

Insights from an EEG study of mechanical engineers problem-solving and designing

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Abstract

This paper presents results from an experiment to determine brain activation differences between problem-solving and designing of mechanical engineers. The study adopted and extended the tasks described in a prior fMRI study of design cognition and measured brain activation using EEG. The experiment consists of multiple tasks: problem-solving, basic design and open design using a tangible interface. Statistical analyses indicate increased activation when designing compared to problem-solving.

Keywords: design neurocognition, problem-solving, designing, mechanical engineers

1 Background

The study described in this paper is part of a larger research project whose goal is to correlate design cognition to brain activation of designers across disciplines. Preliminary results from bringing neuroscience methods to design research is contributing to a better understanding of human behavior in designing. One of the questions that design research has studied is whether designing differs from problem-solving and if design specific characteristics make it independent of any domain of application [1, 2]. The study reported in this paper elucidates the design neurocognition and brain behaviour of mechanical engineers when designing and problem-solving. Non-invasive tools have provided access to brain behaviour through objective measurements of various aspects of brain neurophysiology producing the field of neurocognition [3]. This has opened the way for the first steps in understanding design neurocognition – the neurocognition of designing. Functional magnetic resonance imaging (fMRI)-based design studies are at the exploratory stage with one well-controlled experiment published [4] and others that focus on design related behaviours rather than the acts of designing [5]. Results show higher activation of the dorsolateral prefrontal cortex consistently for design tasks and ill-structured problems and recruits a more extensive network of brain areas than problem-solving [4, 6]. fMRI has very high spatial resolution which helps in narrowing to very specific brain regions that are activated during any task, but it has low temporal resolution. Designing is a temporal activity. EEG's high temporal resolution during cognition can help elucidate the stages of designing while providing the temporal basis for information processing [7]. Averaging the measurements yields a measure of the EEG voltages that are consistently related to the sensory, perceptual and decision-making processes [8]. By taking advantage of the electroencephalography (EEG) method's high temporal resolution, we focus on the investigation of time-related design tasks. Design neurocognition EEG-based studies are emerging at an exploratory stage with a few reported domain-specific studies on engineering design, architecture and industrial design. Results from controlled experiments of engineering-design based studies identify the relationship between neurophysiological EEG signals to study effort, fatigue and concentration and problem statements and cognitive behaviors in conceptual design [9, 10]. Time-related neural responses during problem-solving compared to design tasks are as yet unknown. The study reported here is based on the analysis of participants' brain waves using an EEG headset in the context of performing problem-solving and design tasks in an experimental environment. The objective of the study is:

- investigate the use of the EEG technique to distinguish design from problem-solving.

In this study, we adopted and then extended the tasks described in a previous fMRI study of design cognition reported in the literature [4]. With this study we aim to answer the research question: How far EEG can help distinguish design from problem solving? We postulate the following hypotheses:

Hypothesis 1. Design neurocognition of mechanical engineers when problem-solving and designing are different.

Hypothesis 2. Neurocognitive temporal distributions of activations of mechanical engineers are significantly different across design tasks.

2 Methods and approaches

We have adopted and replicated the tasks described in Alexiou and Zamenopoulos et al. [4], augmenting their results with EEG high temporal resolution. We extend the experiment to a third task. The set of three tasks is preceded by a pre-task so that the participants can familiarize themselves with the physical interface. The three tasks are followed by a fourth open design task where the tangible interface is replaced by free-hand sketching. The replication of the experiment tasks of Alexiou and Zamenopoulos et al. [4], with EEG brain wave data is supported with the analysis of data from video and audio recording.

2.1 Experiment Setup

A tangible interface for individual task performance was built based on magnetic material for easy handling. The Mikado game was given to the participants to play in the breaks between tasks as this action helps them with the tangible interface of the magnetic and movable pieces during the tasks. A pre-task was designed so that participants can familiarize themselves with the use of the EEG headset, maneuvering the magnetic pieces that make up the physical interface and prevent him/her from getting fixated in Task 1. The block experiment consists of a sequence of 3 tasks: problem-solving, basic design and open design, as depicted in Image 1. For the present study we have matched Tasks 1 and 2 with the problem-solving and design tasks from Alexiou et al. [1], in terms of difficulty, number of constraints, stimuli and number of instructions. Task 3 provides an enlargement of the problem and the solution space. The third task provides the opportunity of evaluating and reformulating the design solutions. In Task 4, the participants are asked to propose and represent an outline design for a future personal entertainment system.

