

Neuro-cognitive Feedback as a Tool for Improving Cognitive Endurance in Engineering Design

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The purpose of this study was to explore the influence of neurofeedback on engineering design ideation. Professional civil engineers (n=122) were randomly divided into three groups: to receive neurofeedback, fake feedback that was pre-recorded (active control), or no feedback (control). The neurofeedback intervention provided designers with a dynamic heatmap displaying oxygenated hemoglobin (oxy-Hb) in their prefrontal cortex (PFC). The feedback groups were told to maintain the oxy-Hb in their PFC while ideating based on the heatmap. Designers verbalized their responses to the ideation tasks. Their verbalizations were recorded and transcribed. The time designers spent ideating and the number of words used to describe their design concepts were used as metrics for comparisons. The results indicate a significant increase in both the time designers spent ideating and the number of words used to describe their design concepts in the neurofeedback group compared to the other two groups. This research begins to highlight the potential use of neurofeedback as a tool to enhance design cognition. Future research is needed to explore changes in concepts, creativity, and idea production.

Introduction

Improving how designers solve problems is an ongoing process. Methods such as framing the design problem in multiple ways [1], applying structured

design principles to generate new ideas [2], allowing time for reflection [3], and engaging with stakeholders [4] have all been applied with varying degrees of success. Common to all these approaches is idea generation. Many kinds of stimuli exist to improve engineering design ideation [5]. For example, human interaction [6], chemical stimuli (caffeine) [7], and tDCS [8].

Neuro-cognitive feedback is a unique type of stimulus because it improves performance through self-regulation [9]. It is also customizable to each designer, and it does not require additional human resources (e.g., peer interaction). Neuro-cognitive feedback can reduce stress through heightened self-awareness [10], enhanced memory [11], and attention [12]. These cognitive functions are often requisites for engineering design ideation.

The distinction between neurofeedback and neuro-cognitive feedback is a function of the application. Neurofeedback targets brain function by providing real-time feedback on brain activity. The purpose of neurofeedback is often therapeutic and used to treat conditions like ADHD and anxiety [13]. The role of neuro-cognitive feedback is to enhance cognitive functions such as attention and memory [14]. Neuro-cognitive feedback often uses fMRI and fNIRS to provide feedback on the neural correlates of cognitive tasks [15].

The motivation for the study in this paper was to improve engineering design ideation by providing the foundation for and testing of a neuro-cognitive feedback tool. This study applies neuro-cognitive feedback to a cohort of professional engineers to assess its utility to enhance design ideation. Empirically testing the effects of real-time neuro-cognitive feedback with engineering professionals can open new avenues of research. The contribution of this research is the application of cognitive neuroscience to the engineering design process. While much current research advances computers to replace humans, the vision here is a future where neuro-cognitive feedback aids, rather than replaces, human cognition. Understanding how particular feedback methods can enhance cognitive activity can pave the way to future performance enhancement. The remainder of the paper is as follows. The Background section provides a short overview of neuro-cognitive feedback and is followed by the research questions. The Methods section outlines the empirical study to measure its effect. The Results and Discussion sections present the findings and offer some explanation and future direction for the use of neuro-cognitive feedback to enhance design.

Background

Engineering design is a process of problem generation, exploration, ideation, solution evaluation, and design communication [1]. The ideation phase during engineering design is critical to producing creative solutions to complex systems problems [1, 2]. Ideation is the time to bring together problem understanding, engineering science, social factors, and practical knowledge to develop possible solutions [16]. The quality and quantity of solutions generated inform and even determine the outcome of design [2, 4]. Only after ideation can a solution be chosen for further development.

Neuro-cognitive feedback to enhance engineering design ideation

Brainstorming produces a high cognitive response early during the solution-generation process, but this high cognitive response is not sustained over time. To improve the duration of the cognitive response, neuro-cognitive feedback can be applied to reduce the decay of cognitive activation during brainstorming. Neuro-cognitive feedback has been used to improve performance by making information about hidden brain states accessible to our consciousness [13]. It has also been used to provide a feedback loop to induce learning mechanisms that allow individuals to search for appropriate mental strategies through self-regulatory control of brain activity [15]. Neuro-cognitive feedback has been used to effectively change localized brain activity by tapping into learning processes [12]. People who receive neuro-cognitive feedback learn to increase a specific component of their cognitive activity, and that enhanced activity facilitates semantic processing in working memory and attention [5, 18].

Neuro-cognitive feedback holds the potential to significantly increase the time designers spend designing by providing real-time insights into brain behavior. By monitoring brain activity and physiological responses, designers can potentially gain an understanding of their cognitive states during the design process. This feedback could help them identify moments of greater creativity, concentration, or cognitive load.

How does neuro-cognitive feedback enhance ideation?

Neuro-cognitive feedback is executed by placing sensors on the scalp to measure cortical activity, analyzing this data in real-time, and then feeding back the current brain state to the participant using a display of the resulting activation. The efficacy of this type of feedback has been validated through multiple studies [19], systematic reviews [13], and clinical trials [19]. This

type of feedback provides a framework to facilitate learning, providing touch points for self-regulation [15].

Why functional near-infrared spectroscopy?

Functional near-infrared spectroscopy (fNIRS) measures oxygen levels in the blood flow in the brain and these are proxies for cognitive activity. fNIRS was selected for this application, over electroencephalography (EEG), because fNIRS can localize activity to specific regions of the brain with higher precision. This precision allows for near real-time display of spatial brain activation. The mobility of fNIRS also allows for data collection with engineers in more realistic settings compared to functional magnetic resonance imaging (fMRI) [17]. A limitation of fNIRS is the measure of cortical activation.

Research Questions

Neuro-cognitive feedback is an effective tool for improving cognitive function. What remains underexplored is how this specific type of feedback can enhance engineering design. Does neuro-cognitive feedback result in engineering designers spending more time and effort on the task? By testing the influence of neuro-cognitive feedback and comparing it to designers, giving false feedback (active control), and no feedback (control), this research measures the differences in the time and effort spent on design. The research questions were:

1. What is the effect of neuro-cognitive feedback on the time spent designing?
2. What is the effect of neuro-cognitive feedback on the effort spent designing?

The two hypotheses are: H1 the time spent on the task will be greater in the group receiving neuro-cognitive feedback compared to the groups receiving fake feedback and no feedback, and H2 the effort, measured by the number of words used to describe design concepts, will be greater in the group receiving neuro-cognitive feedback than the other two groups.

Methods

The experiment was approved by Virginia Tech's Institutional Review Board. In July and August of 2023, 122 civil engineering professionals were

recruited to participate in this study. Recruitment occurred at ten engineering companies. The companies were in Washington, DC, Richmond, VA, Blacksburg, VA, and Charlotte, NC. A continuing education lecture was hosted at each company office. The lecture was broadly about engineering design but did not include any mention of neuro-cognitive feedback. Potential participants were provided lunch during the lecture and asked to participate in the research study about design cognition following the lecture. No additional compensation for their participation was provided.

