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UNDERSTANDING THE DESIGN NEUROCOGNITION OF MECHANICAL ENGINEERS WHEN DESIGNING AND PROBLEM-SOLVING.

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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 is part of a research project whose goal is to correlate design cognition with brain behavior across design domains. The study adopted and extended the tasks described in a fMRI study of design cognition and measured brain activation using EEG. By taking the advantage of EEG's temporal resolution we focus on time-related neural responses during problem-solving compared to design tasks. Statistical analyses indicate increased activation when designing compared to problem-solving. Results of time-related neural responses connected to Brodmann areas cognitive functions, contribute to a better understanding of mechanical engineers' cognition in open design tasks.

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

1. INTRODUCTION

The study of the cognitive behavior of mechanical engineers while designing, based on methods from psychology, such as protocol analysis [1,2], have elucidated a number of characteristics of mechanical engineers' design cognition [3]. The "think-aloud" method, adopted by many researchers, has produced important results covering foundational aspects of design cognition, such as cognitive effects of design education and insights on how mechanical engineers' cognitive processes progress during the designing process [4]. The notions of problem space and solution space have populated design research interpretations of the designing process [5] throughout its half century of formal study [6]. The problem-solving view of design claims that the designing process commences with an exploration within the problem space [7]. Alternative perspectives assert that design thinking is primarily solution focused [8,9,10,11]. One of the initial and core research questions is whether designing as a cognitive process is distinct from problem-solving [7,12]. In problem-solving all the characteristics of the problem are firstly defined, therefore problem-solving is a closed task based on known constants and known variables. Designing relates to the search for variables that relate to what is not known, such variables are context sensitive, can bring change and have variant meaning and intonation according to the design situation [13]. In designing the characteristics of the problem are not all defined from the start, or a problem-solving situation is opened up with the introduction of variables, becoming an open task. Variables are based on knowns and unknowns and evolve through evaluation processes and interdependency within design issues, comprised of constants and variables that evolve through a process of reduction of uncertainty towards completion [14].

Although it is still not possible to fully assess how designers think and act while designing neurophysiological studies offer an integrative perspective and insights into how brain behavior progress during the designing process and commensurability of measurements which makes them a robust tool for connecting to design cognition. Design studies based on functional magnetic resonance imaging (fMRI) have started a decade ago [15] with a controlled experiment reporting preliminary results on the distinction between design and problem-solving. Distinguishing design from problem-solving is still a gap in our knowledge, and evidence of such can have implications for design research and design education, generally based on problem-solving theories.

Recent fMRI studies focused on domain related design issues, sustainability judgments [16] design ideation and inspirational stimuli [17] in mechanical engineering, graphic design [18] and

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architecture [19]. Studies using the electroencephalography technique (EEG) investigating creativity commenced 45 years ago [20] investigating cortical activation during creative tasks. Some 20 years later a study on categorization tasks of experts and novices [21], made use of EEG in design research. In the last 10 years, single domain-related EEG design studies [22,23,24,25,26] and functional near-infrared spectroscopy (fNIRS) [27] attempt to understand acts of designing from a neurophysiological perspective. The present paper describes a study from a larger research project whose goal is to correlate design cognition with brain activation of designers across design domains, namely mechanical engineering, industrial design and architecture. EEG's high temporal resolution makes it a more suitable tool than fMRI [28,29] to investigate the designing as a temporal activity. The study reported in this paper is based on the analysis of mechanical engineers' brain activation using an EEG headset in the context of performing problem-solving and design tasks in a laboratory setting. The objective of the study is:

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

We adopt and extend the tasks described in a well-controlled experiment of an fMRI-based design study [15]. That study suggested higher activation of the dorsolateral prefrontal cortex is consistent for design tasks and ill-structured problems and recruits a more extensive network of brain areas than problem-solving. We postulate the following hypotheses:

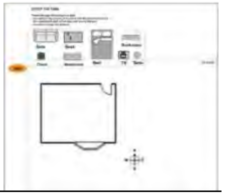
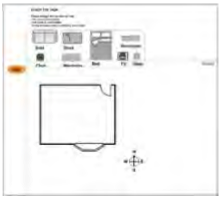
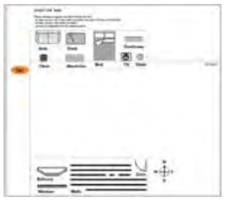
Hypothesis. Design neurocognition of mechanical engineers when problem-solving and designing are different.

