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Industrial designers problem-solving and designing: an EEG study

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This paper presents results from an experiment to determine brain activation differences between problem-solving and designing of industrial designers. The study adopted and extended the tasks described in a fMRI study of design cognition and measured brain activation using electroencephalography (EEG). By taking advantage of EEG's high temporal resolution we focus on time-related neural responses during problem-solving compared to design tasks. The experiment consists of multiple tasks: problem-solving, basic design and open design using a tangible interface. The tasks are preceded by a familiarizing pre-task and then extended to a fourth open design task using free-hand sketching. The results indicate design cognition differences in the brain measurements of task-related power and temporal analysis of transformed power between the constrained problem-solving task and the open design tasks. Statistical analyses indicate increased brain 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 industrial designers' cognition in open and constrained design spaces and how the problem statement can constrain or expand conceptual expansion.

Keywords: design, problem-solving, industrial designers, design neurocognition.

Introduction

The study of the cognitive behavior of industrial designers while designing, based on methods such as protocol analysis (Ericsson and Simon, 1983, Kan and Gero, 2017), has produced important results covering foundational aspects of design cognition. The notions of problem space and solution space have been the ground of interpretations of the designing process (e.g., Kruger and Cross, 2006) in the last fifty years of design research (Jones, 1963). The problem-solving view of design claims that the designing process commences with an exploration within the problem space (Goel and Pirolli, 1992). Alternative perspectives assert that design thinking is primarily solution focused (Dorst, 2011; Darke, 1979). One of the initial and core research questions is whether designing as a cognitive process is distinct from problem-solving (Goel and Pirolli, 1992; Visser, 2009). Neurophysiological studies offer a new integrative perspective into how brain behavior progresses during the designing process, which makes them a robust tool for connecting to design cognition. Recent design studies based on functional magnetic resonance imaging (fMRI) (Alexiou, et al., 2009; Goucher-Lambert, et al., 2017), electroencephalography (EEG) (Liu et al., 2018; Liu et al., 2016; Liang, et al., 2017) and functional near-infrared spectroscopy (fNIRS) (Shealy, Hu and Gero, 2018) attempt to understand 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. EEG's high temporal resolution makes it a more suitable tool than fMRI (Hinterberger, et al. 2014; Dickter and Kieffaber, 2014) to investigate designing as a temporal activity. The study reported in this paper is based on the analysis of industrial designers' 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 in industrial designers.

We adopt and extend the tasks described in a controlled experiment of an fMRI-based design study (Alexiou, et al., 2009). 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 1. Design neurocognition of industrial designers when problem-solving and designing are different.

Hypothesis 2. Neurocognitive temporal distributions of activations of industrial designers are significantly different across design tasks.

Experiment Design

We have adopted and replicated two of the layout tasks described in the Alexiou, et al. (2009) fMRI-based study. We extended their experiment to a third open layout design task with the purpose of opening the solution space to produce a block experiment as depicted in Table 1 and Figure 1. The set of three tasks is preceded by a pre-task so that participants can become acquainted with the physical interface and headset. The three tasks are followed by a fourth open design free-hand sketching task. A tangible interface for individual task performance was built based on magnetic material for easy handling. The pre-task was designed so that participants can familiarize themselves with the use of the EEG headset, and necessary corrections can be made before advancing to the block experiment, manoeuvring the magnetic pieces that make up the physical interface and prevent participants from getting fixated in the problem-solving Task 1. The block experiment consists of a sequence of 3 tasks: problem-solving, basic design and open layout design, as illustrated in Figure 1. We have matched Tasks 1 and 2 with the problem-solving and design tasks from Alexiou, et al. (2009) 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. In Task 4, the participants are asked to propose and represent the outline design of a future personal entertainment system, which is an ill-defined and fully unconstrained task unrelated to formal problem-solving. The Mikado pick up sticks game was given to the participants to play in the breaks between tasks to break their focus on the tasks.

