Engineering Design Graphics Journal (EDGJ)
Fall 2018, Vol. 82, No. 3
http://www.edgj.org

ISSN: 1949-9167

Spatial Working Memory and Neural Efficiency in Mental Rotations: An Insight from Pupillometry

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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 educational 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 illustrated 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). It is also associated with the more general task of real world wayfinding (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). 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 recognised for its particular importance in human cognition (Maeda & Yoon, 2012).

Investigations into spatial ability and particularly mental rotations have revealed a gender difference favouring 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 women preferring a more analytical piecemeal approach, the role of spatial working memory (SWM) 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

Items within mental rotation tests commonly involve the presentation of a target rotation which includes an abstract stimulus presented in an initial state and in a goal state. A second item stimulus is then presented in an initial state. The objective is to apply the rotation(s) presented through the target stimulus to the item stimulus and select the correct goal state from a selection of potential solutions (e.g. Guay, 1977). It is posited within this study that SWM is a critical psychological mechanism inherent within this process. 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). This short period of time refers to a period of seconds, differentiating it from the iconic memory which has a span of approximately half a second (Delvenne & Bruyer, 2004). SWM is also recognised as having a capacity and temporal limitation which restricts the amount of visual and/or spatial information which can be contained within it and for how long it can be retained without rehearsal (Cowan, 2001; Miller, 1956; Peterson & Peterson, 1959). These findings ultimately led to the conception of cognitive load theory which describes how mental effort can be induced by tasks relative to working memory limitations (Sweller, 1988). In the context of mental rotations, particularly where multiple rotations or steps are required, it is posited that the spatial information pertaining to the 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

Just and Carpenter have shown that in the mental rotation of 2-dimensional stimuli, pupil dilation, an indicator of mental effort, increased monotonically relative to an increase in angular disparity (Just & Carpenter, 1995; Just, Carpenter, & Miyake, 2003). This work also showed that pupil size changes were more substantial for low visualizers. From this they posited that the demand on spatial resources was more for low visualizers than for high visualizers. Considering this postulated role of SWM in mental rotations, it is hypothesised that participants with lower levels of spatial ability will need to exert a greater amount of mental effort during a 3-dimensional mental rotations task than people with higher levels of spatial ability. It is also hypothesised that the magnitude of this variance will increase as item difficulty increases where item difficulty is classified by number of rotations and number of axes of rotation. The work conducted by Sorby (2009) has established that mental rotation ability can be developed, however the psychological mechanisms underpinning this development are relatively unknown.

Method

Approach

There are multiple approaches to measuring mental effort or cognitive load including self-report measures, dual task analyses, behavioural measures, neurological measures, and physiological measures (Brünken, Plass & Leutner, 2003). Kahneman (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). All cognitive effort causes pupil dilation (Kahneman & Beatty, 1966) with this dilation reflecting an overall working memory capacity utilisation (Just et al., 2003). This infers that pupil dilation can be used to indicate overall cognitive functioning in a particular task (Van Der Meer et al., 2010). This inference is supported by research showing increased pupil dilation relative to increased task difficulty (Nuthmann & van der Meer, 2005; Raisig, Welke, Hagendorf, & van der Meer, 2007). However, the allocation of cognitive resources is not solely dependent on task difficulty but also on the level of engagement (Ahern & Beatty, 1979; Van Der Meer et al., 2010). Therefore, it is important that pupillometric methodologies are designed and subsequent data is interpreted with this consideration. As this study purported to examine SWM in mental rotations, based on this research, pupillometry was adopted as the principle method of investigation.

Participants

This specific study using pupillometry was part of a larger study examining the effects of cognitive strategies on spatial ability performance. The cohort consisted of 2nd Year undergraduate Initial Technology Teacher Education (ITTE) students (N = 85) of which 80 were male and five were female, however not all participants engaged with this particular part of the study. The low representation of females in the cohort is reflective of the gender distribution in technology education in Ireland where the study was conducted. Initially, the Paper Folding Test (PFT) (Ekstrom, French, Harman, & Derman, 1976) was administered to the full cohort (N = 85) 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 (Q1 ≤ 9, Q2 10 - 11, Q3 12 - 14, Q4 15 - 20). The cohort for this part of the study (n = 16) which involved the use of pupillometry comprised of four participants from each quartile to ensure a range of spatial ability levels was represented. Considering the low number of females in the full cohort, it was not possible to include adequate representation of females in this part of the study. Additionally, 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 who engaged with the pupillometry aspect (n = 16) 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.