2. EXPERIMENT DESIGN

We have adopted and replicated the problem-solving and layout design tasks described in Alexiou et al. [15] fMRI-based study. That study found activation differences in a number of Brodmann areas. We extended that experiment by adding an open layout design task to produce a block experiment in order to determine whether the open layout design task produces different results to the semi-closed layout task, Task 2, Table 1. As with all the block experiments, each subsequent task is potentially primed by the previous task. We added a fourth completely open design task that uses free-hand sketching after Task 3 to determine differences between an open layout task and an open design task. The set of four tasks is preceded by a pre-task so that participants can get acquainted with the physical interface and headset.

A tangible interface for individual task performance was built based on magnetic material for easy handling. A pre-task was designed so that participants can familiarize themselves with the use of the EEG headset and with maneuvering the magnetic pieces that make up the physical interface and prevent participants from getting fixated in the problem-solving Task 1. After this, necessary corrections can be made before advancing to the block experiment. The block experiment consists of a sequence of 3 tasks: problem solving, basic design and open layout design. We have matched Tasks 1 and 2 with the problem-solving and design tasks from Alexiou et al. [15] in terms of requests, number of constraints, stimuli and number of instructions. The open layout design Task 3 provides an enlargement of the problem space and the solution space and the opportunity of evaluating and reformulating the previous design solutions. Task 4, is an ill-defined and fully unconstrained task unrelated to formal problem-solving. The Mikado game was given to the participants to play in the breaks between tasks.

TABLE 1: DESCRIPTION OF THE TASKS.

Task 1 Problem-solving	
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.	
Task 2 Basic layout design	
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 function and comfort using at least three pieces.	
Task 3 Open Layout design	
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.	
Task 4 Open Sketching design	
In Task 4, the participants are asked to propose and represent the outline design of a future personal entertainment system.	

Differently from the original tasks [15], the magnetic pieces were placed at the top of the vertical magnetic board to prevent signal noise due to eye and head horizontal movements as tested. Two video cameras for capturing the participant's face and activity and the audio recorder were streamed in Panopto software (https://www.panopto.com/), Figure 1.

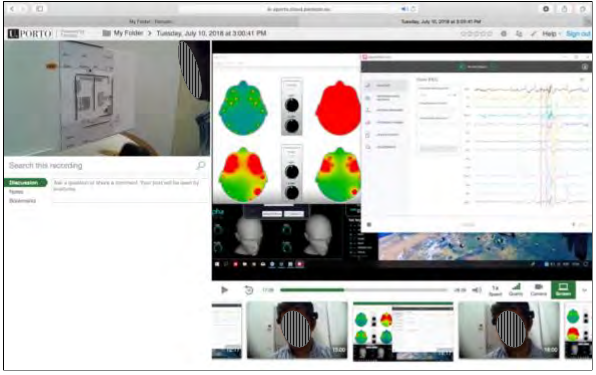


FIGURE 1: AUDIO, VIDEO AND SCREEN STREAMING IN PANOPTO.

One researcher was present in each individual experiment to instruct and record the participant's performance. A period of 10 minutes for setting up and a few minutes for a short introduction were necessary for the participant to read, sign the consent agreement and discuss the experiment with the researcher. The researcher sets the room temperature and draws each participant's attention to minimize the following actions as these affect the signal capture, namely: blinking, muscle contractions, rotating the head, horizontal eye movements, neck movements, pressing lips and teeth, and making silly faces in particular during the tasks. The researcher follows a script to conduct the experiment so that each participant is given the same information and stimuli. The researcher positioned the participants at the desk and checked for metallic accessories that could produce electromagnetic interference. Before each task, participants were asked to start by reading the text which took an average of 10s. Then the subjects performed the sequence of five tasks previously described. In the breaks between the tasks, participants played the Mikado game.