Engineering professionals who participated in the study were randomly selected to receive neuro-cognitive feedback ($n = 41$), fake feedback (active control; $n = 40$), or no feedback (control; $n = 41$). Multiple output parameters were collected from everyone in each cohort. The focus of this paper is on the time each engineering design professional spent engaged in the ideation task and whether this time and the length of the description of their ideas generated differed among the groups. The length of the description was used as a proxy for the cognitive effort on the task. None of the participants had practiced neuro-cognitive feedback before this study. Demographic data, including age, gender, and geographic location was collected. No significant demographic differences were observed between the groups. The average age of the participants was 31 years, with an average of 8 years of experience. Of the 122 participants, 87 were male.

Neuro-cognitive Feedback Display

Obelab's functional near-infrared spectroscopy (fNIRS) system and its NIRSIT software were used to provide feedback to the participants (<https://www.obelab.com/>). The software converts hemoglobin data into a heat map on an animated three-dimensional brain where the warmer colors indicate an increase in oxy-Hb. Participants in the study received feedback about the change in oxy-Hb in their prefrontal cortex and were told to sustain high levels of activation (red colors) across their prefrontal cortex in the heatmap in front of them. No additional training was provided to participants about how to increase oxy-Hb represented in the heatmap. While many regions of the brain are involved in the cognitive process of design ideation, the region of interest here was the prefrontal cortex because of its known involvement in executive functions, critical to ideation. The active control group was given the same instructions as the feedback group; however, their heat map was a previously recorded video. The video was continuous throughout all six design prompts. The control group faced a blank screen without a heatmap or a video of a heatmap.

Ideation Task

Participants in the study were asked to develop as many ideas as possible to six ideation prompts. There was no time limit. They were instructed to indicate when they were finished ideating and were ready to advance to the next prompt. The time participants spent on each prompt and the ideas they developed were recorded. Between tasks, participants were asked to respond to five single-digit multiplication problems. These multiplication problems were meant to provide a cognitive rest between ideation sessions and reduce the time participants spent reflecting on their performance on prior tasks. Participants were given 30 seconds for rest or five seconds per single-digit multiplication problem. The order of the ideation prompts was randomized. The average time ideating was 30 minutes cumulatively for all six prompts. The six prompts were as follows:

1. Describe as many elements of a comprehensive plan as you can if you were developing a town from the ground up.
2. Describe as many design ideas as you can to make traditional development projects more pedestrian-friendly.
3. Describe as many design ideas as you can to transform a vacant urban lot into a sustainable public park.
4. Describe as many design ideas as you can to manage stormwater runoff on a typical industrial site.
5. Describe as many alternative uses as you can for an old Walmart shopping center.
6. Describe as many steps as you can of designing the ideal process, from the initial meeting with a client to the successful completion of their project.

The ideation prompts were developed to include the various stages and challenges often encountered in civil engineering design projects, including urban planning, environmental sustainability, infrastructure management, and client communication. By focusing on these diverse aspects, the study aimed to assess participants' ability to generate ideas across different domains within civil engineering. The randomization of task order helped mitigate any potential bias or learning effects, ensuring that each task was approached independently.

The prompts were also checked for content validity before recruitment. Four industry professionals, each with five-plus years of experience were given the prompts. Their feedback included suggestions to clarify certain terms and concepts, add further details to enhance realism, and reword prompts to improve coherence and alignment with industry practices. Data collection began with the first multiplication problem. All the multiplication problems and the design prompts were read aloud to the participants.

Data Analysis

The total time spent designing was recorded for each participant in each group. Analysis of Variance and Tukey's HSD test were used to assess the differences among the sample means. Tukey's HSD tests all the pairwise differences while controlling the probability of making one or more Type I errors [20]. To measure the effect of neuro-cognitive feedback on the effort spent on each task, audio recordings for each participant were transcribed and an estimate for the number of design concepts generated was determined by counting the unique concepts or ideas expressed in each transcript. This was done using the Natural Language Toolkit package within the Python programming language. Participants in each group were compared based on the number of design concepts generated, using similar statistical analyses as the time spent designing.

Results

The total time spent designing was greater for the neuro-cognitive feedback group compared to the active control and control group. This is consistent with hypothesis one. The group that received neuro-cognitive feedback had the highest average time spent ideating. The feedback group spent 12.7 (SD = 5.48) minutes on average ideating, across all six tasks. This is higher than the 10.11 (SD = 3.94) minutes on average for the active control group and the 8.1 (SD = 4.14) minutes on average for the control group. The results of the ANOVA with multiple comparisons using post-hoc Tukey HSD are presented in Table 1. There is a significant difference on the time spent on the task between the control and feedback groups and the active control and feedback groups.

Table 1. Multiple Comparison using Tukey HSD of Mean Time on Task

Group 1	Group 2	Mean Diff	p	lower	upper
Control	Active Control	2.01	0.123	-0.4	4.42
Control	Feedback	4.612	0.0001	2.21	7
Active Control	Feedback	2.6	0.0315	0.18	5.02

The difference between the feedback and control groups produced a high effect size, Cohen's D, of 0.9490, shown in Table 2. The differences between the feedback and active control, and the active control and control

are moderate. The Pearson coefficient, r , is a linearity effect size metric, which was moderate across the three comparisons.

Table 2. Effect Size for Time Spent Designing

Group 1	Group 2	Cohen's D	Pearson Coefficient, r
Control	Active Control	0.4971	0.2412
Control	Feedback	0.9490	0.4287
Active Control	Feedback	0.5452	0.2630

The effort spent on the ideation tasks, measured by the number of design concepts was also greatest among the group that received the neuro-cognitive feedback (1,395 concepts (SD = 921) compared to the active control (1,270 concepts (SD = 890)) and control (933 concepts (SD = 762)). This is consistent with hypothesis two. The difference in concepts was significant between the neuro-cognitive feedback group and the control group (statistic=2.083, p value=0.041), with a medium effect size (Cohen's D of 0.54). However, the number of design concepts was not significantly different between the neuro-cognitive feedback group and the active control group (statistic=0.516, p value=0.607) and the difference between the active control and control was also not significant (statistic=-1.66, p value=0.1). The differences in the mean number of design concepts are illustrated in Figure 1.

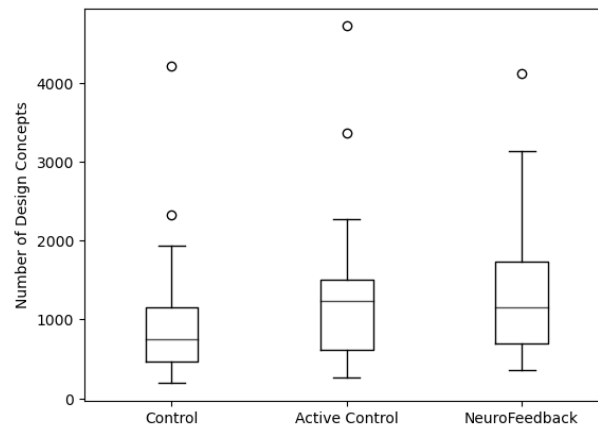


Fig. 1 Number of Design Concepts for Each Group

Discussion

Neuro-cognitive feedback increased the time spent ideating and the number of concepts produced. Providing feedback about brain activity appears to modify behavior and may influence cognition. The theory of learning proposed by B.F. Skinner, known as operant conditioning, provides a theoretical framework for understanding the efficacy of neuro-cognitive feedback for enhancing the time designers spend designing [21]. Operant conditioning suggests that behaviors are influenced by their consequences; positive consequences increase the likelihood of a behavior recurring, while negative consequences decrease it. In the context of neuro-cognitive feedback, receiving positive feedback about brain activity while designing may reinforce the behavior of focused design, leading to increased time spent on the design task and the effort measured by the increase in design concepts. The lack of statistical differences between the active control and control groups further supports the influence of real-time neuro-cognitive feedback and how real feedback reinforces behavior (compared to fake feedback). These results suggest that this type of feedback may have a direct impact on participants' engagement and task performance, independent of their understanding of the feedback tool. This highlights the potential of neuro-cognitive feedback as a tool not only for enhancing specific behaviors but also for possibly shaping cognitive processes underlying those behaviors.