Table 1: Description of the tasks.

Task 1 Problem-solving	Task 2 Basic design	Task 3 Open design
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.	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.	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.

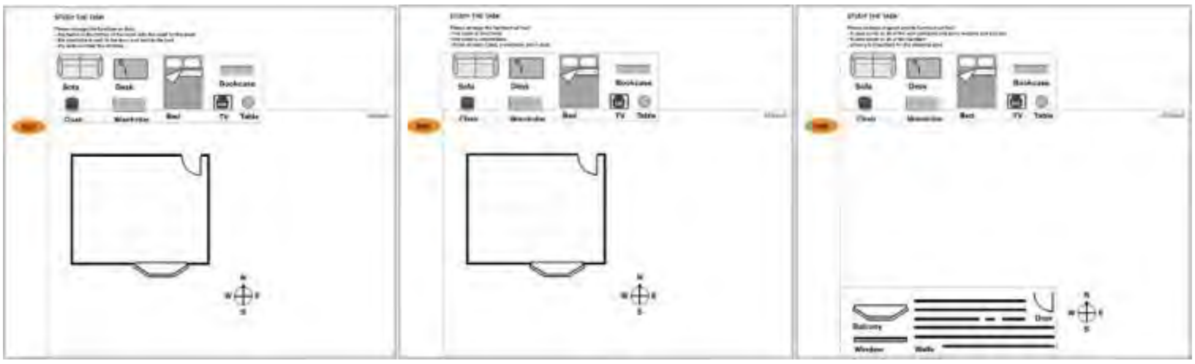

Figure 1: Problem-solving Task 1, Basic Design Task 2 and Open Layout Design Task 3.

Differently from the original tasks (Alexiou, et al. 2009), the magnetic pieces were placed at the top of the vertical magnetic board to prevent signal noise due to eye and head horizontal movements. 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 2. One researcher was present in each individual experiment to instruct and record the participant performance. A period of 10 minutes for setting up and a few minutes for a short introduction were necessary for informing the 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 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 together 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 then open design tasks.

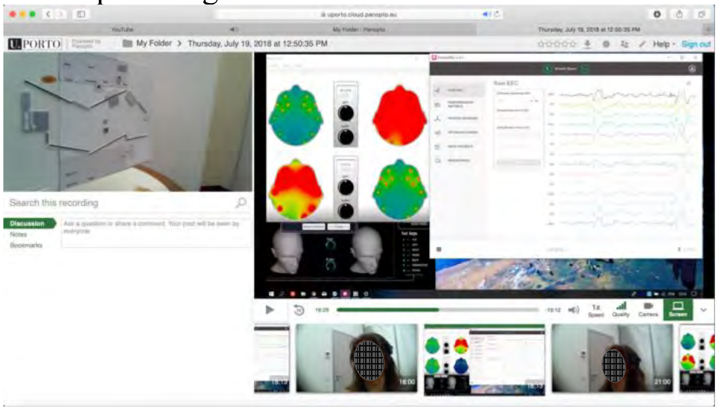

Figure 2: Audio, video and screen streaming in Panopto.

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 between 34 to 67 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 3.

Figure 3: Emotiv Epoc+ Electrodes (10-10 I.S.) and experiment setup.

Participants

A total of 29 experiments were conducted with industrial designers. Due to EEG or video recording issues five 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. 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 two experiments being excluded leaving 22. After the division of the Pow into time deciles (which provides the basis for the temporal analysis) and based on the evidence of threshold values above two and a half average plus standard deviation per channel, a further 4 experiments had to be excluded leaving 18.
The analysis is based on the experimental data of 18 industrial designers, aged 25-43 (M = 31.7, SD = 7.3), 10 men (age M = 35.1, SD = 7.2) and 8 women (age M = 27.5, SD = 5.1), all right-handed. The study was approved by the local ethics committee of the University of 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 too 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. Average time taken per task is as follows: Pretask, 101s, Task1, 90s, Task2, 97s, Task3, 373s and Task 4, 725s.