The participants performed the tasks in a linear sequence as the objective of the study is the measurement of brain activation of designers through a sequence of tasks that gradually expand the design solution space from a problem-solving to basic and open design tasks. Electromagnetic interference of the room was checked for frequencies below 60Hz. The experiments took place between March and July of 2017 and June and September 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 experiments took a total of between 34 to 61 minutes. The EEG activity was recorded using a portable 14-channel system Emotiv Epoc+. Electrodes are arranged according to the 10-10 I.S, Figure 2.

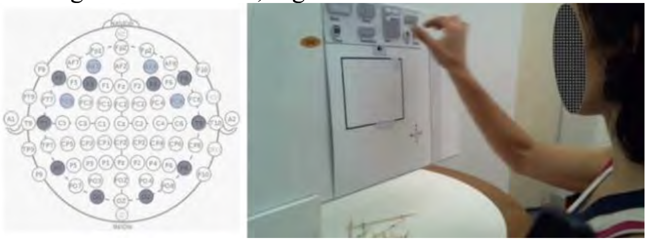


FIGURE 2: EMOTIV EPOC+ ELECTRODES (10-10 I.S.) AND EXPERIMENT SETUP

2.1 Participants

This paper describes 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. The 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 sat each participant at the desk, asking him/her to untie hair and remove earrings and other metallic accessories, check if they are using contact lenses as these may cause to much blinking and interfere with data collection. Within a limit, time was given to the participants, in particular in Tasks 3 and 4 so they could find a satisfactory solution. Average time taken per task is as follows: Pretask, 113s, Task1, 91s, Task2, 80s, Task3, 261s and Task 4, 699s.

2.2 Data Processing

The fourteen electrodes were disposed according to the 10-10 I.S, 256 Hz sampling rate, low cutoff 0.1 Hz, high cutoff 50 Hz. Several methods in the literature [30] seek to split the EEG signal into components, assuming that the measurements are characterized by two different underlying patterns, whose mathematical correlations between similar components and non-correlations between different components can be empirically extracted along the signal measured in time. We adopted the blind source separation (BSS) technique based on canonical correlation analysis (CCA) for the removal of muscle artifacts from EEG recordings [31, 32] adapted to remove the short EMG bursts due to articulation of spoken language, attenuating the muscle contamination on the EEG recordings [33]. As Task 4 involves different muscular activity given that participants sketched, the procedure described in [32] was used to attenuate muscle contamination. The BSS-CCA algorithm, by using correlation as a criterion to measure independence of signals, takes into account temporal correlation. By establishing an ordering system of the separated singular valued components of the signal the outputted components are sorted so that the highest correlated sources represent EEG sources and the least correlated sources represent noise. By systematically eliminating a subset of the bottom sources, the EEG signal from all subjects used in this study were cleaned. More specifically, by turning the last 4 sources to zero the cleaned EEG signal is reconstructed as a combination of the remaining sources identified. Thus, data processing includes the removal of Emotiv specific DC offset with the Infinite Impulse Response (IIR) filter and BSS-CCA. Data analysis included total and band power values on individual and aggregate levels using MatLab and EEGLab open source software. For the present analysis all the EEG segments of the recorded data were used for averaging throughout the entire tasks, from beginning to end, and tasks temporal deciles.

