Neural efficiency and spatial task difficulty: A road forward to mapping students' neural engagement in spatial cognition

Abstract

The current study examined the neural correlates of spatial rotation in eight engineering undergraduates. Mastering engineering graphics requires students to mentally visualize in 3D and mentally rotate parts when developing 2D drawings. Students' spatial rotation skills play a significant role in learning and mastering engineering graphics. Traditionally, the assessment of students' spatial skills involves no measurements of neural activity during student performance of spatial rotation tasks. We used electroencephalography (EEG) to record neural activity while students performed the Revised Purdue Spatial Visualization Test: Visualization of Rotations (Revised PSVT:R). The two main objectives were to 1) determine whether high versus low performers on the Revised PSVT:R show differences in EEG oscillations and 2) identify EEG oscillatory frequency bands sensitive to item difficulty on the Revised PSVT:R.

Overall performance on the Revised PSVT:R determined whether participants were considered high or low performers: students scoring 90% or higher were considered high performers (5 students), whereas students scoring under 90% were considered low performers (3 students). Time-frequency analysis of the EEG data quantified power in several oscillatory frequency bands (alpha, beta, theta, gamma, delta) for comparison between low and high performers, as well as between difficulty levels of the spatial rotation problems.

Although we did not find any significant effects of performance type (high, low) on EEG power, we observed a trend in reduced absolute delta and gamma power for hard problems relative to easier problems. Decreases in delta power have been reported elsewhere for difficult relative to easy arithmetic calculations, and attributed to greater external attention (e.g., attention to the stimuli/numbers), and consequently, reduced internal attention (e.g., mentally performing the calculation). In the current task, a total of three spatial objects are presented. An example rotation stimulus is presented, showing a spatial object before and after rotation. A target stimulus, or spatial object before rotation is then displayed. Students must choose one of five stimuli (multiple choice options) that indicates the correct representation of the object after rotation. Reduced delta power in the current task implies that students showed greater attention to the example and target stimuli for the hard problem, relative to the moderate and easy problems. Therefore, preliminary findings suggest that students are less efficient at encoding the target stimuli (external attention) prior to mental rotation (internal attention) when task difficulty increases.

Our findings indicate that delta power may be used to identify spatial rotation items that are especially challenging for students. We may then determine the efficacy of spatial rotation interventions among engineering education students, using delta power as an index for increases in internal attention (e.g., increased delta power). Further, in future work, we will also use eye-tracking to assess whether our intervention decreases

eye fixation (e.g., time spent viewing) toward the target stimulus on
the Revised PSVT:R. By simultaneously using EEG and eye-tracking, we may identify changes in internal attention and encoding of the target stimuli that are predictive of improvements in spatial rotation skills among engineering education students.

Introduction

Spatial reasoning skills are critical for engineering students' academic success. Improving spatial skills increases the retention rate in engineering programs[25]. In addition, college courses geared toward improving spatial skills improve engineering students' grades in graphics courses[25]. Mastering engineering graphics requires students to mentally visualize in 3D and mentally rotate parts when developing 2D drawings[19]. Thus, students' spatial rotation skills play a significant role in their ability to learn and master engineering graphics[5].

Although previous work has established a clear relationship between mental rotation skills and academic success among engineering students[25], there is limited research on the underlying neural correlates of mental rotation. Electroencephalography (EEG) is a useful tool to measure neural activation during cognitive tasks. EEG oscillatory frequencies reflect rhythmic patterns of post-synaptic activity of neurons[23] and are linked to many cognitive processes including attention, working memory, and inhibition[2]. Gamma and beta oscillations are of particular interest in the current study. Gamma oscillations (30-40 Hz) facilitate the encoding of sensory information and are linked to visual and spatial attention[3].In primates, increased attention toward a visual stimulus is associated with gamma synchrony between the frontal eye field and the visual cortex[12]. During mental rotation in humans, gamma synchrony is also observed between the posterior and frontal cortices[4]. Gamma oscillations seem to increase the signal-to-noise ratio, fine-tuning the oscillatory rhythms of activation in brain regions responsible for visual[12] and spatial attention[22].