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 order the remove spurious effects such those produced by eye blinks, jaw muscle contractions and speaking we adopt the blind source separation (BSS) technique based on canonical correlation analysis for the removal of muscle artifacts from EEG recordings (De Clercq, et al. 2006, Vergult, et al. 2007) adapted to remove the short EMG bursts due to articulation of spoken language, attenuating the muscle contamination on the EEG recordings (Vos, et al. 2010). The fourteen electrodes were disposed according to 10-10 I.S, with a 256 Hz sampling rate, a low cutoff 0.1 Hz, and a high cutoff 50 Hz. Data processing includes the removal of DC offset with the IIR procedure, and BSS.

Data Analysis

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. We compare absolute values known as transformed power (Pow), and task-related power (TRP). The Pow is the transformed power, more specifically the mean of the squared values of microvolts per second (µV/s) for each electrode processed signal per task. This measure tells us about the amplitude of the signal per channel and per participant magnified to absolute values. We present Pow values on aggregates of participants' individual results, per total task and for each task deciles for the temporal analysis. The task-related power (TRP) is typically calculated taking the resting state as the reference period per individual (Rominger, et al. 2018, Schwab, et al. 2014). We analyzed the EEG recordings of the resting periods prior to the experiment of some of the participants and their results varied considerably, with some participants showing 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 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 (Pfurtscheller, Lopes da Silva, 1999). 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). Data analysis included Pow and TRP values on individual and aggregate levels using MatLab and open source software.

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. The open design Tasks 3 and 4 show higher TRP from the constrained Task 1. The transformed power (Pow), was calculated for each of the 5 tasks and electrodes. Results between the tasks for the industrial designers are depicted in Figure 4. Higher activation in the open design Tasks 3 and 4, particularly in the channels of the right occipitotemporal cortex (F8 to O1), translates the higher conceptual expansion in the problem and solution spaces.

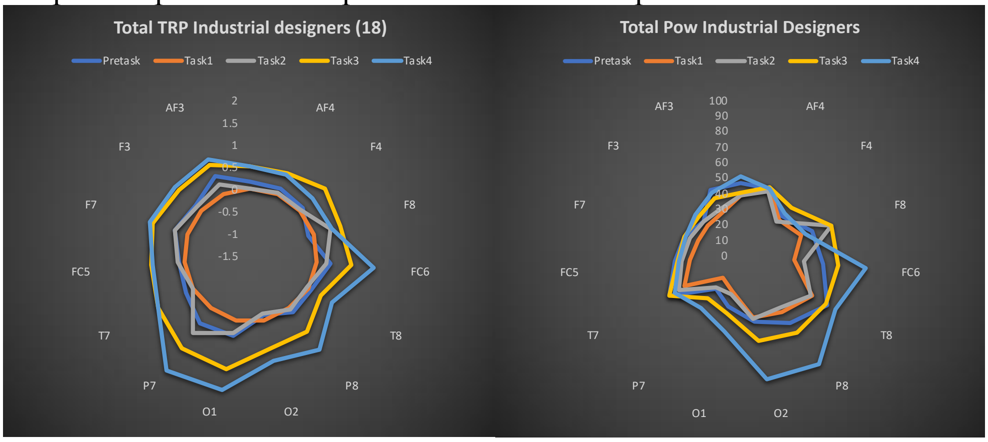

Figure 4: Task-Related Power (TRP) and Transformed Power (Pow).