2.3 Data Analysis

In this paper we only report results from analyzing task-related power (TRP) and transformed power (Pow). Band frequency and hemispheric analyses are left for a further paper. All the results are based on aggregates of participants' individual results. A total of 26 experiments were conducted with mechanical engineers. Due to EEG or video 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 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 aims to determine how the results for problem-solving and designing can be distinguished. The TRP is typically calculated taking the resting state as the reference period per individual [34, 35]. We analyzed the EEG recordings of the resting periods prior to the experiment of some of the participants and their results varied considerably, some participants showed signals that are associated with the state of being nervous and expectant and their cognitive effort and activity is unknown. As the focus of the 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 (Powi, reference) from the activation period (Powi, activation) for each trial j (each one of the five tasks per participant), according to the formula:

$$TRP_i = log(Pow_i, activation)_j - log(Pow_i, reference)_j \qquad (1)$$

By doing this, 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 [36]. TRP scores were quantified for total power and Pow temporal analysis was carried out by dividing each experiment session into deciles per task (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. Results between the tasks for the mechanical engineers are depicted in Figure 3.

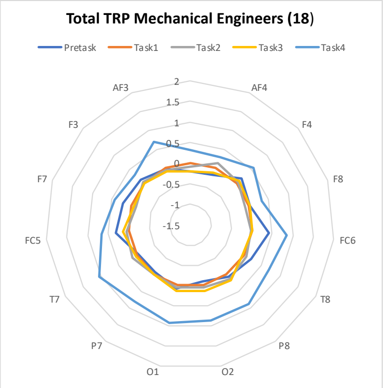


FIGURE 3: TASK-RELATED POWER (TRP).

To compare the TRP scores 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 (*p*=.02) (Appendix A). In addition, we conducted pairwise comparisons to check for differences among participants comparing task, hemisphere and electrode. The pairwise comparisons revealed that Task 4 differs significantly from Pretask (*p*=.03), Task 2 (*p*=.03), and Task 3 (*p*=.02). Total transformed power (Pow) results across the 18 participants are depicted in Figure 4.

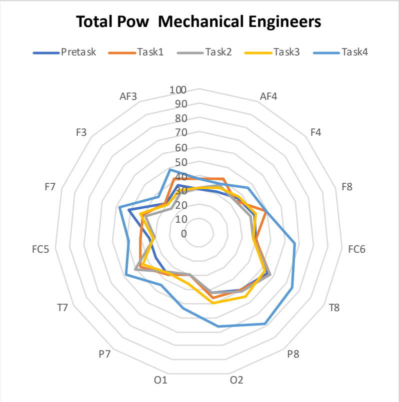


FIGURE 4: TRANSFORMED POWER (POW).

At this stage amplitude leading to two and a half standard deviations from the mean as thresholds values were excluded. The Pow was calculated for each task, electrode and decile for temporal analysis. A visual representation shows how each channel activation varies per task across deciles in Figure 5.

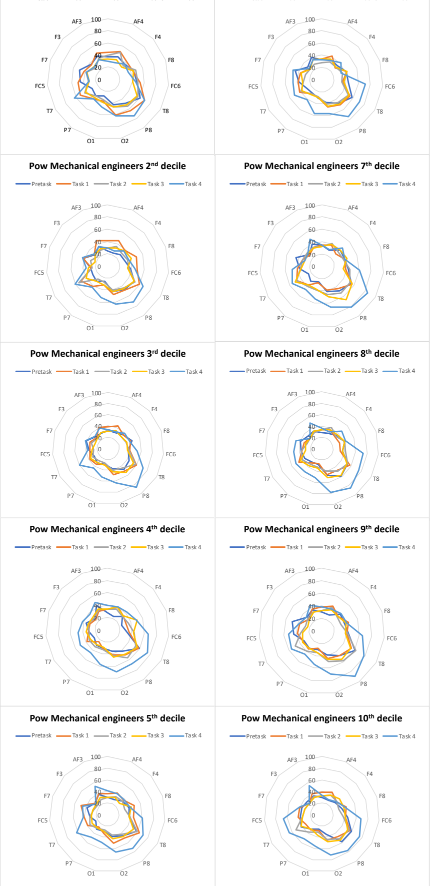


FIGURE 5: TASKS POW DIVIDED IN DECILES.