More research is needed to understand why neuro-cognitive feedback affects the time spent designing and effort designing. Several theories may contribute to this phenomenon, for example, theories such as the Self-Determination Theory suggest that neuro-cognitive feedback may enhance motivation and engagement by providing individuals with a sense of autonomy and competence in their design tasks [22]. The idea of "flow," or Flow Theory, posits that neuro-cognitive feedback could facilitate a state of flow, characterized by focused concentration and enjoyment [23]. The feedback provided in real-time may help designers maintain a higher level of challenge and task production. Relevant to Social Learning Theory, neuro-cognitive feedback may serve as a form of reinforcement, motivating individuals to reinforce strategies observed in the feedback [24]. For example, designers who receive positive feedback about their brain activity while generating ideas for a new project may feel more confident in their abilities, leading them to invest more time and effort into the task. Additionally, Dual-Process Theory, in the context of neuro-cognitive feedback, might suggest that this type of feedback enhances the interaction between the two processing systems [25]. For example, by providing real-

time feedback on brain activity, neuro-cognitive feedback may help individuals become more aware of their autonomous responses (System 1) and learn to regulate them using more deliberate and controlled processes (System 2). This could lead to more effective design. Understanding how these theories may explain neuro-cognitive feedback effects could provide insights into its mechanisms and potential benefits for design. Future research includes exploration into how neuro-cognitive feedback changes not just the time designers spent designing but what they designed.

Conclusion

Neuro-cognitive feedback is an effective tool for enhancing the time and effort spent ideating. The study's findings suggest that providing real-time feedback about brain activity can shape behavior and design cognition. The results support the notion that neuro-cognitive feedback may enhance motivation and engagement, leading to increased time and effort invested in designing tasks. The length of time spent designing and the number of design concepts generated was significantly greater for the neuro-cognitive feedback group compared to the control group. The lack of significant differences between the active control and control groups in both the time designing and number of concepts further supports the idea that real-time neuro-cognitive feedback reinforces behavior, independent of the participants' understanding of the feedback tool.

More research is needed to fully understand why neuro-cognitive feedback has this effect on designing time and effort. Several theories, such as Self-Determination Theory, Flow Theory, Social Learning Theory, and Dual-Process Theory, provide possible explanations for why neuro-cognitive feedback may influence designers' behavior. Further exploration into these theories and their intersection with the effects of neuro-cognitive feedback could provide new insights into its mechanisms and potential benefits for design. Future research should also investigate how neuro-cognitive feedback affects not just the time spent designing but also the quality and creativity of the designs produced. A limitation of the analysis presented here is the use of unique words and ideas expressed in each transcript as a measure of cognitive effort. Future research should expand this analysis. For example, future research could incorporate additional measures such as semantic distance between. These methods can provide a more nuanced understanding of cognitive processes by examining how ideas are related and structured within a design context. Exploration of these aspects can lead to a more comprehensive understanding of the role of

neuro-cognitive feedback in design cognition and its impact on design outcomes.

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Comparing engineering designers' brain activity in visuospatial reasoning tasks

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Knowledge of the cognitive processes underlying engineering design is essential for its comprehensive understanding and subsequent enhancement of the field. This paper contributes to building this knowledge by investigating the brain activity of engineering designers engaged in three visuospatial reasoning tasks of the Purdue Spatial Visualization Test (PSVT). These tasks assess three critical visuospatial factors for engineering design: spatial visualization, mental rotation, and spatial orientation. Brain activity is measured using electroencephalography (EEG) as a non-invasive neuroimaging method. The EEG results reveal significant differences in brain activity between the three tasks, considering three frequency bands (theta, alpha, and beta) and 14 electrodes spatially distributed across two hemispheres and seven cortical areas. Theta and beta task-related power (TRP) appear to be crucial in distinguishing among the visuospatial reasoning tasks at the neurocognitive level.

Introduction

Engineering design is a cognitive activity situated in an engineering designer's mind [1]. Knowledge of cognition underlying engineering design is a requirement for its comprehensive understanding and subsequent enhancement [2]. Consequently, extensive efforts have been made in the

area of design cognition to identify, describe, and map cognitive processes involved in designing. Popular pursuits covered differences between novices and experts (e.g. [3, 4]), engineers and industrial designers or architects (e.g. [5, 6]), collaborative team dynamics versus individual efforts (e.g. [7, 8]), and similar investigations. Furthermore, scholars have investigated the role of design representations (e.g. sketches [9, 10]), along with the impacts of design methods and tools (e.g. ideation methods [11]).

Earlier empirical studies heavily leaned on verbal and non-verbal protocols, employing protocol analysis as a method to scrutinize the cognitive dimensions of design [12]. Nowadays, these methods are complemented with (semi)controlled experiments that harness the capabilities of neuroimaging methodologies to unveil novel insights. Recent literature, exemplified by review papers such as [12–14] attests to the rising number of neuroimaging studies. These investigations employ methods like electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), and functional magnetic resonance imaging (fMRI) to explore design (neuro)cognition.

These previous studies (e.g. [11, 15]) offer valuable insights into designers' thinking. However, at this point, they mostly stand as isolated studies (whose findings cannot be generalised and applied in different contexts) implying differences between variables (such as experience, engineering background or type of design task) and suggesting hypotheses or research questions for future work. Building upon these studies, Hay et al. took the first step toward a shared ontology by extracting cognitive processes involved in designing through an extensive literature review on design cognition studies and correlated them with constructs from cognitive psychology [16]. The subsequent goal that design cognition researchers have been calling for is the development of cognitive models of designers' thinking [1, 12, 16].

This paper represents a step toward the development of one such model, focused on visuospatial reasoning (a mental manipulation of visuospatial information [17]), which is recognized as one of the essential aspects of design cognition [16, 18, 19]. Based on the type of mental manipulation and information to be manipulated, visuospatial reasoning is further clustered in several factors. The five commonly used visuospatial factors are: spatial perception, spatial visualization, mental rotation, spatial relations, and spatial orientation [20]. Although these factors have often been assessed using psychometric tests, their neurocognitive aspects are yet to be researched. Consequently, our first step is to understand whether the visuospatial factors differ at the neurocognitive level. Without that knowledge, it is unclear if further neurocognitive studies on visuospatial reasoning in engineering design should assess each factor individually and

if yes, what neuroimaging features may be the most informative for distinguishing them.