The beta oscillatory frequency (13-30 Hz) provides a reliable index of attentional resources utilized during cognitive tasks[17,7]. Beta power increases with greater cognitive load[18] and when individuals are particularly focused on the task at hand[17]. In previous work, we found group differences in beta activation based on student performance on the Revised Purdue Spatial Visualization Test: Visualization of Rotations[6] (Revised PSVT:R). That is, low performers (determined by overall accuracy scores) showed higher increases in beta activation than high performers. These findings are consistent with the neural efficiency hypothesis, which holds that individuals who have more experience in a given task require fewer cognitive resources to perform the task relative to their more novice counterparts[13,14]. Thus, reduced cortical activation during a cognitive task reflects more efficient neural processing.

The goal of the current work-in-progress study was to identify whether changes in EEG oscillatory frequencies are predictive of students' spatial rotation skills. Therefore, the two main objectives of the current study was to 1) determine whether high versus low performers on the Revised PSVT:R show differences in EEG oscillations and 2) identify

EEG oscillatory frequency bands sensitive to item difficulty on the Revised PSVT:R. According to our previous findings[6] and the neural efficiency hypothesis, we expected to observe higher power, specifically in the beta and gamma bands, in the high performers when compared to the low performers. In addition, we expected increases in EEG power in the beta and gamma bands as a function of task difficulty.

Method

Participants

Eight male undergraduate students between the ages of 20 and 30, were recruited from engineering programs at a public land-grant research university in the Mountain West area of the U.S. All procedures detailed in the current work were approved by the Institutional Review Board at the University. Informed consent was obtained from all participants.

Revised Purdue Spatial Visualization Test: Visualization of Rotations (Revised PSVT:R)

The Revised PSVT:R[26] assesses the spatial visualization ability of mental rotation in participants ages 13 and older. This instrument contains two practice items and 30 test items. Thirteen of the 30 items consist of symmetrical figures of 3-D objects, whereas 17 items contain asymmetrical figures of 3-D objects. For each item, students are to study the object on the top line, which shows the orientation of an object after rotation. Students were instructed to "picture in their mind what the object shown in the middle line looks like when rotated in exactly the same manner". Students must then select which of the five options represents the correct position of the rotated item. Students were given an example PSVT:R item with the correct response. Researchers assured that all students understood the task instructions prior to the start of experimental trials. There were no time constraints on completion of each spatial rotation item. Figure 1 shows examples of spatial rotation trials on the PSVT:R. The test was presented on a monitor using E-prime 3.0[24].

