item. A 4000 ms fixation period was placed between each item. All participants answered 30 items, 15 from the standard version of the PSVT:R and 15 from the experimental version.

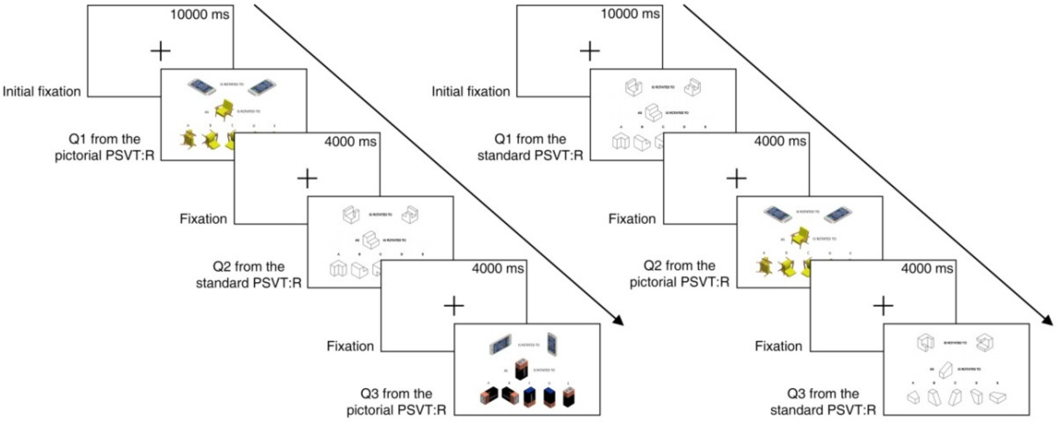


Figure 1. Illustration of test condition one (right) and condition two (left). Items in this figure are sample items not included in the actual tests.

Results

The pupillometry data was analysed to examine mental effort over time. For this part of the analysis, due to the different items administered to participants, four separate datasets were created to separate the abstract and real life stimuli from each test condition. Each dataset contains the results from eight participants. The results of this analysis are presented in Figure 2.

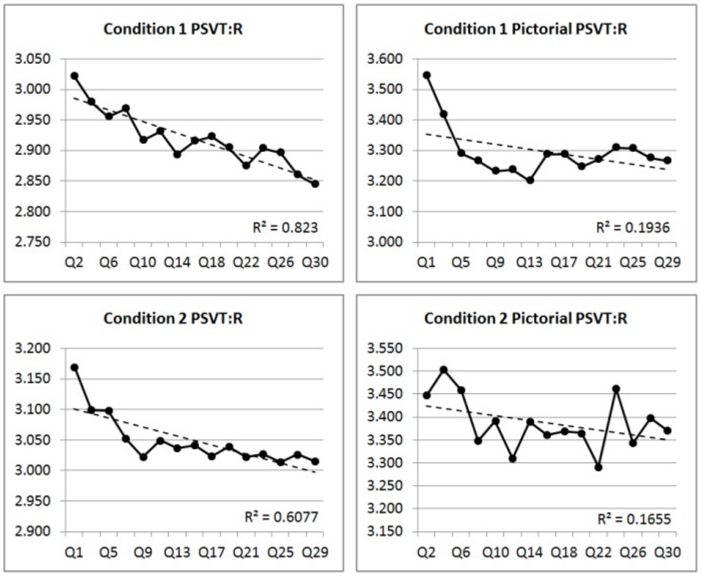
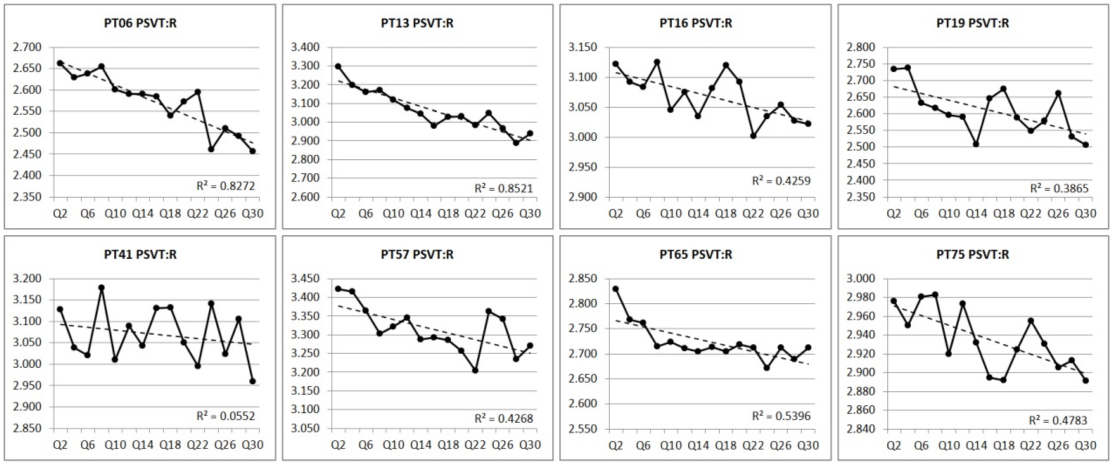


Figure 2. Average pupil dilation for items in each test condition. Vertical axes indicate pupil dilation in millimeters (mm) and horizontal axes indicate test item numbers.