To address the recognized research gap, here presented empirical study involved capturing the brain activity of engineering designers using EEG while they engaged in solving three visuospatial reasoning tasks. The tasks are the integral component of the Purdue Spatial Visualization Test (PSVT) [21]. Each task is associated with a different visuospatial factor. To be more precise, Developments test spatial visualization, Rotations test mental rotation, and Views test spatial orientation. Although visuospatial reasoning underlies each of the three PSVT tasks, it is possible that different neural mechanisms are used to solve them, which may or may not be reflected in EEG signals [22]. As a preliminary step towards resolving this ambiguity, the paper describes frequency-domain EEG features (task-related power; TRP) associated with the particular visuospatial factor tested by the PSVT tasks and compares them to discern potential differences. Hence, the paper aims to address the following research question:

Does TRP differ in visuospatial reasoning tasks associated with spatial visualization, mental rotation, and spatial orientation?

While spatial visualization, mental rotation, and spatial orientation do not exhaust the list of visuospatial factors, they are selected as initial focal points due to their recognised significance in engineering design. Scholars have established correlations between scores on tasks assessing these visuospatial factors and designing (e.g. [20, 23]), thus underscoring their relevance in engineering design. Moreover, due to the types of manipulation (visualization of developments, rotations, and orientations) and manipulated information (volumes presented in isometric and orthographic views), these tasks and the associated factors closely align with the continuous visuospatial transformations of design information occurring throughout engineering design [19, 24]. Similar visuospatial transformations, akin to spatial visualization, mental rotation, and spatial orientation tasks, are integral both to generating new and understanding existing design representations, such as isometric or orthographic views in technical drawings or computer-aided design (CAD) models [18].

To answer the posed research question, the paper begins by reviewing relevant prior work in the Background and related work section. Following this, the methodology employed in the research is detailed in the Research methodology section. The findings of the study are then presented in the Results section. Subsequently, a discussion of the findings alongside their limitations is provided in the following section. Finally, the paper concludes by summarizing the findings and offering directions for future research.

Background and related work

Researchers in engineering design have explored visuospatial reasoning through protocol analysis to better understand how designers think, with the ultimate goal of proposing cognitive models to adequately support them with design tools and methods. Additionally, scholars focusing on engineering education have utilised standardised visuospatial reasoning tests to explore the correlations between visuospatial factors and engineering design performance. Drawing from these findings, scholars aim to enhance educational practices in engineering design. The subsequent subsections provide a brief overview of relevant previous studies.

Models of visuospatial reasoning in (engineering) design

Several models have been proposed to understand visuospatial reasoning in the context of engineering design. These models aim to elucidate the cognitive processes involved in visualizing and manipulating visuospatial information when designing. Two relevant models, applied and validated in the context of design tasks relatable to the PSVT tasks, are explained below.

Park and Kim proposed visual reasoning model composed of interaction of seeing, imagining, and drawing, further classified into eight components of perception, analysis, interpretation, generation, transformation, maintenance, internal representation, and external representation [19]. Through protocol analysis conducted within a case study, the occurrence of these components and their interconnectedness was affirmed. In the experimental task, known as a missing view task, participants were asked to visually generate a 3D solid object by analyzing two two-dimensional (2D) orthographic views and subsequently draw the missing third orthographic view.

Furthermore, Oxman proposed the re-representational model of design reasoning, which elucidates the cognitive mechanisms and abilities that underlie and facilitate the sequential evolution of graphical representations in design [24]. This model was developed based on an empirical study in which designers' behaviours were analysed through protocol analysis during the task of graphically transforming a given design representation to accommodate changing requirements. Participants in the study provided self-reported protocols detailing the performed steps, actions, and underlying reasoning.

These models and studies conducted so far imply the existence of certain visuospatial factors within engineering design tasks. However, it is important to note that they primarily analyse cognitive processes at a lower level of granularity compared to visuospatial factors, owing to the

limitations of protocol analysis. Consequently, relating their findings to the fundamental constructs originating from cognitive psychology can be challenging [16].

Assessing visuospatial reasoning in engineering design

Visuospatial reasoning is commonly assessed as a skill – a cognitive ability to mentally manipulate visuospatial information [17]. Cognitive psychology theoretically distinguishes between various visuospatial factors [25]. To assess one or more of these factors, a range of tests has been utilised. Some examples include the PSVT, Mental Rotations Test (MRT), Mental Cutting Test, and Differential Aptitude Test. However, the field of engineering design often overlooks the significance of various factors. Many studies in this domain have predominantly focused on mental rotations without offering a rationale for this selective approach.

Scholars have identified a positive correlation between scores on individual tests and performance in engineering graphics and CAD courses (e.g. [26]). Consequently, scores on visuospatial reasoning tests have been used as predictors of success in related courses or even in engineering studies in general [27, 28]. These findings underscore the importance of visuospatial reasoning in engineering design. However, more than just the scores of visuospatial reasoning tests is necessary to explain the visuospatial reasoning and the existence of its factors in engineering design.

Furthermore, there is a limited number of studies that assess more than one visuospatial factor in their experiments. Some evidence of differences in subjects' performance (based on achieved scores) on tests evaluating various visuospatial factors is provided by [10] and [14]. Although limited, these empirical findings encourage further investigation into the neurocognition of distinct visuospatial factors assessed with standardized tests. Such investigations could offer potential explanations for identified differences at the neurocognitive level.

EEG studies of visuospatial reasoning tasks

Most EEG studies have concentrated on brain activity during mental rotations tasks, either as an isolated part of the PSVT or using the MRT. For example, Gill et al. monitored alpha power while participants were solving the mental rotations task [29]. They found that the right frontal lobe mediated encoding and comparison/decision processes, while the left parietal and the left temporal brain regions appeared to be most involved in generating mental images and rotating them [29]. Furthermore, Ornstein et al. observed a high left hemisphere engagement during mental rotation compared to other visuospatial tasks in their experiment, such as facial

recognition, picture completion [30]. Conversely, Roberts and Bell reported higher activation in the right parietal then left parietal regions, as evidenced by increased alpha frequency band power (11 – 13 Hz) [31].

Despite the widespread use of visuospatial reasoning tests across various domains, including cognitive psychology, education, and engineering, there is surprisingly limited literature on EEG activity during visuospatial reasoning tasks. To our knowledge, no studies have investigated differences in EEG between spatial visualization, mental rotation, and spatial orientation, particularly as assessed with the PSVT.

Therefore, the literature review reveals a gap in research on EEG (or other neuroimaging) studies directly comparing brain activity during visuospatial reasoning tasks. While some insights exist regarding EEG signals during mental rotations task, little is known about brain activity during spatial visualization and orientation tasks. Hence, it remains unclear if visuospatial factors differ at the neurocognitive level. The research methodology used to provide first insights into this research gap is described in the following section.

Research methodology

The study recruited 27 mechanical engineers (2 female and 25 male) to participate in the experiment. They ranged in age from 25 to 31 years. All the participants were right-handed, had normal or corrected-to-normal vision, and did not report any neurological disorder. An informed consent was obtained from all the participants at the beginning of the experiment.