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, and *hemisphere*, p=.02. There was no main effect for electrode, p=.60. A significant interaction effect between the factors *hemisphere and electrode* was found: p<.01. In addition, we conducted pairwise comparisons to check for differences among participants comparing electrodes, hemisphere and task. The pairwise comparisons revealed that Task 4 differs significantly from Pretask (p=.02) and Task 2 (p<.01). The transformed power (Pow), was calculated for each of the 5 tasks, electrodes and deciles. To compare the Pow scores we performed an analysis by running a 5x2x7 repeated-measurement ANOVA, with the within-subject factors task, hemisphere and electrode. We found a significant main effect of: *task*, *p*<.001, *hemisphere*, *p*<.001, and electrode, *p*<.001. The pairwise comparisons revealed that Task 4 differs significantly from Task 1(*p*<.001) and Task 2 (*p*<.01), and Task 3 differs significantly from Task 1(*p*<.01) and Task 2 (*p*=.01).

Temporal Analysis and Brodmann Areas

For a temporal analysis of the data, each experiment session is divided into ten equal segments called deciles. The transformed power (Pow) for the constrained Task 1, and the open design Tasks 3 and 4 across channels per decile is depicted in Figure 5. Problem-solving Task 1 has increased general activation in deciles one and seven. Task 3 shows increased general activation in deciles one, four, six, seven and ten. Task 4 shows higher variation of temporal distributions of activations.

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 industrial designers we found a significant main effect of: *task*, *p*<.001, *hemisphere*, *p*<.001, *and electrode, p*=.001. A marginally significant main effect was found for decile, *p*=.07.

Significant interaction effects were found between the factors: *task and hemisphere*, *p*=.01, *task and electrode*, *p*<.001, *task and decile, p*<.001, *and hemisphere and electrode*, *p*<.01.

In addition, we conducted pairwise comparisons for hemisphere, electrode, decile and task. The pairwise comparisons revealed that Task 4 differs significantly from Task 1 (*p*<.01) and Task 2 (*p*<.01), Task 3 differs significantly from Task 1 (*p*<.01) and Task 2 (*p*=.02).

The pairwise comparisons also reveal significant differences between deciles: between the first two deciles from which it can be inferred that participants are sorting out how to tackle the tasks request; deciles four and six do not show differences with the others, from which it can be inferred that a more reflective and incubation stage while maturing thinking about the task request takes place; the third, fifth, seventh, eighth and ninth deciles differ from the last one as the refinement of the solutions may differ from searching how to tackle the request.

Statistical analysis indicates significant increased activation of channels placed on the left and right occipital and dorsolateral cortices in the open design tasks compared to the problem-solving task. These channels and their corresponding Brodmann areas (BA), are represented across the deciles in Figure 5. In Figure 5, the circles indicate significant differences and the numerals inside the circles are the Brodmann area number. Brodmann areas refer to unique regions of the cortex and are associated with particular cognitive activities. 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 (Glasser, et al. 2016). Multiple magnetic resonance imaging (MRI) measurements have resulted in an extended map with 97 new areas, besides the 83 areas previously reported (Glasser, et al. 2016) 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).

From the analysis of the open design Task 3, the time span for deciles is 36s. Single channel significant activation takes place in three deciles. In the first decile, channel FC6 shows increased activation of BA 44 whose cognitive functions are associated with inhibition actions, monitoring actions, goals, expressing emotions, working memory, episodic memory and object manipulation (Bernal and Altman, 2009). Such increased activation of FC6 takes place in seven deciles for the open layout design Task 3.