3.1 Temporal Analysis and Brodmann Areas

Designing is a temporal activity, a single value based on aggregating across time hides behaviors. The division of each design session's data into temporal deciles allows a more detailed analysis of the temporal dimension and activation patterns within subject groups, Figure 6.

FIGURE 6: CHANNELS THAT DIFFER FROM TASK 1 TO TASK 3 AND TAKS 4 BY DECILES CORRELATED WITH THEIR BRODMANN AREAS.

To compare the Pow scores for the deciles we performed an analysis by running a 5x2x7x10 repeated-measurement ANOVA, with the within-subject factors of task, hemisphere, electrode and decile. From the analysis of the 18 mechanical engineers we found a significant main effect of: task (*p*=.03); hemisphere (*p*<.001); electrode (*p*=.01); and decile (*p*=.02). Significant interaction effects were found between the factors: hemisphere and electrode (*p*<.001), task and decile (*p*=.01), electrode and decile (*p*<.01) (Appendix B). In addition, we conducted pairwise comparisons for hemisphere, electrode, decile and task. The pairwise comparisons revealed that Task 4 differs significantly from Pretask (*p*=.02), Task 2 (*p*=.03), and Task 3 (*p*=.03). The pairwise comparisons further revealed differences between hemisphere for the 7 electrodes and tasks within each decile. In Table 2 and Figure 6 we report on significant (*p*≤.05) pairwise comparisons found between Task 1 (problem-solving) and Task 3 (open layout design) and Task 1 and Task 4 (open free hand sketching design).

TABLE 2: POW SIGNIFICANT DIFFERENCES FOR FOUR ELECTRODES BETWEEN TASKS 1 AND 3 AND TASKS 1 AND 4 PER DECILE (*p* value).

Decile	AF4	F4	FC6	O2	O1	P7	T7	F7
1		.02						
2	.03		.02					.01
3								
4								
5								
6								
7				.05				
8								
9								
10								
Decile	AF4	F4	FC6	O2	O1	P7	T7	F7
1	.02							
2	.01				.05			
3					.05			
4			.03	.05				
5						.04		
6			.02		.02			
7								
8			.01	.04	.02			
9					.01			
10	.02				.01		.04	

Figure 6 shows the channels with statistically significant differences highlighted with their corresponding Brodmann areas (BA), across the deciles. Brodmann's studies on brain cells' neuron structure and its cytoarchitectural organization in 52 areas (1909) have been refined and correlated to various cortical functions and cognitive activities by measuring blood flow in response to different mental tasks. Such approximate localization of brain activation is based on generalized boundaries, as their actual boundaries requires post mortem histological examination of the individual brains. Research using fMRI over the past decades has contributed to the development of our understanding about the localization of function in the brain and has helped shape a consensus [29]. Multiple magnetic resonance imaging (MRI) measurements have resulted in an extended map with 97 new areas, besides the 83 areas previously reported [37], with each discrete area containing cells with not only similar structure, but also function and connectivity. Various cognitive functions and connectivity have been identified in studies using fMRI and positron emission tomography (PET).