Visuospatial reasoning tasks

The study consisted of three visuospatial reasoning tasks within the PSVT: Developments, Rotations, and Views. Each task contained 12 questions. Developments assess spatial visualization by examining how well participants can visualize the folding of developments into three-dimensional (3D) objects. The second task – Rotations – is designed to test how well participants can visualize the rotation of three-dimensional objects. Finally, twelve questions within the Views task test spatial orientation, examining how well participants can visualize what 3D objects look like from various viewing positions. Figure 1 presents one exemplary question for each of these three types of the task. For more details, please consult the PSVT test [21].

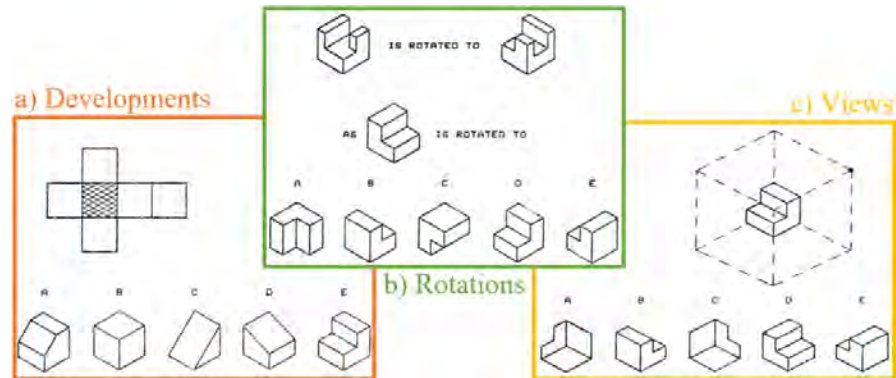


Fig. 1 Developments (panel a), Rotations (panel b) and Views (panel c) task

Experimental procedure

The main part of the experiment consisted of six steps through which the participants solved three PSVT tasks and the baseline task, as shown in Figure 2. The baseline task required participants to stare at the white cross presented in the center of the monitor screen with a grey background for one minute. The baseline tasks preceded each of the three PSVT tasks. Having the baseline before each PSVT task enables mitigating the potential effects of fatigue and cognitive load that may be present since the task order was not randomised. After the baseline task, participants solved one exemplary question to which the solution was revealed upon its completion. Following the exemplary question, participants continued to the twelve core questions within the particular PSVT task. The questions were time-limited, with participants having 40 seconds to complete each of them.

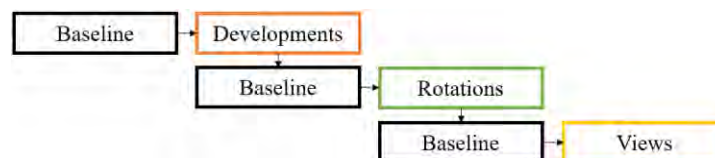


Fig. 2 Experimental procedure

Experimental setup

The study utilized one monitor screen (1920 x 1080 pixels; 60 Hz), a mouse, and a keyboard, all powered by a high-performance computer to run the experimental procedure. Stimuli (baseline and PSVT tasks) and experimental data synchronization were achieved through the iMotions® platform. EEG data were gathered using a 14-channel Emotiv EPOC+

device wirelessly connected to the high-performance computer. The continuous EEG signal was captured throughout the entire experiment via 14 electrodes positioned at the following locations according to the international 10-20 system: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4. The location of each electrode is defined based on the cortical area and the hemisphere. The letters stand for the main cortical area in which the electrode is positioned. Therefore, the electrodes of the used device are positioned in the anterior frontal (AF), frontal (F), frontocentral (FC), parietal (P), temporal (T), and occipital (O) cortical area. The numbers next to the letters define the hemisphere (the odd numbers stand for the left and the even numbers for the right hemisphere) and the distance of the electrode from the midline sagittal plane of the skull (lower number indicating smaller distance). In that way, we distinguish seven cortical areas in which the electrodes are positioned: AF, F7/8, F3/4, FC, T, P, and O.

EEG data pre-processing

The EEG data were pre-processed in MATLAB using the EEGLAB toolbox [32]. An original script developed for EEG data pre-processing was inspired by the pipelines described in [33] and [34]. In the first step, DC offset specific for Emotiv EPOC + devices was removed with the infinite impulse response (IIR) filter (0.16 Hz first order high-pass filter). Secondly, frequencies outside the 4–45 Hz range were eliminated with the finite impulse response (FIR) filter. The filtering was performed with the EEGLAB function “pop_eegfiltnew”, which is hardcoded to a Hamming window.

Afterwards, outliers were identified as EEG data with amplitudes exceeding the threshold of $\pm 100 \mu\text{V}$. The identified outliers were addressed by removing windows (each with a length of one second and a shift of 1/128 seconds) containing the identified outliers at their center. This process involved discarding any one-second-long epoch of EEG data with at least one amplitude surpassing the threshold (across the 14 channels).

In the next step, the EEG data were divided into theta (4–7 Hz), alpha (8–12 Hz), and beta (13–30 Hz) frequency bands using a FIR filter. Following the threshold application, the power of EEG signals (Pow) was calculated as the mean (M) of the squared values, resulting from the band-pass filtering of the EEG signal, utilizing the Fast-Fourier Transformation.

In the final pre-processing step, task-related power (TRP) was calculated by subtracting the transformed power average of a subject j at an electrode i during a baseline task recorded before each PSVT task from the transformed power average of a subject j at an electrode i during the particular PSVT

task. Hence, TRP values were calculated according to the following expression:

$$\text{TRP}_{ij} = \log(\text{Pow}_i(\text{Task})_j) - \log(\text{Pow}_i(\text{Baseline})_j).$$

Given the equation, positive TRP values reflect an increase of power during the PSVT task (compared to the baseline task), whereas negative TRP values reflect a power decrease.

Data analysis

EEG data analysis was conducted using the R language. Descriptive statistics encompassed the calculation of the M as a measure of central tendency and standard deviation (SD) as a measure of variability. In addition, inferential tests enabled the comparison of TRP values in three frequency bands (theta, alpha, beta) between the PSVT tasks, while considering the spatial position of the EEG channels (described through the hemisphere and cortical area).

The repeated measures ANOVA was first employed to evaluate the effect of four within-subject factors on the TRP values. The factors and their levels were as follows: the PSVT task (Developments, Rotations, Views), frequency band (theta, alpha, beta), hemisphere (left, right), and area (AF, F3/4, F7/8, FC, T, P, O).

Before executing the repeated measures ANOVA, data subsets were examined for the outliers. For this purpose, data were grouped into 126 subsets based on the four factors: PSVT task (three levels), frequency band (three levels), hemisphere (two levels) and cortical area (seven levels). Data from six participants were excluded from further analysis as they contained large number of the extreme outliers. Additionally, the normality assumption was tested using the Shapiro-Wilk normality test. After removing six participants from the analysis, majority of the subsets were normally distributed (109/126). The Shapiro-Wilk test was complemented by visual inspection through the QQ plots to confirm the approximately normal distribution of the subsets. Any potential violation of the sphericity assumption was addressed with the Greenhouse-Geisser sphericity correction.

Post-hoc tests involved a detailed examination of simple main effects and pairwise comparisons. Simple main effects were tested with repeated measures ANOVA, starting with the three-way option, and progressively narrowing down to one-way ANOVA. Pairwise comparisons accompanying one-way ANOVA were conducted using the Wilcoxon signed-rank test.