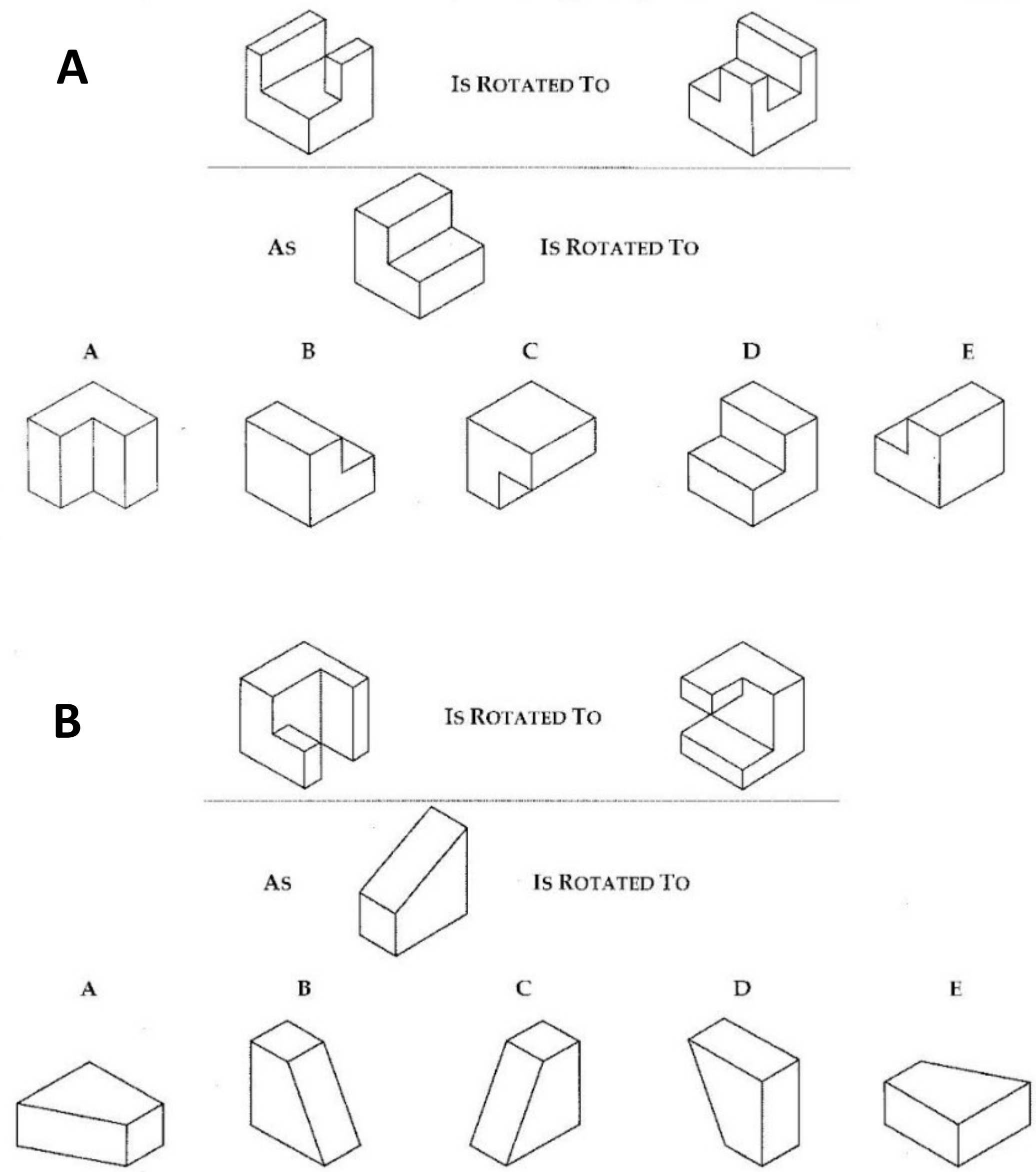


Figure 1. Revised PSVT:R Practice Items[26]. A) Example of an easy practice item on the Revised PSVT:R. The correct answer for this item is (d). B) Example of a more complex practice item. The correct answer for this item is (b).

EEG Recording and Preprocessing

EEG data were continuously recorded from 64 electrodes, digitized at 500 Hz, using an acti64 Champ System[1] while participants completed the Revised PSVT:R. Impedance levels were monitored throughout the experiment, maintained at less than 10 kOhms. EEG data were preprocessed and analyzed using EEGLAB[8], and according to our previous approach[6]. EEG data were filtered using a high-pass filter of 0.1 Hz and a low-pass filter of 59 Hz and re-referenced to the average reference. Ocular and motor artifacts were corrected by manual visual inspection of all EEG data for each participant.

After manual rejection of artifacts, independent component analysis was used to detect and remove any remaining, repetitive artifacts in the data.

EEG Epochs

EEG data were segmented to create three epochs for each PSVT:R item difficulty condition: easy, moderate, hard. Each epoch spanned from -1.0 to +5.30 seconds. This epoch window was determined by the shortest trial response time when evaluating all participants. Using this time window for all epochs allowed for reliable power estimates across all frequencies. All epochs were baseline corrected from -200 to 0 ms.

Time-frequency Analysis

Time-frequency analysis of EEG data was conducted in MatLAB 2019b[20]. Power spectrum analysis of EEG data were decomposed using a Fast Fourier transformation. Absolute power metrics were calculated using a power-based logarithmic transform[6], for all frequency bands: theta (4-8 Hz), delta (1-4 Hz), alpha (8-13 Hz), beta (13-30 Hz), gamma (30-40 Hz) and for all PSVT:R difficulty levels (easy, moderate, hard) across all 64 channels. Absolute power tables and time-frequency code can be accessed at https://osf.io/fpqy6/.

Results

Behavioral Analysis

The mean accuracy for performance on the Revised PSVT:R across all eight engineering students was 89% with a standard deviation of 31%. Table 1 shows accuracy for each student and overall mean trial response times. Table 2 shows mean accuracy and response times for the three item difficulty conditions.