In Figure 6 we show channels with co-activation (deciles 2, 4, 6, 8 and 10) and single activation (deciles 1, 3, 5, 7 and 9) of statistically significant differences in Task 3 and Task 4 from Task 1. Such activations can be connected to these channels' corresponding Brodmann areas with their cognitive functions. It also shows distinctively higher activation of channels of no statistically significant differences. For example, as Task 4 is an open design free-hand sketching task, drawing activates BA37 in the right temporal cortex [38] and BA18 of the secondary visual cortex in almost all deciles. Among other, BA37 is associated with the functions of monitoring shape [39], drawing [38], episodic encoding [40], structural judgments of familiar objects [41], and visual fixation [42]. BA18, associated with visuo-spatial information processing in the right secondary visual cortex [43], has significantly different activations in two deciles. BA18, is also associated with visual mental imagery [44] and visual word form in the left secondary visual cortex [45]. It has significantly different activations in six deciles. BA44 is associated with motor inhibition in the right hemisphere [46], as part of circuities with a complicated function involving working memory, attention, semantic decision, and motivation modules. BA44 also shows significantly different activations in three deciles. We infer that a network relevant for designing and distinct from problem-solving emerges in these 3 moments (deciles 4, 6 and 8). Other channels of co-activation, namely BA42, BA09 and BA37, seem to be part of this distinctive network when designing. BA42 is associated with auditory working memory [47] and priming effect repetition when engaged in reading visual words when there is no environmental oral or auditory component [48]. The channel corresponding to BA09 is associated with coordinating visual spatial memory in the right prefrontal cortex [49], remembering previously experienced events [50], and planning [51] shows decreased activation in Task 4 compared to Task 1. The average time span for deciles of Task 4 is 69s.

Figure 6 also shows problem-solving Task 1 with increased general activation in deciles 1, 2, 5 and 7. Task 3 with minor differences and Task 4 showing higher variation of temporal distributions of activations across deciles.

Statistically significant differences between the open layout design Task 3 and problem-solving Task 1 occur four times in four channels placed on the prefrontal cortex and one on the right secondary visual cortex. While, statistically significant differences between the open design sketching Task 4 and Task 1 occur eight times in two channels placed on the left and right secondary visual cortices, twice in two channels of the left dorsolateral cortex and three times in two channels of the prefrontal cortex when designing compared to problem-solving. The distinct nature of the open design Task 3 and Task 4 is reflected in the networks that distinguish them from the problem-solving Task 1. Co-activation channels in the open layout design Task 3 only show a distinct network from the problem-solving Task 1 in decile 2. Channels corresponding to BA47 and BA44 constitute this network. Single channel significant activation of corresponding BA08 and BA18 take place in deciles 1 and 7 respectively. With the exception of channel related to BA18, all the other three show decreased activation from the problem-solving Task 1. BA47 is associated with semantic processing in the left hemisphere [52] and implementing reflective processes that support both working memory and long-term memory [53]. BA08 in the right hemisphere is associated with memory retrieval [54]. As in Task 4, the channel corresponding to BA09 [49,50,51] also shows decrease in activation in Task 3 compared to Task 1. The time span for deciles in Task 3 is 32s.

The pairwise comparisons also reveal significant differences between the deciles across all tasks as shown in Table 3. Results are of interest for connecting design neurocognition to cognition.

TABLE 3: SIGNIFICANT DIFFERENCES BETWEEN DECILES FOR ALL TASKS (*p* value).

Decile	1	2	3	4	5	6	7	8	9	10
1		<.01	.03	.02						
2	<.01						<.01	.03	02	
3	.03						.03			
4	.02						.03	.01	.03	
5										
6										.03
7		<.01	.03	.03						
8		.03		.01						
9		.02		.03						
10						.03				

The first four deciles show sequential significant differences, from which it can be inferred that participants are sorting out different approaches to tackle the tasks, eventually thinking of different solutions. Decile 5 do not show differences with the others, from which it can be inferred that a more reflective and incubation stage takes place in the middle of the tasks while maturing thinking about the task. The last three deciles show significant differences with deciles 2 and 4, and one of them with decile 3, as the refinement of the solutions may differ from searching how to tackle the task, thinking about the problem or the solution.

Effect Size

Cohen's *d* was calculated to measure the effect size for each electrode transformed power (Pow), per decile 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 4.

In Figure 7 we display the significant ($p \leq .05$) pairwise comparisons found between the open layout design Task 3 and the open free hand sketching design Task 4.

TABLE 4: COHEN'S *d* FOR TEN CHANNELS BETWEEN TASK 3 AND TASK 4 PER DECILE.