Method

Psychometric Tests

In addition to the PFT, the Shape Memory Test (SMT) (Ekstrom et al., 1976) as a measure of SWM and the Ravens Advanced Progressive Matrices Test (RAPM) (Raven, Raven, & Court, 1998) as a measure of fluid intelligence were also administered. These tests were selected as additional variables to investigate their potential role in mental rotations tasks.

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. Initial items require a mental rotation of 90º about one axis and progress to more difficult items requiring a rotation of 90º about one axis followed by another rotation of 180º about a second axis. Thirty experimental items were also included which were designed based on the items included in the PSVT:R. 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 those within the standard test.

Implementation

All testing was conducted individually with participants. Initially the psychometric tests described above were administered in paper and pencil format. The order of administration was varied for each participant to avoid inducing an order bias. After all paper and pencil tests were administered, participants engaged with the mental rotations test items electronically. Test items were displayed on a monitor and pupil dilation was recoded using the Tobii X120 system. The Tobii X120 system tracks both eyes, has a sampling rate of 120 Hz and a spatial resolution of 0.2º. 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 then preceded by a 10000 ms fixation period. For test condition one, even numbered items from the standard PSVT:R were mixed with the odd numbered items from the experimental pictorial version. For test condition two, odd numbered items from the standard PSVT:R were mixed with even numbered items from the experimental pictorial version. 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.

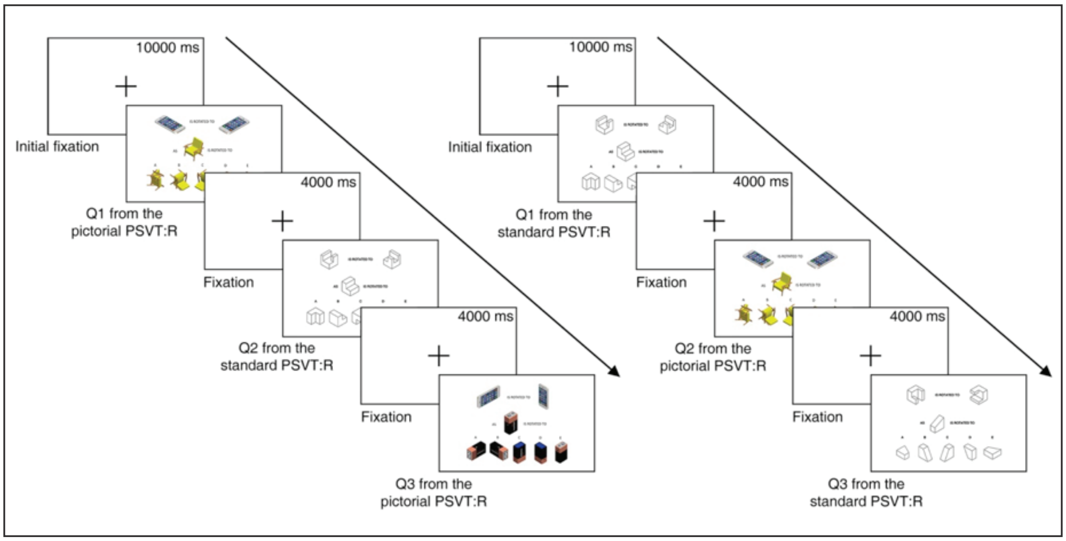


Figure 1. Illustration of test condition one (left) and condition two (right). Items in this figure are sample items not included in the actual tests.

Results

A Spearman's correlation analysis was conducted to identify any relationships between performance in the psychometric tests and mental effort exerted in the mental rotations items as measured by the participants' pupil dilation (Table 1). No statistically significant correlations were observed between pupil dilation indices and performance in the psychometric tests. Statistically significant moderate correlations were observed between the performance in the mental rotation items and both the PFT ($\rho = .574$, $p < .05$) and RAPM ($\rho = .547$, $p < .05$). Furthermore, a statistically significant strong correlation was

Table 1
Correlation matrix indicating Spearman's rho (ρ) correlations (n = 16)

	PSVT:R Dilation	Pictorial PSVT:R Dilation	Mental Rotation Performance	PFT	SMT
Pictorial PSVT:R Dilation	.956**				
Mental Rotation Performance	-.003	-.006			
PFT	.043	-.007	.574*		
SMT	-.095	-.133	.382	.435	
RAPM	.135	.072	.547*	.471	.774**

Note. PFT = Paper Folding Test. SMT = Shape Memory Test. RAMP = Ravens Advanced Progressive Matrices. ** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

observed between the RAPM and the SMT (ρ = .774, $p < .01$) and a statistically significant very strong correlation was found between participants average pupil dilation in standard and pictorial mental rotation items (ρ = .956, $p < .01$). Due to the low sample size and resulting low statistical power, these correlations should be considered with caution.