Table1: Description of the tasks.

Task 1 Problem-solving	Task 2 Basic design	Task 3 Open design
<p>In Task 1 the design of a set of furniture is available and three conditions are given as requirements. The task consists of placing the magnetic pieces inside a given area of a room with a door, a window and a balcony.</p>	<p>In Task 2 the same design set of furniture is available, and three requests are made. The basic design task consists of placing the furniture inside a given room area according to each participant notions of functional and comfortable using at least three pieces.</p>	<p>In Task 3 the same design available is complemented with a second board of movable pieces that comprise all the fixed elements of the previous tasks, namely, the walls, the door, the window and the balcony. The participant is told to arrange a space.</p>

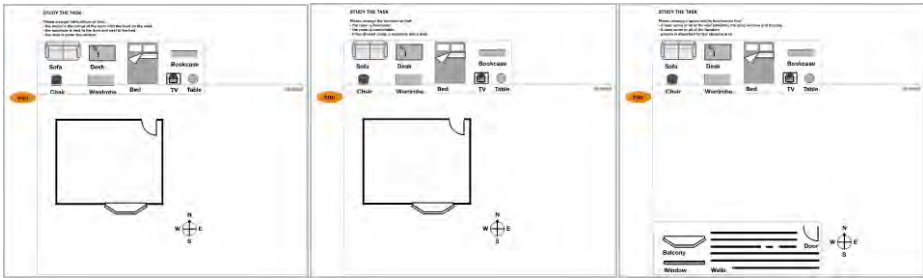


Image 1: Depiction of the problem-solving Task 1, basic design Task 2, and open design Task 3.

The movable pieces were placed at the top of a vertical magnetic board to prevent signal noise due to eye and head movements as tested in the physical magnetic board. The EEG activity is recorded using a portable 14-channel system Emotiv EPOC+. Electrodes are arranged according to the 10-10 I.S, Image 2. The subjects performed the tasks on a physical magnetic board. The two video cameras for capturing the participant face and activity and the audio recorder were streaming in Panopto software (<https://www.panopto.com/>), Image 3. One researcher is present in each experiment episode for recordings and instructing the participant. A period of 10 minutes for setting up and a few minutes for a short introduction are necessary for informing each participant, reading and signing of the consent agreement and discussing the experiment. The researcher sets the room temperature and draws each participant's attention to minimize neck movements, blinking, muscle contractions, rotating the head, horizontal eye movements, pressing the lips and teeth, and silly faces in

particular during the tasks, as these affect the signal capture. Electromagnetic interference of the room was checked for frequencies below 60Hz.



Image 2: Emotiv EPOC+ electrodes arrangement (10-10 I.S.) and experiment setup using the headset.

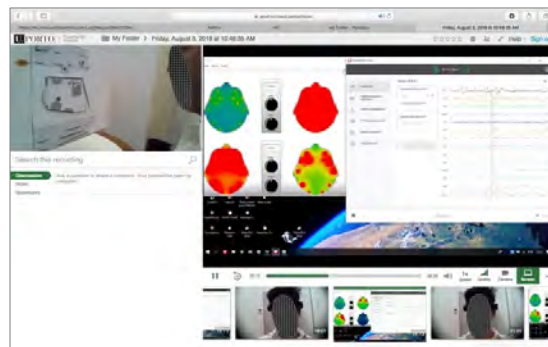


Image 3: Audio, video and screen captures streaming in Panopto.

The researcher follows a script to conduct the experiment so that each participant is given the same information and stimuli. Before each task, participants were asked to start by reading the text which took an average of 10s of reading period. Then the subjects performed the sequence of five tasks previously described with breaks in between where they play Mikado. The experiments took a total of between 34 to 61 minutes. The experiments took place between March and July of 2017 and June and September of 2018 in a room with the necessary conditions for the experiment, such as natural lighting from above sufficient for performing experiments between 9:00 and 15:00 and no electromagnetic interference. The researcher positioned the participants at the desk and checked for metallic accessories for electromagnetic interference.