The left temporal cortex and secondary visual cortex have differences in the second, third, fifth, sixth and ninth deciles, with increased activation of BA37 associated with the functions of monitoring shape, intentions, drawing, episodes, familiarity judgments and visual fixation (Le, Pardo, Hu, 1998), and BA18, associated with the functions of spatial and emotional visual processing, on the right hemisphere and visual word form and mental imagery on the left hemisphere (Waberski, et al., 2008). Evidence for higher activation of the right dorsolateral prefrontal cortex happens in the fifth, sixth and tenth deciles in the open layout task. Single activation of channels in this region happen in the third and seventh deciles. No channel shows decreased activation compared to the constrained problem-solving Task 1. From the analysis of the open design Task 4, the time span for deciles is 70s. For each decile of 70s, statistically significant differences between Task 4 and Task 1 take place in all the deciles. Channel FC6 increased activation of corresponding BA 44, whose cognitive functions are associated with inhibition actions, monitoring actions, goals, expressing emotions, working memory, episodic memory and object manipulation (Bernal and Altman, 2009) takes place in all the deciles as well. The right and left temporal and secondary visual cortices have differentiating contributions in the second to the sixth and in the eighth to the ninth deciles, with increased activation of BA37, associated with the functions of monitoring shape, intentions, drawing, episodes, familiarity judgments and visual fixation (Le, Pardo, Hu, 1998). As Task 4 is an open design free-hand sketching task, drawing activates BA37 (Le, Pardo, Hu, 1998), and other areas of the secondary visual cortex such as BA18 associated with the functions of spatial and emotional visual processing, on the right hemisphere and visual word form and mental imagery on the left hemisphere (Waberski, et al., 2008). Evidence for higher activation of the right dorsolateral prefrontal cortex just takes place in the tenth decile. Spatial memory, recall and planning among other functions attributed to BA09 (Slotnik, Moo, 2006) connected to channel AF4, just show increase in