Decile	FC6	T8	P8	O2	O1	P7	T7	FC5	F7	AF3
1			-.57				-.55			
2			-.69	-.70	-.68		-.50		-.64	
3	-.58		-.69	-.64	-.77		-.63		-.57	
4	-.57			-.68	-.82	-.59	-.67			-.50
5	-.60		-.67	-.69	-.75	-.64	-.83		-.58	-.57
6	-.75		-.66		-.80					
7	-.69									-.56
8	-.88	-.54	-.60	-.65	-.60			-.55		-.60
9	-.66	-.58	-.69	-.73	-.58		-.72	-.58	-.54	-.65
10	-.63	-.51	-.56	-.65	-.58	-.68	-.54	-.69		-.71

The plots show channels with single and co-activation of statistically significant differences between the design tasks and distinctively higher activation of channels of no statistically significant differences.

The networks between the channels have three moments of increasing engagement differentiating the open design sketching Task 4 from the open layout design Task 3.

FIGURE 7: NETWORKS OF STATISTICALLY SIGNIFICANTLY DIFFERENT CHANNELS FROM TASK 4 TO TASK 3 CORRELATED WITH THEIR BRODMANN AREAS.

The co-activation of channels of the left occipitotemporal cortex, for Task 4 shows an expanded approach to the task than in Task 3. As Task 3 is also an open design task, we further investigate what the EEG measurements can tell us about the constrained approach participants had to Task 3 and how the participants' approach to the previous tasks might have played a role in the non-expansion of channels' activation in Task 3. Another channel of statistically significant differences between Task 3 and Task 4 is BA 44 which corresponds to Broca's area (Br) usually associated with language, but also to co-engage during goal-intensive processing, occurs in deciles 9 and 10.

In Figure 8 we report on significant (p≤.05) pairwise comparisons found between Task 2 and Tasks 3 and 4.

FIGURE 8: STATISTICALLY SIGNIFICANTLY DIFFERENT CHANNELS FROM TASK 2 TO TASKS 3 AND 4 CORRELATED WITH THEIR BRODMANN AREAS.

Figure 8 shows a similar cognitive effort in terms of channels' activation for Tasks 2 and Task 3. After the constrained problem-solving Task 1, participants did not expand their approach to the less well-defined Task 2 and Task 3. The significantly different decrease in activation of the channel corresponding to BA 09 in the first decile correlates to coordinate visual spatial memory in the right prefrontal cortex [49], remembering previously experienced events [50], and planning [51], also occurs in Task 4 from Task 2. Once again, the participants appear to rely on the solutions they know and which they are familiar with when facing open tasks. A deactivation of the F3 channel across the deciles is observed. This channel corresponds to BA08 associated with inductive reasoning in the left hemisphere [55]. From fMRI studies, deductive reasoning activates BA45 and BA47, inductive reasoning activates BA08, BA09, BA24 and BA32 [55].

As happens between Task 1 and Task 4, the channels corresponding to BA44 and BA18 also have significantly different activations in Task 4 from Task 2, in two deciles.

Other results

The averages and standard deviations were calculated for each channel across tasks and deciles. Some channels show continuous high engagement (T8, T7, and F8) correspond to BA21, BA42 and BA45. Other channels show continuous low engagement (F3, F4, AF4) corresponding to BA08, left and right hemispheres and BA09, and other channels show medium engagement (FC5, P7, O1) corresponding to Broca' area, BA37 and BA18 in the left hemisphere , across the deciles and tasks without indicating differentiating statistical results. Thus, it is hypothesized that such networks of channels might constitute part of the basic layer of the problem-solving default network associated to the training acquired in the domain. These channels might be involved in default networks that do not distinguish between design and problem-solving, but support both thinking modes. The channels O1, O2, P8, FC6, FC5 and F7 show higher engagement in open design tasks for these mechanical engineers.