The results of Figure 2 illustrate negative trends in each circumstance indicating that in general, as item difficulty increased, exerted mental effort decreased. As the difficulty level increased with each item, it was hypothesized that the required mental effort would also increase. Therefore, a more detailed analysis was conducted for the results from each participant. The results of this analysis are presented in Figure 3 (standard PSVT:R items) and Figure 4 (experimental items) respectively.

Condition one results



Condition two results

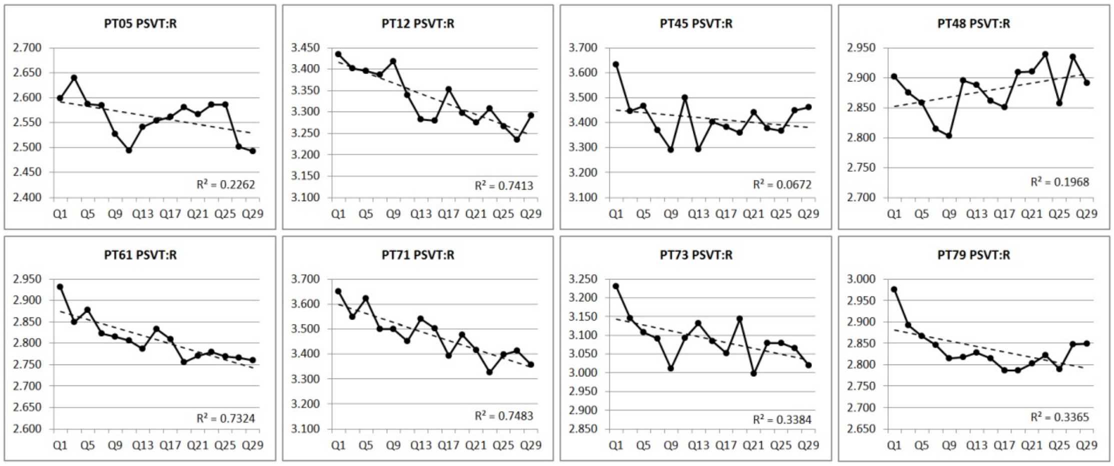
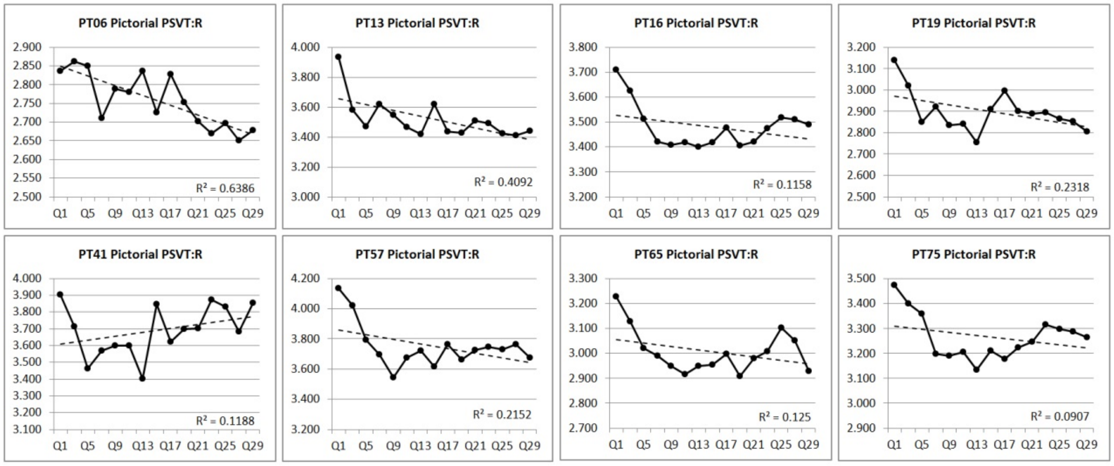


Figure 3. Pupil dilation results for each participant for the standard PSVT:R items. Vertical axes indicate pupil dilation in millimeters (mm) and horizontal axes indicate test item numbers.