Further analysis of the pupillometry data was conducted to examine mental effort over time as the item difficulty increased. For this part of the analysis, due to the different items administered to participants, four separate datasets were created. These included the standard PSVT:R items from test condition one, the experimental PSVT:R items from test condition one, the standard PSVT:R items from test condition two, and the experimental PSVT:R items from test condition two. Each dataset contains the results from eight participants. The results of this analysis are presented in Figure 2.

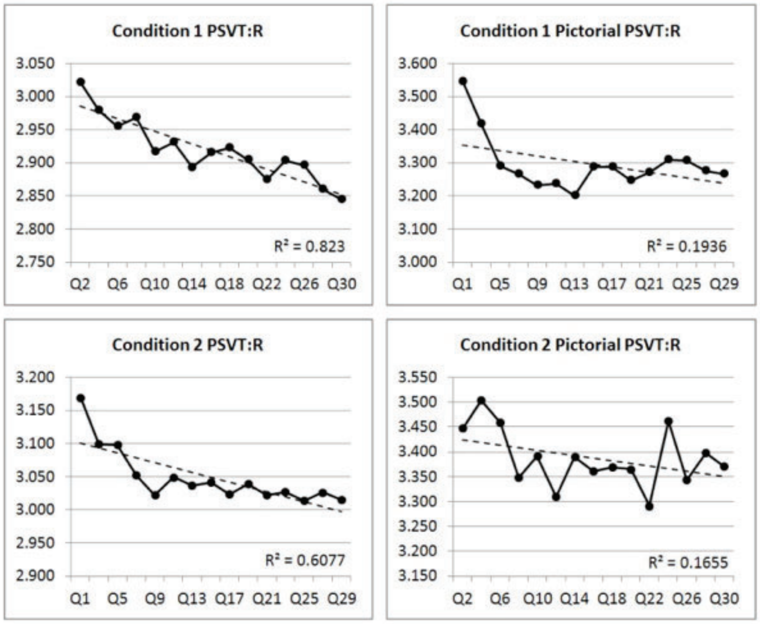


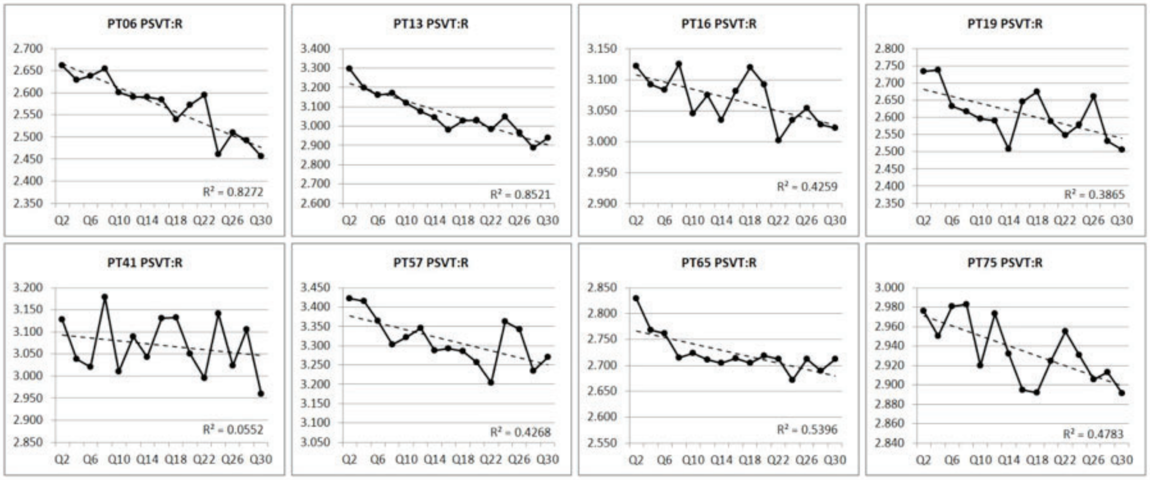
Figure 2. Average pupil dilation for items in each test condition. Vertical axes indicate pupil dilation in millimetres (mm) and horizontal axes indicate test item numbers.