The three-way repeated measures ANOVA was performed at each level of the frequency band factor. After that, the two-way repeated measures ANOVA tested the interaction effect of the task and the area for each

combination of the frequency band and the hemisphere. One-way repeated measures ANOVA explored the effect of the task on the TRP values for each combination of the frequency band, hemisphere, and area. Finally, pairwise comparisons between the PSVT tasks were carried out using the Wilcoxon signed-rank test with Bonferroni adjusted p-value. The same correction method was applied in ANOVA tests when analysing the effects across two or more levels. In addition to the (adjusted) p-values, the effect size (reported as the r-value) of the Wilcoxon signed-rank test was calculated by dividing the test statistic by the square root of the number of observations.

The following section presents the results of these tests in two formats: graphically, in figures and numerically, in tables.

Results

The repeated measures ANOVA unveiled statistically significant interactions between the PSVT task, frequency band, hemisphere, and area. Additionally, significant simple main effects of all the four factors on the TRP values were observed. The interaction effects are detailed in Table 1.

Table 1 Interaction effects

Effect	DFn	DFd	F	p
T : FB : H	4.00	80.00	3.46	$1.20 \cdot 10^{-2}$
T : FB : A	24.00	480.00	17.45	$4.95 \cdot 10^{-51}$
T : FB : A : H	24.00	480.00	16.59	$9.41 \cdot 10^{-49}$

Legend: Task (T), Frequency band (FB), Hemisphere (H), Area (A)

Moreover, the three-way ANOVA indicated that the interaction effect of the PSVT task, hemisphere, and area was statistically significant for the TRP in the theta and beta frequency bands, as illustrated in Table 2. After applying the Bonferroni correction, the significance level for this test is $p = 1.7 \cdot 10^{-2}$.

Table 2 Effects at each level of the frequency band

FB	Effect	DFn	DFd	F	p
Theta	T	2.00	40.00	56.48	$2.24 \cdot 10^{-12}$
	T : H	1.00	20.00	19.40	$2.73 \cdot 10^{-4}$
	T : A	2.15	43.05	20.77	$2.75 \cdot 10^{-7}$
	T : H : A	12.00	240.00	13.38	$5.14 \cdot 10^{-21}$
Alpha	T	2.00	40.00	9.48	$4.28 \cdot 10^{-4}$
	T : A	12.00	240.00	23.40	$4.63 \cdot 10^{-34}$
Beta	T	2.00	40.00	20.08	$9.18 \cdot 10^{-7}$

	T : A	12.00	240.00	3.98	$1.26 \cdot 10^{-5}$
	T : H : A	12.00	240.00	7.14	$4.07 \cdot 10^{-11}$

Legend: Task (T), Frequency band (FB), Hemisphere (H), Area (A)

Since the interaction effect of the PSVT task, hemisphere, and area was not significant for alpha frequency band, further analysis focuses on theta and beta frequency bands. The two-way repeated measures ANOVA showed a significant two-way interaction between the PSVT task and area at each combination of the frequency band level (theta, beta) and the hemisphere (left and right). The results are detailed in Table 3. Given the applied Bonferroni correction, the significance level for this test is $p = 8.33 \cdot 10^{-3}$.

Table 3 Effects at each level of the frequency band and the hemisphere

FB	H	Effect	DFn	DFd	F	p
Theta	Left	T	2.00	40.00	46.32	$3.87 \cdot 10^{-11}$
	Right	T	2.00	40.00	43.01	$1.08 \cdot 10^{-10}$
	Left	T : C	12.00	240.00	27.13	$3.24 \cdot 10^{-38}$
	Right	T : C	12.00	240.00	18.25	$9.81 \cdot 10^{-28}$
Beta	Left	T	2.00	40.00	23.20	$2.05 \cdot 10^{-7}$
	Right	T	2.00	40.00	15.36	$1.13 \cdot 10^{-5}$
	Left	T : C	12.00	240.00	5.18	$1.04 \cdot 10^{-7}$
	Right	T : C	12.00	240.00	4.04	$1.02 \cdot 10^{-5}$

Legend: Task (T), Frequency band (FB), Hemisphere (H), Area (A)

The one-way repeated measures ANOVA revealed a significant effect of the PSVT task on theta TRP captured from 10 electrodes (AF3, F3, F7, FC5, P8, T8, FC6, F8, F4, AF4) and beta TRP captured from 13 electrodes (AF3, F3, F7, FC5, T7, P7, O1, O2, P8, FC6, F8, F4, AF4). The results are not detailed in this paper due to the space limitations. However, only these electrodes for which the effect of the PSVT task to theta and/or beta TRP was significant are further considered in the following pairwise comparisons.

Pairwise comparisons demonstrated statistically significant differences in the M theta or beta TRP between Developments and Rotations at eight electrodes, Developments and Views at 21 electrodes, and Rotations and Views at 28 electrodes. These differences are detailed in the following subsections.

Developments vs. Rotations

Significant differences in theta TRP, captured from the FC5 and FC6 electrodes, were observed between the Developments and Rotations. These

differences are visually represented in Figure 3 (panel a), highlighted in blue, and numerically detailed in Table 4. Additionally, these two tasks differed in beta TRP captured from the following six electrodes: AF3, F3, F7, FC5, AF4, F8. The electrodes at which significant differences in beta TRP between the Developments and Rotations were identified are highlighted in pink in Figure 3 (panel b) and accompanied by numerical explanations in Table 4.

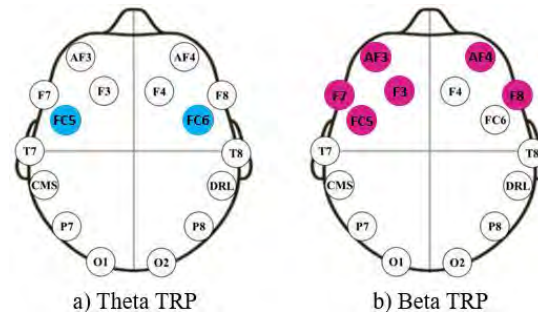


Fig. 3 Differences in a) theta and b) beta TRP between Developments and Rotations

Table 4 Developments vs. Rotations: theta and beta frequency bands

Task	FB	Electrode	M	SD	Statistic	p	r	
D	Theta	FC5	0.51	0.38	29	$5.00 \cdot 10^{-3}$	0.66	
R			0.63	0.34				
D		FC6	$7.30 \cdot 10^{-2}$	0.40	42			$2.70 \cdot 10^{-2}$
R			0.13	0.38				
D	Beta	AF3	$-7.70 \cdot 10^{-2}$	0.36	193	$1.70 \cdot 10^{-2}$	0.59	
R			-0.22	0.44				
D		F3	$1.30 \cdot 10^{-2}$	0.47	216			$3.93 \cdot 10^{-4}$
R			-0.13	0.44				
D		F7	$9.60 \cdot 10^{-2}$	0.31	204	$4.00 \cdot 10^{-3}$		
R			$-2.80 \cdot 10^{-2}$	0.34				
D		FC5	$-4.70 \cdot 10^{-2}$	0.36	229		$8.58 \cdot 10^{-6}$	
R			-0.26	0.39				
D		AF4	$-4.90 \cdot 10^{-2}$	0.36	193	$1.70 \cdot 10^{-2}$		
R			-0.15	0.39				
D		F8	-0.13	0.32	224		$5.43 \cdot 10^{-5}$	
R			-0.14	0.32				

Legend: Developments (D), Rotations (R), Frequency band (FB)

Developments vs. Views

Furthermore, significant differences in beta TRP were observed between Developments and Views tasks at the AF3, F3, F7, FC5, FC6, F8, F4, and AF4 electrodes. These differences are detailed in Figure 4 (panel a).