4. DISCUSSION

Results from this study demonstrate that it is possible to address the overall objective of this research: investigate the use of the EEG technique to distinguish design from problem-solving. The results of the analysis of the EEG data of the 18 participants show differences in the design neurocognition of these mechanical engineers across tasks and provide initial support for Hypothesis 1: the design neurocognition of mechanical engineers when problem-solving and designing is different. Mechanical engineers show higher transformed power (Pow) and distinct TRP differences from Task 4 to the problem-solving task. The Pow of mechanical engineers varies between the problem-solving and design tasks, across the deciles. On a qualitative level the current study shows evidence of a distinct characteristic of increased Pow and TRP of Task 4 from the reference problem-solving task for mechanical engineers. No evidence was found for higher activation of the dorsolateral prefrontal cortex across design tasks [15,56]. Contrary to the results reported in the fMRI study from which we replicate Task 1 and Task 2 [15], the current EEG results do not show significant differences between Task 1 and Task 2. However, evidence from the fMRI study [15] of a more extensive network of brain areas in designing than problem-solving and the (de)activation of BA09 in the right hemisphere can be inferred from these EEG results, particularly for open design tasks within networks of significantly different co-activated channels. Relatedly, BA21 shows continuous high engagement in design tasks but also in problem-solving. Evidence for higher activation of the right occipitotemporal cortex is consistent for design tasks too. Further detailed analyses providing a more in-depth and comprehensive understanding of the neurophysiological differences between closed and open creativity tasks are based on the temporal analysis of frequency bands from alpha power studies based on closed and open verbal task [57, 58].

Neuroimaging studies (i.e. fMRI, EEG, fNIRS) are more advanced in creative cognition [59,60,61,62,20,63] and visual creativity, architecture and the arts as reviewed [64], than in design research. However, no consensus has been found as results do not converge among studies due to the different nature of the tasks and focus. It has also been suggested that creative cognition studies with focus on insight and divergent thinking problems, may not be particularly central to understand creativity in the context of designing artifacts for the real world [65]. Consequently, the design neurocognition field emerges as promising to further a better understanding of the acts of designing across domains and perhaps a more in-depth distinction of creativity in higher order mental processes.

Results from the time-related neural responses connected to Brodmann' areas' cognitive functions, contribute to a better understanding of mechanical engineers' cognition in open design tasks. Implications for a more in-depth approach to the design education of mechanical engineering might consider the development of methods promoting inductive reasoning to open up the solution space of mechanical engineering students when given open design tasks.

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Appendix A

To compare the TRP scores 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, $F_{GG}(1.87,\ 31.81)=4.57$, $p=.02$, η2partial=.21) (corrected for Greenhouse-Geisser estimates of sphericity, ε=.62). No other significant main effect nor interaction effect between the factors was found.

Appendix B

To compare the Pow scores for the deciles we performed an analysis by running a 5x2x7x10 repeated-measurement ANOVA, with the within-subject factors of task, hemisphere, electrode and decile. From the analysis of the 18 mechanical engineers we found a significant main effect of: task, $F(4,\ 68)=2.95$, $p=.03$, η2partial=.15); hemisphere, $F_{GG}(1,\ 17)=48.64$, $p<.001$, η2partial=.74) (corrected for Greenhouse-Geisser estimates of sphericity, ε=1); electrode, $F(6,\ 102)=2.89$, $p=.01$, η2partial=.15); and decile $F_{GG}(4.29,\ 72.94)=3.09$, $p=.02$, η2partial=.15) (corrected for Greenhouse-Geisser estimates of sphericity, ε=.48). Significant interaction effects were found between the factors: hemisphere and electrode, $F_{GG}(6,\ 102)=6.59$, $p<.001$, η2partial=.27); task and decile, $F_{GG}(8.17,\ 138.89)=1.65$, $p=.01$, η2partial=.10) (corrected for Greenhouse-Geisser estimates of sphericity, ε=.23); electrode and decile, $F_{GG}(8.18,\ 139.08)=1.58$, $p<.01$, η2partial=.09) (corrected for Greenhouse-Geisser estimates of sphericity, ε=.15.