ISSN: 1949-9167

Figure 2. Average pupil dilation for items in each test condition. Vertical axes indicate pupil dilation in millimetres (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 hypothesised 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

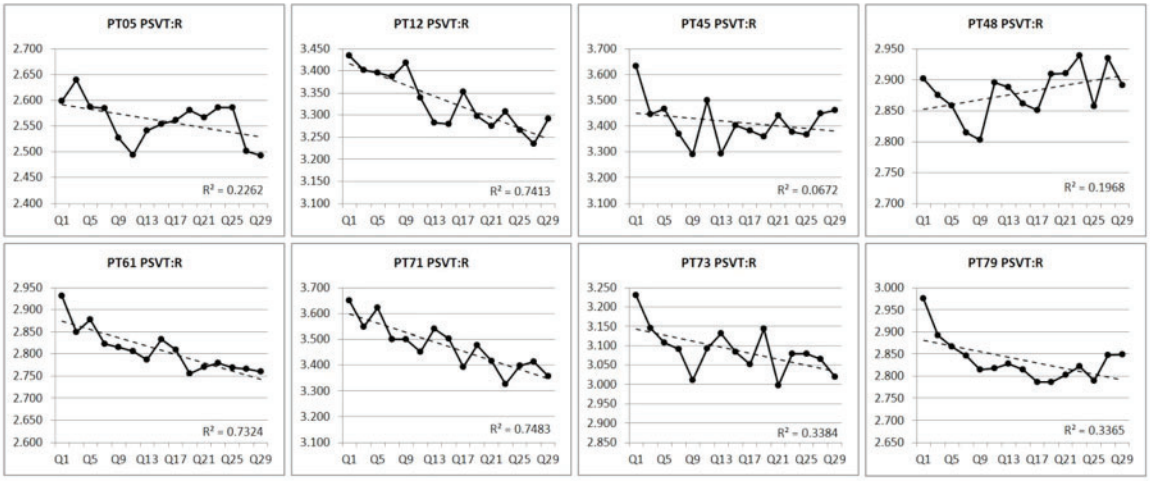
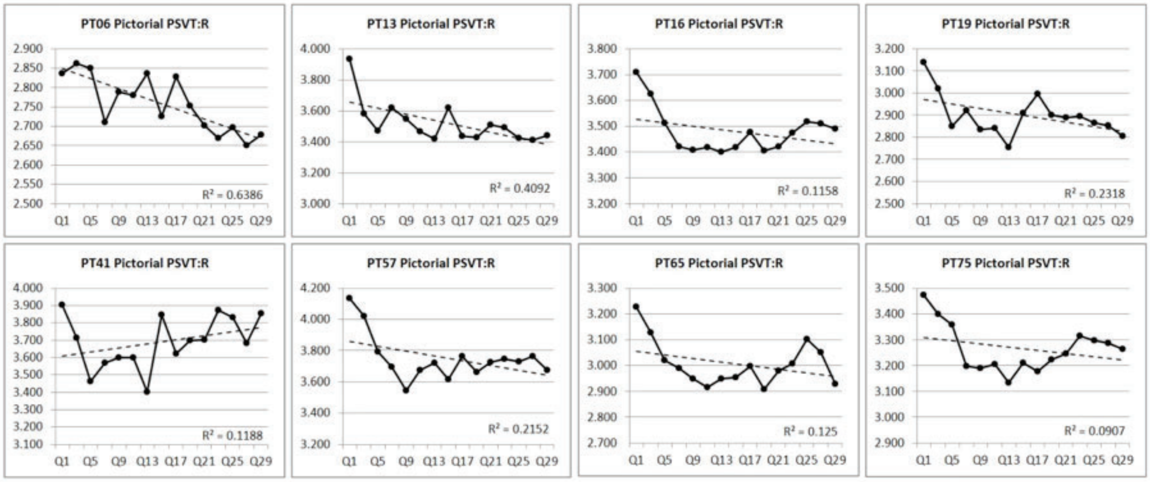


Figure 3. Pupil dilation results for each participant for the standard PSVT:R items. Vertical axes indicate pupil dilation in millimetres (mm) and horizontal axes indicate test item numbers.