2.2 Participants

In this paper we describe the analysis of 18 mechanical engineers. Results are based on 18 individuals aged 25-40 ($M = 28.9$, $SD = 4.2$). The sample include 10 men (age $M = 29$, $SD = 5.3$) and 8 women (age $M = 28.7$, $SD = 2.5$), all right-handed. This study was approved by the local ethics committee of the University of Porto. Each participant was reminded to use the bathroom and spit out any gum before the start of the experiment. The researcher sits each participant at the desk, asks him/her to untie hair and remove earrings and other metallic accessories of electromagnetic interference, check if they are using contact lenses as these may cause to much blinking and interfere with data collection. Time was given to the participants, in particular in Tasks 3 and 4 so they could find a satisfactory solution.

2.3 Data Processing

For the present analysis all the EEG segments of the recorded data were used for averaging throughout the entire tasks, from beginning to end. In this research we adopt the blind source separation (BSS) technique based on canonical correlation analysis for the removal of muscle artifacts from EEG recordings [11, 12] adapted to remove the short EMG bursts due to articulation of spoken language, attenuating the muscle contamination on the EEG recordings [13]. The fourteen electrodes were disposed according to 10-20 I.S, 256 Hz sampling rate, low cutoff 0.1 Hz, high cutoff 50 Hz. Data processing includes the removal of DC offset with the IIR procedure, and the previously mentioned BSS. Data analysis included total and band power values on individual and aggregate levels in MatLab and open source software.

In the short interviews conducted at the end of Tasks 3 and 4 the researcher asks participants four open questions. A 5 Factor Personality Test was given to each participant after the experiment. Results of the interviews and the personality tests will be reported elsewhere.

2.4 Data Analysis

A total of 26 experiments were conducted with mechanical engineers. Due to EEG recording issues two experiments were excluded. The analysis then proceeded based on the EEG data recorded and processed for each of the 24 remaining experiments, and each of the 14 electrodes used for averaging, for each of the tasks. For the analysis of the transformed power (Pow) across tasks per participant a z-transform was conducted to determine outliers. The criteria for excluding participants were based on the evidence of 6 or more threshold z-score values above 1.96 or below -1.96 and individual measurements above

2.81 or under -2.81. This resulted in a further six experiments being excluded leaving 18. We focus on the overall activation per channel, per task, per participant as the study aim is to determine how far results for problem-solving and designing can be discriminated. The task-related power (TRP) is typically calculated taking the resting state as the reference period per individual. We analyzed the EEG recordings of the resting periods prior to the experiment of a few participants and their results vary considerably, some participants showed signals that can be associated with the state of being nervous and expectant and their cognitive effort and activity is unknown. As the focus of the present study is to determine how well designing can be distinguished from problem-solving we take the problem-solving Task 1 as the reference period for the TRP calculations. Thus, for each electrode, the following formula was applied taking the mean of the corresponding electrode i , in Task 1 as the reference period. By subtracting the log-transformed power of the reference period (Pow_i , reference) from the activation period (Pow_i , activation) for each trial j (each one of the five tasks per participant), according to the formula:

$$TRP_i = \log (Pow_{i, activation})_j - \log (Pow_{i, reference})_j$$

By doing this, the negative values indicate a decrease of task-related power from the reference (problem-solving Task 1) for the activation period, while positive values express a power increase [14]. TRP scores were quantified for total power and temporal analysis was initially carried out by dividing each experiment session into halves per task across domains (power and activation refer to brain wave amplitude).

3 Analysis and Results

Preliminary results of total task-related power (TRP) across the 18 participants indicate that the tasks can potentially be distinguished from each other using the TRP values.

3.1 Task-Related Power of Mechanical Engineers

The analysis of task-related power (TRP) allows a preliminary comparison of differences across the tasks. Results between the tasks for the mechanical engineers are depicted in Image 4. To compare the TRP of mechanical engineers we performed an analysis by running a 4x2x7 repeated-measurement ANOVA, with the within-subject factors task, hemisphere and electrode. From the analysis of the 18 participants we found a significant main effect of task, $F(1.87, 31.81)=4.57, p=.02, \eta^2_{partial}=.21$ (corrected for Greenhouse-Geisser estimates of sphericity, $\epsilon=.62$). None of the other factors showed a significant

main effect. No two-way interactions were found to be significant or close to significant at this level of analysis.