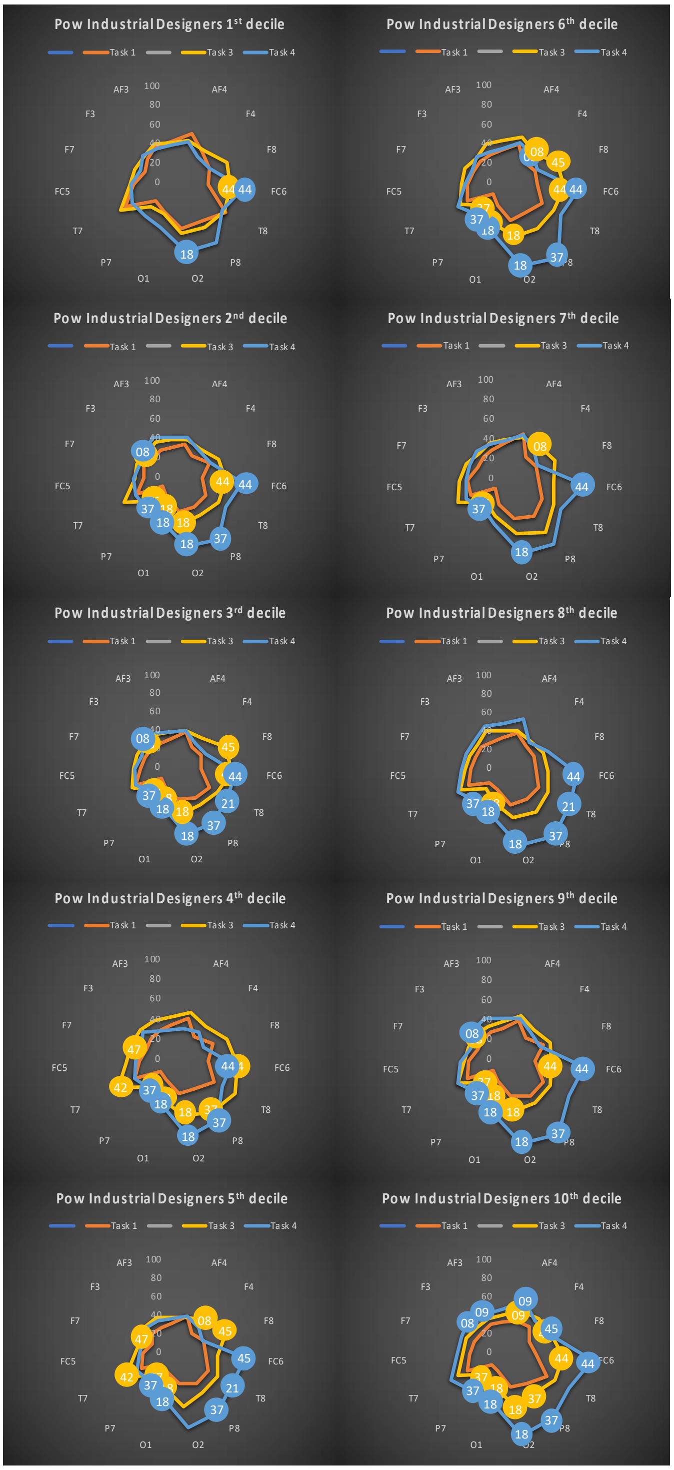

Figure 5: Circles indicate channels that differ from Task 1 to Task 3 and Task 4 by deciles correlated with their Brodmann areas (numerals inside circles).

activation compared to Task 1 in the tenth decile. No channel shows decreased activation compared to Task 1. The co-activation of channels of significant differences have two moments of continuous and increasing engagement before and after the seventh decile.

Discussion and Conclusion

Results from this study demonstrate that EEG is both a practical and relevant technique to study differences in industrial designers while problem-solving and designing. The results of the analysis of the EEG data of the 18 participants show differences in the neurophysiological activations of these industrial designers across tasks and provide initial support for Hypothesis 1: the design neurocognition of industrial designers when problem-solving and designing is different, particularly in open design tasks, Task 3 and Task 4. Industrial designers show higher transformed power (Pow) and distinct task-related power (TRP) differences from the open design Task 3 and Task 4 to the constrained design Task 1. The neurocognitive temporal distributions of activations are non-uniform, providing initial support for Hypothesis 2: industrial designers show variation in the Pow 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 3 and Task 4. Increased activation is associated with conceptual expansion (Abrahams, 2019) from which we infer that the design space inherently expands as well in the designers' search for the problem and the solution. Evidence for higher activation of the right dorsolateral prefrontal cortex across in design tasks (Alexiou, et al. 2009; Kounios and Beeman, 2009) is shown, particularly in the open layout design Task 3. Evidence from fMRI studies (Alexiou, et al.2009) of a more extensive network of brain areas in designing than problem-solving can be inferred from these EEG results. Evidence for higher activation of the right occipitotemporal cortex is consistent for both open design tasks. We can propose that for open design tasks the co-activation of channels of significant differences, is consistent for the channels P7, O1, O2, P8 and FC6. In particular for the open layout design, F4 and F8 also integrate the co-activation of channels of significant differences, whose associated cognitive functions seem to be relevant for the design of spatial solutions. Results from the time-related neural responses connected to Brodmann areas' cognitive functions, contribute to a better understanding of industrial designers' cognition in open design tasks. These results can be correlated with previous cognitive studies that explore similar hypotheses (Jiang, Gero and Yen, 2014).

Further detailed analyses are being carried out to provide a more in-depth and comprehensive understanding of the neurophysiological differences between the tasks based on the temporal analysis of frequency bands and their relation to cognitive functions.

Neuroimaging studies (i.e. fMRI, EEG, fNIRS) are more advanced in creative cognition (Abrahams, 2019; Benedek, Jung, Vartanian, 2018; Gero, 2008; Gero, 2015; Kowatari et al., 2009; Martindale and Hines, 1975; Vartanian and Goel, 2005; Xue et al., 2018), and visual creativity, architecture and the arts (see review by Pidgeon, et al. 2016), 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. Results from 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 (Goel, 2014). 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 the mental processes associated with design.

Cognitive studies of designers commenced some 50 years ago (Eastman, 1968) with the bulk of the studies occurring in the last twenty years. Neuroimaging studies are a new approach to studying design cognition that have the potential to provide an objective measurement of brain behavior connected to cognition. The potential contributions of neuroimaging studies of design cover a large number of areas including studying the effects of: design domains, tasks, teams, tools and experience on design cognition. In particular, neuroimaging studies contribute to a better understanding of design cognition and have implications for design education, the development of design support and the management of design.