Condition one results



Condition two results

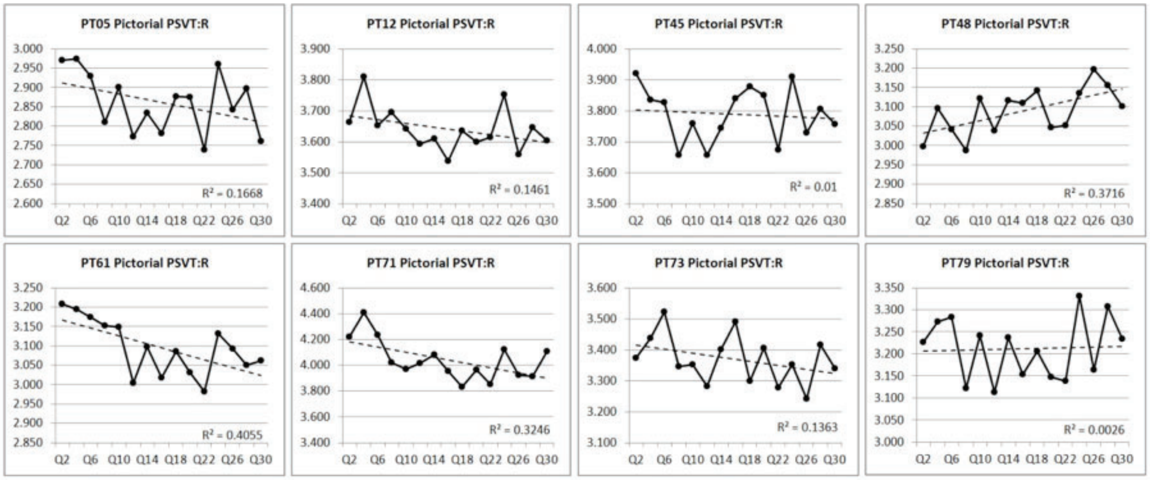


Figure 4. Pupil dilation results for each participant for the experimental PSVT:R items. Vertical axes indicate pupil dilation in millimetres (mm) and horizontal axes indicate test item numbers.

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

The results of this study were unexpected especially considering the work of Just and Carpenter (Just & Carpenter, 1995; Just et al., 2003). 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. It is possible that the negative trends exist as a result of increased boredom or disengagement over time during the test. However, if this were the case it would also be expected that performance would decrease as a result or that there would be a low level of reliability. The decreasing trend is observable from the initial items however performance scores (M = 18.938, SD = 5.323) suggest that sufficient effort was exerted to perform well until at least the middle of the test and the reliability of the test was high (α = .795) indicating that participants didn't resort to guessing in order to finish the test quickly. The time taken by participants to complete the test was short (M = 9.48 min, SD = 3.48 min) considering the standard 20 min time limit. Therefore, while it is plausible for boredom, disengagement, or reduced enthusiasm to have caused the negative trends, these variables did not affect participants enough to impact substantially on performance. The relationship between these and related emotions with test taking behaviour requires further investigation to make more precise inferences on these results.

The results of this study 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 (Haier, 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.

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.

With respect to the differences between the abstract and familiar stimuli, R^2 values were typically higher for the standard items. This is likely due to it being a validated instrument. It is interesting however that the results from the items with familiar stimuli show a similar trend as these items were experimental and not statistically validated prior to this

ISSN: 1949-9167

study. 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.

Conclusion

Considering that mental rotation ability is a strong predictor of educational success in STEM, it is paramount that a causal explanation for this phenomenon is determined to facilitate the scientific development of associated pedagogical approaches and training interventions. Determining more clearly the role of SWM in mental rotations would aid in identifying its underlying cognitive processes and knowing these would aid establishing why this ability is related to STEM performance. Additionally, as mental rotation ability can be trained, it may be possible to enhance such interventions through the incorporation of working memory training and increase the effect size that can be obtained both in terms of increasing spatial ability capacity and STEM performance. Finally, if it is the case the either a strategy can be developed in the initial test items or that a degree of efficiency can be achieved making more mental resources available in more difficult items, this has implications for research aiming to adapt the PSVT:R and potentially other related tests. Shortening these tests for pragmatic reasons may affect the strategies used by test takers if sufficient time is not available at the beginning prior to more difficult items affecting their psychometric properties.

Note

The preliminary results of this study were presented at the 72nd ASEE Engineering Design Graphics Division Midyear Conference in Montego Bay, Jamaica.

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