Similarly, significant differences in beta TRP between the same two tasks were found at nearly all electrodes, except T8 (refer to Figure 4, panel b). For further details on the significance of these differences, please consult Table 5.

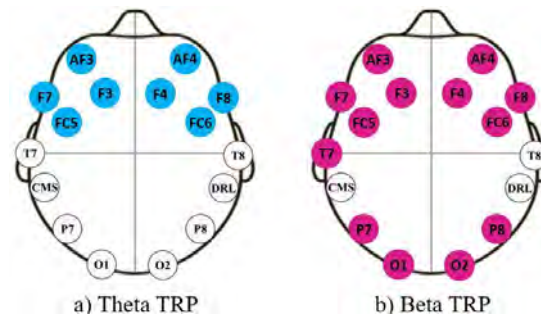


Fig. 4 Differences in a) theta and b) beta TRP between Developments and Views

Table 5 Developments vs. Views: theta and beta frequency bands

Task	FB	Electrode	M	SD	Statistic	p	r
D	Theta	AF3	0.84	0.58	231	$2.86 \cdot 10^{-6}$	0.88
V			0.35	0.63			
D		F3	0.40	0.55	229	$8.58 \cdot 10^{-6}$	0.86
V			0.12	0.47			
D		F7	0.74	0.54	230	$5.73 \cdot 10^{-6}$	0.87
V			0.31	0.57			
D		FC5	0.51	0.38	230	$5.76 \cdot 10^{-6}$	0.87
V			0.24	0.34			
D		AF4	0.91	0.57	231	$2.86 \cdot 10^{-6}$	0.88
V			$-1.10 \cdot 10^{-2}$	0.55			
D		F8	$3.10 \cdot 10^{-2}$	0.55	209	$4.00 \cdot 10^{-3}$	0.66
V			-0.13	0.50			
D		F4	0.35	0.34	221	$1.23 \cdot 10^{-4}$	0.80
V			0.14	0.31			
D		FC6	$7.30 \cdot 10^{-2}$	0.40	195	$1.30 \cdot 10^{-2}$	0.60
V			$-1.10 \cdot 10^{-2}$	0.38			
D	Beta	AF3	$-7.70 \cdot 10^{-2}$	0.36	206	$3.00 \cdot 10^{-3}$	0.69
V			-0.25	0.44			
D		F3	$-1.30 \cdot 10^{-2}$	0.47	229	$8.85 \cdot 10^{-6}$	0.86
V			-0.17	0.44			
D		F7	$9.60 \cdot 10^{-2}$	0.31	203	$4.00 \cdot 10^{-3}$	0.66
V			$-2.80 \cdot 10^{-2}$	0.34			
D		FC5	$-4.70 \cdot 10^{-2}$	0.36	230	$5.73 \cdot 10^{-6}$	0.87
V			-0.28	0.39			
D		T7	-0.22	0.43	195	$1.30 \cdot 10^{-2}$	0.60
V			-0.39	0.37			
D		P7	-0.23	0.38	208		0.70

V			-0.38	0.37		$2.00 \cdot 10^{-3}$	
D			-0.31	0.31	192	$1.90 \cdot 10^{-2}$	0.58
V		O1	-0.40	0.31			
D			$-4.90 \cdot 10^{-2}$	0.33	231	$2.86 \cdot 10^{-6}$	0.69
V		AF4	-0.22	0.39			
D			$3.00 \cdot 10^{-2}$	0.34	231	$2.86 \cdot 10^{-6}$	0.86
V		F4	-0.22	0.33			
D			-0.13	0.32	209	$2.00 \cdot 10^{-3}$	0.66
V		F8	-0.26	0.32			
D			-0.24	0.32	217	$3.15 \cdot 10^{-4}$	0.87
V		FC6	-0.41	0.33			
D			-0.24	0.39	202	$5.00 \cdot 10^{-3}$	0.70
V		P8	-0.36	0.41			
D			-0.27	0.35	207	$2.00 \cdot 10^{-3}$	0.69
V		O2	-0.38	0.41			

Legend: Developments (D), Views (V), Frequency band (FB)

Rotations vs. Views

Rotations and Views differed significantly in the theta TRP captured from the following ten electrodes: AF3, F3, F7, FC5, P8, T8, FC6, F8, F4, AF4. These electrodes are highlighted in Figure 5 (panel a) while differences are detailed numerically in Table 6. In addition, these two tasks differed in beta TRP captured from all the electrodes except T8, as illustrated in Figure 5 (panel b).

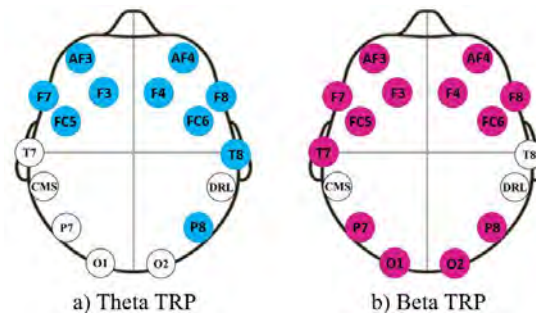


Fig. 5 Differences in a) theta and b) beta TRP between Rotations and Views

Table 6 Rotations vs. Views: theta and beta frequency band

Task	FB	Electrode	M	SD	Statistic	p	r
R	Theta	AF3	0.86	0.63	231	$1.82 \cdot 10^{-4}$	0.88
V			0.35	0.63			
R		F3	0.29	0.47	231	$1.85 \cdot 10^{-4}$	0.88
V			0.12	0.47			
R		F7	0.83	0.57	231	$1.77 \cdot 10^{-4}$	0.88
V			0.31	0.57			