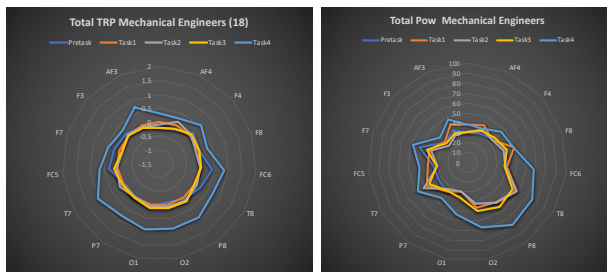


Image 4: Task-related power (TRP) and Transformed power (Pow).

In addition, we conducted pairwise comparisons to check for differences among mechanical engineers comparing them for electrodes, hemisphere and task. The pairwise comparisons revealed that Task 4 differs significantly from the Pretask ($p=.03$), Task 2 ($p=.03$) and Task 3 ($p=.02$). The transformed power (Pow), was calculated for each of the 5 tasks and 14 electrodes.

Temporal Analysis

The transformed power (Pow) was calculated for each fifth per task. Results across the 18 participants are depicted in Image 5. At this stage amplitude values above 200 $\mu\text{V}/\text{m}$ were excluded leading to 2 standard deviations from the mean as thresholds.

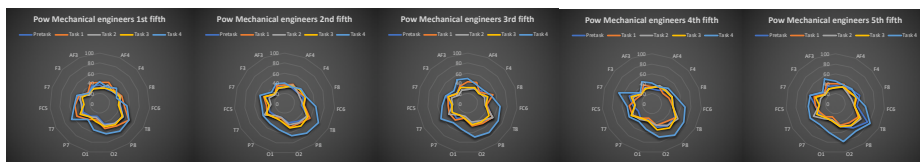


Image 5: Mechanical engineers and tasks divided in fifths.

To compare the Pow scores for the fifths of mechanical engineers we performed an analysis by running a $4 \times 2 \times 7 \times 5$ repeated-measurement ANOVA, with the within-subject factors task, hemisphere, electrode and fifth. From the analysis of the 18 mechanical engineers we found a significant main effect of hemisphere, $F(1, 17)=23.44$, $p<.001$, $\eta^2_{\text{partial}}=.58$; electrode, $F_{GD}(3.65, 61.97)=3.33$, $p=.02$, $\eta^2_{\text{partial}}=.16$) (corrected for Greenhouse-Geisser estimates of sphericity, $\epsilon=.61$), ($p=.034$); and fifth, $F_{GD}(2.53, 42.98)=3.58$, $p=.03$,

$\eta^2_{\text{partial}}=.17$) (corrected for Greenhouse-Geisser estimates of sphericity, $\epsilon=.63$). No significant main effect was found of task, $F_{GG}(2.81, 47.78)=1.82$, $p=.16$, $\eta^2_{\text{partial}}=.10$) (corrected for Greenhouse-Geisser estimates of sphericity, $\epsilon=.70$). Further, the ANOVA revealed a significant interaction effect between the factors hemisphere and electrode, $F_{GG}(2.32, 39.35)=3.31$, $p=.04$, $\eta^2_{\text{partial}}=.16$) (corrected for Greenhouse-Geisser estimates of sphericity, $\epsilon=.39$). No other two-way interactions were found. In addition, we conducted pairwise comparisons for hemisphere, electrode, fifth and task. Below we report on significant ($p \leq .05$) pairwise comparisons. The pairwise comparisons revealed that the second fifth differs significantly from the fourth ($p < .01$) and fifth ($p = .02$) fifths, and the third fifth differs significantly from the fourth ($p = .01$) and fifth ($p = .04$) fifths. The pairwise comparisons also revealed differences comparing hemisphere, the 7 electrodes and tasks within each fifth. Below we report on the significant ($p \leq .05$) pairwise comparisons found mainly between Task 1 (problem-solving) and Task 4 (free hand sketching). For the right hemisphere, electrodes FC6 ($p = 0.05$) in the second fifth, FC6 ($p = 0.03$) in the third fifth, P8 ($p = .04$) in the fourth fifth and O2 ($p = 0.03$) in the fifth fifth are significant. For the left hemisphere, electrodes O1 ($p = 0.04$) in the second fifth, O1 ($p = 0.03$) in the third fifth, T7 ($p = 0.04$) and F7 ($p = 0.04$) in the fourth fifth and electrode O1 ($p = 0.01$) in the fifth fifth, are significant.