Condition one results



Condition two results

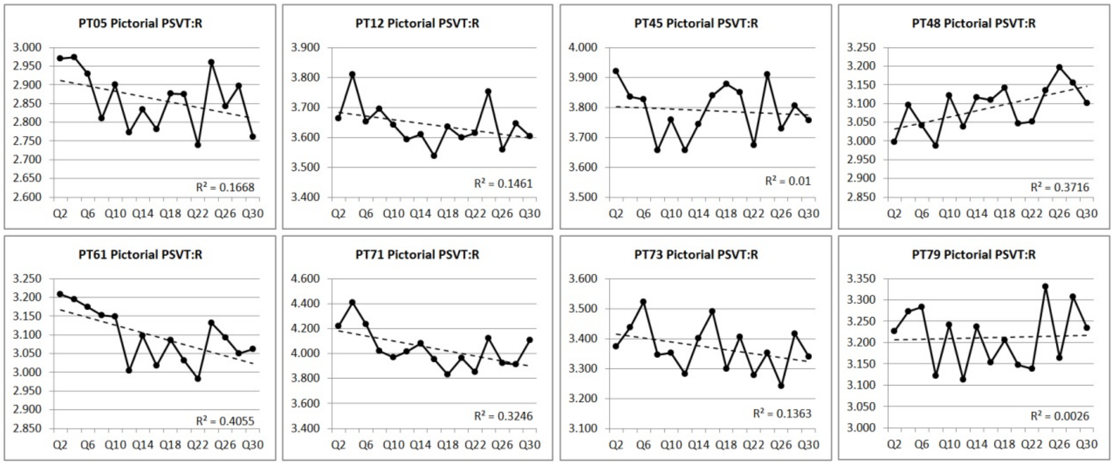


Figure 4. Pupil dilation results for each participant for the experimental PSVT:R items. Vertical axes indicate pupil dilation in millimeters (mm) and horizontal axes indicate test item numbers.

As can be observed from Figure 3 and Figure 4, 28 out of the 32 results from individual participants illustrate a negative trend in mental effort exerted over time despite item difficulty increasing. In addition to this, when comparing the R^2 values for the trends between individual students effort on the standard and experimental items, in 14 of the 16 cases the R^2 values are higher for the standard PSVT:R items containing the abstract stimuli.

Discussion and Conclusion

The results of this study were unexpected. The study aspired to investigate a hypothesis predicated on the assumption that as item difficulty increased, mental effort associated with SWM would also increase relative to the demands of the task. However, the results illustrate a negative trend indicating that despite an increase in item difficulty, exerted mental effort tended to decrease over time. These findings do however align with the neural efficiency hypothesis which suggests that intelligence is a function of how efficient the brain works and not how hard it works (Haler, Siegel, Tang, Abel, & Buchsbaum, 1992). Evidence of neural efficiency illustrates that a decrease in cognitive effort can be found subsequent to learning or training. In this study, early items may have provided an opportunity for such learning to occur reducing the mental effort associated with SWM storage as this process became more efficient. However, the idea that such efficiency could develop so quickly throughout the first number of test items is surprising and warrants further inquiry to determine if this is the case. Examining mental rotations from this perspective also provides a case for examining cognitive strategies. It may be possible that a strategy was developed in the early items which when applied in later items facilitated a reduction in required effort.

In addition to further enquiry being warranted for the potential development of neural efficiency in SWM and mental rotations, another question emerges from these results associated with performance. If the mental effort required to engage in more difficult questions is lower than previous and easier questions, suggesting more cognitive resources are available to engage in the task, why is performance poorer in these questions? Woodman and Vecera (2011) illustrate that accessing object features in the visual working memory degrades the representations of other stored objects. The increased number of rotations in more difficult questions may require more continued access to object features and therefore despite the rotation seemingly becoming more efficient, the degrading of the target rotation may be the reason people get the harder items incorrect. This would explain why the apparently reduced effort required doesn’t result in increased performance.

Unfortunately, mental effort could not be compared between the types of stimuli due to luminance difference in the items. Further work is warranted where this variable is controlled to examine if the familiarity of the stimuli affects the required mental effort. In relation to potential differences, Mayer, Kim, and Park (2011) have shown that abstract or novel stimuli are more easily encoded in the working memory and therefore the hypothesis may be generated that less mental effort will be needed in mental rotation tasks with abstract rather than familiar tasks. Alternatively, familiar objects may be able to be retrieved from long-term memory storage rather than needing to be encoded into the SWM which may facilitate an easier mental rotation.

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