REFERENCES

Abrahams, A. (2019). *The Neuroscience of Creativity,* Cambridge, UK: Cambridge University Press.

Alexiou, K., Zamenopoulos, T., Johnson, J. H., Gilbert S. J. (2009). Exploring the neurological basis of design cognition using brain imaging: some preliminary results. *Design Studies,* 30(6), 623-647.

Benedek,M., Jung, R., Vartanian, O. (2018). The neural bases of creativity and intelligence: common ground and differences. *Neuropsychologia,* 118, 1-3.

Bernal, B., Altman, N. (2009). Neural networks of motor and cognitive inhibition are dissociated between brain hemispheres: an fMRI study. Int J Neurosci. 119, 10, 1848-1880.

Darke, J. (1979). The primary generator and the design process. *Design Studies,* 1(1), 36-44.

De Clercq, W., Vergult, A., Vanrumste, B., Van Paesschen, W., Van Huffel, S. (2006). Canonical correlation analysis applied to remove muscle artifacts from the electroencephalogram. *IEEE Transactions on Biomedical Engineering, 53*, 2583-2587.

Dickter, C., Kieffaber, P. (2014). *EEG Methods for the Psychological Sciences.* Sage.

Dorst,K., (2011). The core of 'design thinking' and its application. *Design Studies,* 32(6), 521-532.

Eastman, C. M., (1968). Exploration in the cognitive processes of design, *Defense Documentation Repor*t No. AD 671158, ARPA, Carnegie-Mellon University.

Ericsson, K. A., Simon, A. H. (1984). *Protocol Analysis: Verbal reports as data*. MIT Press.

Gero, J. S. (ed) (2008). *Studying Design Creativity,* Key Centre of Design Computing and Cognition, University of Sydney, Australia.

Gero, J. S. (ed) (2015). *Studying Visual and Spatial Reasoning for Design Creativity*, Dordrecht, Netherlands: Springer.

Glasser, M., Coalson, T., Robinson, E., Hacker, C., Harwell, J., Yacoub, E., Ugurbil, K., Andersson, J., Beckmann, C., Jenkinson, M., Smith, S., Van Essen, D. (2016). A multi-modal parcellation of human cerebral cortex. Nature. 536 (7615), 171-178.

Le, T., Pardo, P., Hu, X. "4 T-fMRI Study of Nonspatial Shifting of Selective Attention: Cerebellar and Parietal Contributions. The American Physiological Society. Vol.79 No.3. 1998:1535-1548.

Goel, V. (2014). Creative brains: designing in the real world. *Frontiers in Psychology*, 8, 1-14.

Goel, V., Pirolli, P. (1992). The structure of design problem spaces. *Cognitive Science,* 16, 395-429.

Goucher-Lambert, K., Moss, J., Cagan ,J. (2017). Inside the mind: Using neuroimaging to understand moral product preference judgments involving sustainability. *ASME Journal of Mechanical Design,* 139(4), 041103-041103-11.

Hinterberger, T., Zlabinger, M., Blaser, K. (2014). Neurophysiological correlates of various mental perspectives. *Frontiers in Human Neuroscience* (8): 1-16.

Jiang, H., Gero, J. S., Yen, C. C. (2014). Exploring designing styles using Problem-Solution indexes,.In J. S. Gero (ed), *Design Computing and Cognition'12*, Springer, pp. 85-101.

Jones, J. C., Thornley, D. G. (eds) (1963). *Conference on Design Methods*. Oxford, UK: Pergamon Press.

Kan, J. W.T., Gero, J. S. (2017). *Quantitative Methods for Studying Design Protocols*. Springer.

Kounios, J., Beeman, M. (2009). The Aha! moment: The cognitive neuroscience of insight. *Current Directions in Psychological Science,* 18(4), 210-216.