Table 1. Overall accuracy scores and mean response times on the Revised PSVT:R

Student	Accuracy (%)	Mean Response Time (seconds)
1	90	22.38
2	97	31.75
3	83	32.44
4	97	21.34
5	87	24.01
6	70	32.57
7	90	20.58
8	100	26.02

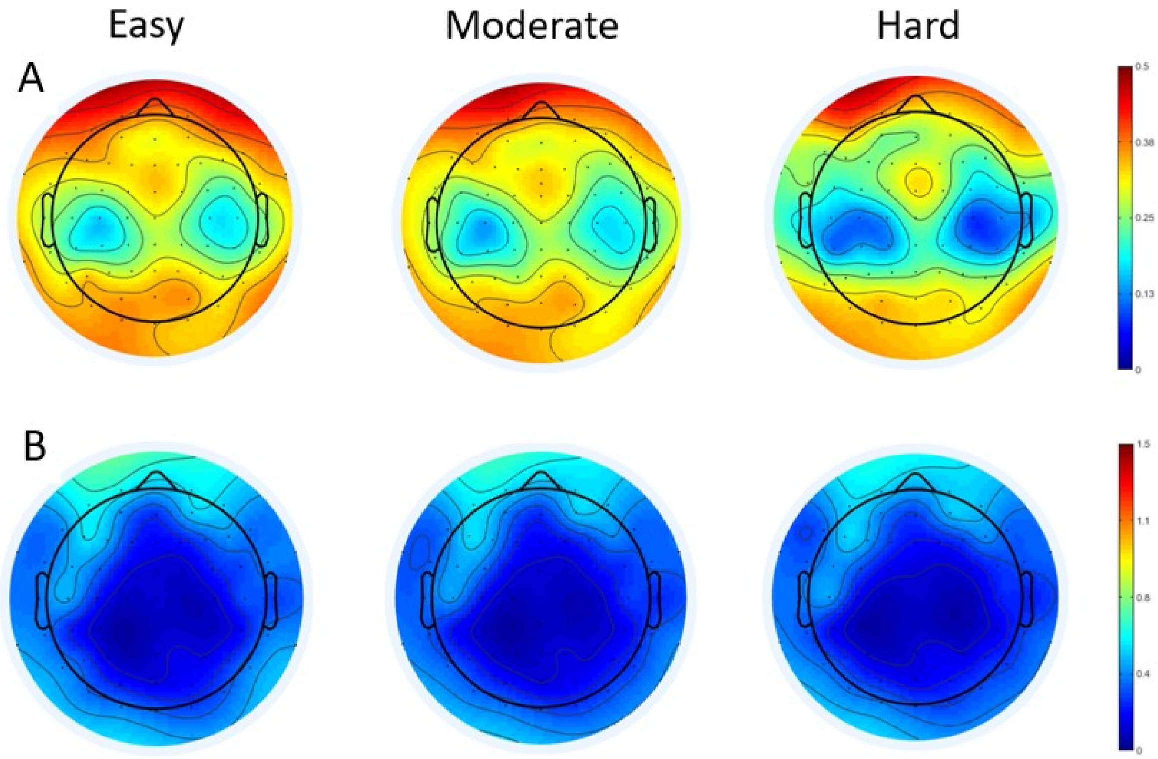
Table 2. Revised PSVT:R mean scores for easy, moderate, and hard items

Condition	Mean Accuracy (+/- s.d.)	Mean Response Time in seconds (+/- s.d.)
Easy	95% +/- 22%	16.523 +/- 10.526
Moderate	89% +/- 32%	30.894 +/- 17.911
Hard	38% +/- 52%	39.405 +/- 23.675

Neural Analysis

A Levene's test was used to assess normality of EEG absolute power values. The Levene's test revealed a non-normal distribution of EEG data. To meet normality assumptions, a log10 transformation was used to transform absolute power values. A mixed design ANOVA was used to assess effects of factors group (high, low), band (alpha, beta, delta, theta, gamma) and difficulty (easy, moderate, hard) on absolute power values. The ANOVA showed a significant frequency band x item difficulty interaction, $F(8, 48)=2.48$, $p < .05$. Paired samples t-tests showed a trend in reduced power for the hard difficulty items for the gamma and delta bands: delta easy (M=0.15,SD=0.29) > delta hard (M=-0.02,SD=0.32), t(4.93)=, p=.001; delta moderate (M=0.10,SD=0.28) > delta hard (M=-0.02,SD=0.32), t(4.03)=, p=.001; gamma easy (M=-0.90,SD=0.40) > gamma hard (M=-1.04,SD=0.39), t(3.64)=, p=.001. Figure 1 shows the topographies for the delta and gamma powers by item difficulty after the log10 transformation. An overall trend in reduced power for the hard condition may indicate a decrease in engagement, or depleting mental energy when students work on the hard item relative to the moderate and easy items.