R		FC5	0.63	0.34	231	$1.78 \cdot 10^{-4}$	0.88
V			0.24	0.34			
R		AF4	0.88	0.55	231	$1.74 \cdot 10^{-4}$	0.88
V			0.38	0.55			
R		F4	0.27	0.31	231	$1.63 \cdot 10^{-4}$	0.88
V			0.14	0.31			
R		F8	$7.50 \cdot 10^{-2}$	0.50	231	$1.82 \cdot 10^{-4}$	0.88
V			-0.13	0.50			
R		FC6	0.13	0.38	231	$1.78 \cdot 10^{-4}$	0.88
V			$-1.10 \cdot 10^{-2}$	0.38			
R		T8	$-2.60 \cdot 10^{-2}$	0.49	231	$1.80 \cdot 10^{-4}$	0.88
V			-0.13	0.49			
R		P8	-0.15	0.54	231	$1.68 \cdot 10^{-4}$	0.88
V			-0.22	0.54			
R	Beta	AF3	0.22	0.43	231	$1.82 \cdot 10^{-4}$	0.88
V			0.25	0.43			
R		F3	-0.13	0.44	231	$1.73 \cdot 10^{-4}$	0.88
V			-0.17	0.44			
R		F7	$-2.80 \cdot 10^{-2}$	0.34	0	$1.30 \cdot 10^{-4}$	0.90
V			$-2.80 \cdot 10^{-2}$	0.34			
R		FC5	-0.26	0.37	231	$1.82 \cdot 10^{-4}$	0.88
V			-0.28	0.39			
R		T7	-0.19	0.37	231	$1.82 \cdot 10^{-4}$	0.88
V			-0.39	0.37			
R		P7	-0.26	0.37	231	$1.88 \cdot 10^{-4}$	0.88
V			-0.38	0.37			
R		O1	-0.34	0.31	231	$1.33 \cdot 10^{-4}$	0.88
V			-0.40	0.31			
R		AF4	-0.15	0.39	231	$1.83 \cdot 10^{-4}$	0.88
V			-0.22	0.39			
R		F4	-0.15	0.33	231	$1.82 \cdot 10^{-4}$	0.88
V			-0.22	0.33			
R		F8	-0.14	0.32	231	$1.60 \cdot 10^{-4}$	0.89
V			-0.26	0.32			
R		FC6	-0.30	0.33	231	$1.76 \cdot 10^{-4}$	0.88
V			-0.41	0.33			
R		P8	-0.29	0.41	231	$1.88 \cdot 10^{-4}$	0.88
V			-0.36	0.41			
R		O2	-0.32	0.41	231	$1.84 \cdot 10^{-4}$	0.88
V			-0.38	0.41			

Legend: Developments (D), Views (V), Frequency band (FB)

Discussion

This study initiates an investigation into visuospatial reasoning in engineering design by grounding itself in three visuospatial factors defined

by cognitive psychology, thereby adopting a bottom-up approach, as suggested by Tversky [17]. This methodological approach aligns with the recommendation of Hay et al. to build research on theoretical foundations from cognitive psychology, which serves as the origin of the concepts under investigation [16]. By employing EEG, the study takes an initial step in constructing an additional layer of knowledge vital for progressing the bottom-up approach. Notably, no prior studies have been identified that compare EEG signals of subjects engaged in different visuospatial reasoning tasks. Consequently, the establishment of this knowledge serves as the primary task for researchers in the field of design (neuro)cognition.

The results of our study reveal significant task-specific differences in TRP, thus providing a positive answer to the posed research question. In particular, the findings denoted significant distinctions in all three investigated frequency bands between spatial visualization and mental rotation, spatial visualization and spatial orientation, as well as between mental rotation and spatial orientation. These results suggest that visuospatial factors should be investigated individually when exploring visuospatial reasoning in engineering design and building cognitive models. Furthermore, they support the assumption that visuospatial reasoning tasks associated with spatial visualization, mental rotation, and spatial orientation involve distinct cognitive strategies, which are reflected in employing different neural mechanisms. Moreover, the results demonstrate that differences between the visuospatial factors at the neurocognitive level can be identified using EEG, with theta, alpha, and beta TRP serving as some of the EEG features. Given the absence of prior EEG signal comparisons between different visuospatial reasoning tasks, we lack comparative basis for our results. Nevertheless, the results are consistent with earlier studies suggesting a differentiation between mental rotation and spatial orientation based on theoretical and performance-based comparisons [25].

With a positive response to the research question, our further work will focus on identifying and extracting EEG patterns associated with engineering designers' visuospatial reasoning. Subsequently, we aim to track these patterns in (real) design tasks to develop a cognitive model of visuospatial reasoning. Similar efforts have been made by Yin et al., who proposed a theoretical basis for an EEG-based decoding method to identify cognitive factors occurring in a creative design process [35]. By doing so, we intend to augment the existing cognitive models of visuospatial reasoning in engineering design, such as those proposed by Park and Kim [19] and Oxman [24]. The usage of EEG may enable the observation of the constructs suggested in these models at the level of visuospatial factors, which could be challenging if relying solely on protocol analysis. For example, in such a way, "interpretation" within "seeing" and

“transformation” within “imagining” within Park and Kim’s model may be observed at a higher level of granularity [19]. Similarly, in Oxman’s model [24] transformations underlying re-representations in design tasks may be addressed more effectively.

The results of our analysis revealed differences in the TRP values between the tasks at various levels: the entire skull (across all 14 electrodes cumulatively), hemispheres, cortical areas, and individual electrodes. This multi-level analysis allows us to focus further investigation on EEG features that may be the most indicative of differences and therefore strong candidates for inclusion when defining EEG patterns for each visuospatial factor. The results showed that differences were not significant at all levels for all three frequency bands. In particular, significant differences in alpha TRP were observed only when considering the entire skull and the cortical areas, irrespective of the hemisphere (as noticeable from Table 2). However, both theta and beta frequency bands denoted significant distinctions between all three combinations of the PSVT tasks across all levels – from the entire skull and both hemispheres to the seven cortical areas (see Table 3) to the 14 individual electrodes (as shown in Figure 3, Figure 4, and Figure 5). For instance, as depicted in Figure 3, frontal theta and beta TRP can be used to distinguish between Developments and Rotations, with the most prominent effect observed in beta TRP from the electrode FC5 ($r = 0.86$). Furthermore, frontal theta TRP distinguishes Developments from Views, while beta TRP differs significantly across all the electrodes except T8. Similarly, beta TRP from all the electrodes beside T8 significantly differed when comparing Rotations and Views, with the effect size of $r = 0.88$ or greater (as outlined in Table 6). Additionally, theta TRP distinguishes Developments from Views at all eight electrodes in frontal area with addition of T8 and P8. Therefore, the best candidates for distinguishing Developments from Views and Rotations from Views are not that obvious.

Several limitations of the presented study should be noted. Firstly, the findings are constrained by the EEG device utilized, which has a relatively low spatial resolution due to its 14 electrodes. Secondly, the study focuses on disparities among three visuospatial tasks integral to the PSVT, commonly employed in engineering design and associated with three visuospatial factors. However, it would benefit from a more comprehensive approach to visuospatial tasks, as the ones tested do not encompass the full list of visuospatial factors.

Conclusions and further work

The study compared engineering designers' EEG signals captured while engaged in three distinct visuospatial reasoning tasks within the PSVT. Each task allowed for the assessment of a specific visuospatial factor, namely spatial visualization, mental rotation, and spatial orientation. The findings suggest that distinct neural mechanisms may be involved during the tasks associated with these visuospatial factors. Particularly, the theta and beta frequency bands appear to play a crucial role in distinguishing brain activity associated with the three tested visuospatial factors at the level of individual EEG electrode. Our observations confirm that EEG signals indeed differ between the spatial visualization, mental rotation, and spatial orientation, highlighting both the importance and feasibility of distinguishing them using EEG. As we broaden our analysis in future work, our aim is to uncover specific EEG patterns relatable to visuospatial factors that can be sought in engineering design tasks. In doing so, our research contributes to the advancement of models of design cognition, providing a foundation for tracking the occurrence of visuospatial reasoning in an engineering context and evaluating the relative importance of its factors for engineering design.

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