Kowatari Y., Lee S.H., Yamamura H., Nagamori Y., Levy P., Yamane S., Yamamoto M. (2009). Neural Networks Involved in Artistic Creativity. *Human Brain Mapping*, 30, 1678-1690.
Kruger, C., Cross, N. (2006). Solution driven versus problem driven design: Strategies and outcomes. *Design Studies,* 27(5), 527-548.
Liang, C., Lin, C., Yao, C., Chang, W., Liu, Y., Chen, S. (2017). Visual attention and association: An electroencephalography study in expert designers. *Design Studies,* 48, 76-95.
Liu, L., Li, Y., Xiong, Y., Cao, J., Yuan, P. (2018). An EEG study of the relationship between design problem statements and cognitive behaviors during conceptual design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing,* 32, 351–362.
Liu, L., Nguyen, T., Zeng, Y., Ben Hamza, A. (2016). Identification of Relationships Between Electroencephalography (EEG) Bands and Design Activities. ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 7: 28th International Conference on Design Theory and Methodology. Charlotte, North Carolina, USA, August 21–24, 2016.
Martindale, C., Hines, D. (1975). Creativity and cortical activation during creative, intellectual and EEG feedback tasks. *Biological Psychology,* 3, 91-100.
Pfurtscheller, G., Lopes da Silva, F. (1999). Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clin. Neurophysiol.* 110, 1842-1857.
Pidgeon, L., Grealy, M., Duffy, A., Hay, L., McTeague, C., Vuletic, T., Coyle, D., Gilbert, S. (2016). Functional neuroimaging of visual creativity: a systematic review and meta-analysis. *Brain and Behavior*, 6(10), 1-26.
Purcell, T., Williams, P. & Gero, J. S., Colbron, B. (1993). Fixation effects: Do they exist in design problem solving? *Environment and Planning B,* 20, 333-345.
Rominger, C., Papousek, I., Perchtold, C., Weber, B., Weiss, E., Fink, F. (2018). The creative brain in the figural domain: Distinct patterns of EEG alpha power during idea generation and idea elaboration. *Neuropsychologia,* 118, 13-19.
Shealy, T., Hu, M. and Gero, J. S. (2018) Neuro-cognitive differences between brainstorming, morphologivcal analysis and TRIZ, ASME IDETC.
Schwab, D., Benedek, M., Papousek, I., Weiss, E., Fink, A. (2014). The time-course of EEG alpha power changes in creative ideation. Frontiers in Human Neuroscience, 8, 1-8.
Slotnick, S., Moo, L. (2006). Prefrontal cortex hemispheric specialization for categorical and coordinate visual spatial memory. Neuropsychologia. 44, 9, 1560-1568.
Vartanian, O. and Goel, V. (2005). Neural correlates of creative cognition, in C. Martindale, P. Locher and V. Petrov (eds) *Evolutionary and Neurocognitive Approaches to the Arts*, Baywood Publishing Company, 195-206.
Vergult, A., De Clercq, W., Palmini, A., Vanrumste, B., Dupont, P., Van Huffel, S., et al. (2007). Improving the interpretation of ictal scalp eeg: BSS-cca algorithm for muscle artifact removal. *Epilepsia,* 48, 950-958.
Vos, D., Riès, S., Vanderperren, K., Vanrumste, B., Alario, F., Huffel, V., Burle, B. (2010). Removal of muscle artifacts from EEG recordings of spoken language production. *Neuroinform,* 8, 135-150.
Visser, W. (2009). Design: one, but in different forms. *Design Studies,* 30(3), 187-223.
Waberski, T. Gobbele, R., Lamberty, K., Buchner, H., Marshall, J., Fink, G. (2008). Timing of visuo-spatial information processing: Electrical source imaging related to line bisection judgements. Neuropsychologia. 46, 1201–1210.