Figure 1. Topographical plots of delta and gamma power averaged across all 8 students. A) Mean delta power (1-4 Hz) as a function of item difficulty across all 8 students. B) Mean gamma power (30-40 Hz) as a function of item difficulty across all 8 students. The color bar shows the range of power values depicted in the plots: dark red indicates higher power whereas dark blue indicates lower power.



Discussions

Our study used EEG during the Revised PSVT:R to assess the neural frequencies of engineering students during mental spatial rotation. Contrary to our hypothesis and our previous work[6], we did not observe any differences in absolute power between high and low performers across the five frequency bands for the Revised PSVT:R. According to the neural efficiency hypothesis, as individuals become more skilled in a cognitive task, they require less neural resources to perform the task[14,15]. Therefore, we expected that engineering students with higher accuracy scores on the Revised PSVT:R would show higher neural efficiency when performing mental rotation. In previous work[6], we observed higher beta activation for low versus high performers on the PSVT:R. However, a failure to replicate these findings in the current study is likely due to differences in the assessment of EEG power. Here, we assessed group differences in

EEG frequency bands using absolute power, whereas in the previous study[6], we examined group differences using relative power (e.g., a percent increase in beta power relative to baseline/rest). Further studies are needed to determine the best approach for examining group differences in EEG power during spatial rotation tasks.

Interestingly, we found that the level of difficulty of spatial rotation items effected EEG frequencies. Specifically, we observed a decrease in absolute power in the delta and gamma frequency bands for the most challenging spatial rotation item relative to easy items on the Revised PSVT:R. A reduction in delta power has been observed with increases in task difficulty for mental arithmetic tasks[9,10,15]. These studies interpret decreases in delta power as a reflection of greater external attention, specifically, attention to the stimuli involved in the task at hand. As external attention increases, consequently, internal attention decreases. In the current study, decreases in delta power for difficult spatial rotation items likely indicates greater external attention to the example and target spatial rotation stimuli with concurrent decreases in internal attention (e.g., mental rotation of the target stimulus). Increases in frontal delta power during mental tasks are associated with inhibitory processes, such as successfully inhibiting a motor response during a Go/NoGo task[11,16]. Thus, a decrease in delta power may also be interpreted as a failure to inhibit external attentional processes and distractions during difficult mental rotation.

In addition to effects of spatial rotation item difficulty on absolute delta power, we also observed decreases in absolute power in the gamma frequency band for the difficult spatial rotation item. Increases in gamma activation during mental rotation are believed to reflect encoding of visual stimuli[21]. In our study, decreases in gamma activation as task demands increase during spatial rotation may indicate students' difficulty to efficiently encode a mental representation of the spatial target object. In summary, our preliminary findings suggest that students are less efficient at encoding the target stimuli and may rely more on the example spatial rotation stimuli as task demands increase. Further, our findings indicate that reduced power in the delta and gamma bands may be used as a proxy for identifying challenging spatial rotation items/tasks.

Limitations of the Current Study

The current study is limited due to the constraints of the item difficulty on the Revised PSVT:R. The majority of subjects scored 90% or higher on the task, with one item that was especially challenging for engineering students, in which only 32.4% of students answered correctly (item 30 on the Revised PSVT:R). This resulted in a single trial being included in the hard condition. Therefore, our findings have limited power and future studies should include a wider range of item difficulty, with more challenging spatial rotation items. In addition, the engineering students who participated in the current study were all male. Future studies are needed to assess the neural correlates of spatial rotation in both male and female engineering students.

Future Work

Future work will identify spatial rotation items that are most challenging for engineering students and assess spatial rotation skills across a more diverse sample of engineering students. Upon identifying a set of spatial rotation items showing a wider range of difficulty, we will employ a spatial rotation intervention to assess whether changes in the absolute power of EEG frequencies (specifically in the delta and gamma bands) are predictive of improvements in mental rotation. In addition to using EEG, we will include methods to examine whether other psychophysiological markers (e.g., eye movements, pupil size) are predictive of improvements in spatial rotation performance. Our preliminary findings suggest that eye-tracking will be a valuable tool to further examine visual encoding of spatial stimuli. Collectively, this work will provide insight into alternative methods that may be used to a) identify areas of improvement and b) track progress of spatial abilities, by evaluating the cognitive demands of spatial rotation in engineering students.

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