Cohen's d was calculated for each electrode, per fifth using a comparison between sequential tasks. This revealed medium (.50) and large (.80) size effects between Task 3 and Task 4, as shown in Table 1.

Table2: Cohen's d for eight electrodes between Task 3 and Task 4 per fifth.

T3/T4	FC6	P8	O2	O1	P7	T7	FC5	AF3	Fifth
									1st
	.66	.56		.53					2nd
<i>d</i>	.68	.67	.71	.78	.62	.64	.51		3rd
	.57			.56				.52	4th
	.60		.80	.65	.54		.57	.63	5th

Dynamic Average

Statistical analysis indicates increased activation of the left and right occipitotemporal cortex when designing compared to problem-solving. Electrodes P8, O1, O2 and T7 Pow values differ significantly for design Task 4 from all the

other tasks. These electrodes corresponding Brodmann area (BA) are BA37 (P8), BA42(T7) and BA18 (O1 and O2). It is known that drawing activates right BA37. In the frontoparietal cortex, electrodes FC6, F7 Pow and FC5 Cohen's d values differ significantly from the design Task 4 to all the other tasks as well. The dynamic average was calculated for electrodes FC6, O2, O1 and FC5 for Task 1 and Task 4 as depicted in Image 7.

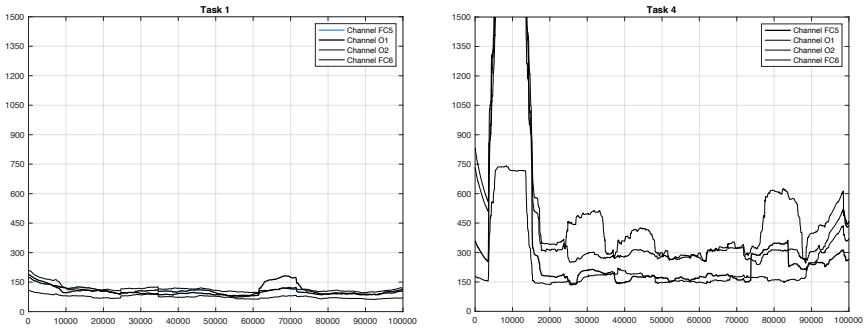


Image 6: Dynamic average of FC5, O1, O2, FC6, Tasks 1 and 4.

4 Outcomes and Discussion

Results from this study demonstrate that it is possible to address the overall objectives of this research: investigate the use of the EEG technique to distinguish design from problem-solving. The results of this preliminary analysis of the EEG data of the 18 participants show differences in the design neurocognition of mechanical engineers across tasks and provide initial support for Hypothesis 1: the design neurocognition of mechanical engineers when problem-solving and designing is different, particularly in Task 4. Mechanical engineers show higher transformed power (Pow) and distinct TRP differences from Task 4 to the problem-solving tasks. The neurocognitive temporal distributions of activations are non-uniform, providing initial support for Hypothesis 2: as mechanical engineers show variation in the Pow and TRP between the problem-solving and design tasks, across the fifths, particularly in Task 1 and Task 4. On a qualitative level the current study shows evidence of a distinct characteristic of increased Pow and TRP of Task4 from the reference problem-solving task for mechanical engineers. No evidence for higher activation of the dorsolateral prefrontal cortex across design tasks [4, 6] is provided.

Further detailed analyses are being carried out to provide a more comprehensive understanding of the neurophysiological differences between the tasks.

Such analyses include using a finer temporal division and bandwidth studies. Once a comprehensive articulation of the brain behaviour derived using EEG becomes available, we will be in a position to correlate that behaviour with cognitive behaviour.

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