Design Science

The neurophysiological activations of mechanical engineers and industrial designers while designing and problem-solving

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Abstract

This paper presents results from an experiment using electroencephalography to measure neurophysiological activations of mechanical engineers and industrial designers when designing and problem-solving. In this study, we adopted and then extended the tasks described in a previous functional magnetic resonance imaging study reported in the literature. The block experiment consists of a sequence of three tasks: problem-solving, basic design and open design using a physical interface. The block is preceded by a familiarizing pre-task and then extended to a fourth open design task using free-hand sketching. This paper presents the neurophysiological results from 36 experimental sessions of mechanical engineers and industrial designers. Results indicate significant differences in activations between the problem-solving and the open design tasks. The paper focuses on the two prototypical tasks of problem-solving layout and open design sketching and presents results for both aggregate and temporal activations across participants within each domain and across domains.

Keywords: designing, problem-solving, mechanical engineers, industrial designers, electroencephalography

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1. Introduction

Designing is an activity that is carried out over time. Design research has focussed on design cognition as a multimodal activity with a temporal aspect, different from problem-solving (Dorst 2011; Gero 1990). The emerging field of design neurocognition distinguishes itself from the traditional field of cognitive neuroscience by studying the temporal and multimodal behaviour involved in designing (Park & Alderman 2018). Designing entails a range of cognitive activities that can take minutes to generate solutions. Using neurophysiological measurements for assessing well-defined cognitive processes that only take seconds, with repeated tasks, is a reductionist viewpoint not applicable to the complex activities of concurrent cognitive processes occurring while designing. Neural responses of cognitive processes cannot be observed in isolation from other ongoing processes (Benedek *et al.* 2019). Shorter tasks do not allow gathering more complex behavioural assessments of higher order cognitive functions. The advantages and disadvantages of different neurophysiological measurements are beyond the scope of this paper. Designing involves many different processes and strategies that may vary over time (Hay *et al.* 2017). Understanding how the brain interacts to produce higher cognitive functions such as those involved in designing and disentangling its cognitive processes through neurophysiological measurements asks for a macro perspective by distinguishing phases or stages of designing from theoretical models (Gero & Kannengiesser 2004; Hatchuel & Weil 2009). Measurements of brain activity while designing provide a more objective foundation on which to confirm or build temporal theories of designing, than do cognitive measurements from protocol studies alone. Design neurocognition provides the context for the convergence of researchers from diverse disciplines and encourages contributions from the fields of neurocognition, cognitive psychology, neurophysiology, artificial intelligence and design theory, among others. This research context allows testing and verifying to what extent designing is different from other cognitive processes (Dorst 2011; Gero 1990) and how it unfolds.

The present study does not look into cognitive processes, but at the neurophysiological activations throughout entire design tasks performed by designers from two different domains. We look at how problem-solving and designing translate into neurophysiological activations and unfold over time with the cognitive processes involved. We describe preliminary results from a controlled experiment that takes advantage of the temporal resolution of electroencephalography (EEG). A low-cost portable EEG device is used to measure neurophysiological activations across time when mechanical engineers and industrial designers are problem-solving and designing. This approach augments prior work on design cognition based on protocol studies, comparing mechanical engineers and industrial designers.

1.1. Designing and problem-solving

The study of the cognitive behaviour of designers based on methods from cognitive psychology, such as protocol analysis (Ericsson & Simon 1993; Crutcher 1994; Kan & Gero 2017), has elucidated a number of characteristics of design cognition (Purcell *et al.* 1993; Jiang *et al.* 2014; Hay *et al.* 2017). The notions of problem space and solution space have populated design research interpretations of the designing process (Dorst & Cross 2001; Kruger & Cross 2006) throughout its half century of formal study (Jones & Thornley 1963). One of the initial and core research questions is whether designing, as a cognitive process, is distinct from problem-solving (Goel & Pirolli 1989, 1992; Visser 2009). 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 involves the search for variables that relate to what is not known, such variables are context sensitive, can bring change and have variant meanings according to the design situation (Gero 1990). In designing the characteristics of the problem are not all defined from the start, making designing an open task. Variables are introduced and change through evaluation processes and interdependencies within design issues (Vieira 2012). Distinguishing designing from problem-solving has implications for design research and design education in particular, since much of education is based on problem-solving theories.

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1.2. Neurophysiological studies in design research

Neurophysiological studies offer insights into brain activity during the designing process. It has commensurability of measurements which makes such studies a robust approach for design research (Pidgeon *et al.* 2016; Borgianni & Maccioni 2020). Neurophysiological design studies based on functional magnetic resonance imaging (fMRI) started a decade ago (Alexiou *et al.* 2009) with a controlled experiment reporting preliminary results on the distinction between designing and problem-solving. Recent fMRI studies focussed on domain-related design issues (Hay *et al.* 2020), sustainability judgments (Goucher-Lambert, Moss & Cagan 2017), design ideation and inspirational stimuli (Goucher-Lambert, Moss & Cagan 2019) of mechanical engineers, graphic designers (Ellamil *et al.* 2011), and architects (Bermudez *et al.* 2017).

Studies using electroencephalography (EEG) commenced more than 40 years ago (Martindale & Hines 1975) investigating cortical activation during multiple tasks. Some 20 years later a study on categorization tasks of experts and novices made use of EEG in design research (Göker 1997). In the last 10 years, single domain-related EEG design studies (Nguyen & Zheng 2010; Vecchiato *et al.* 2015; Liu, Zeng & Ben Hamza 2016; Liang *et al.* 2017; Liang *et al.* 2018; Liu *et al.* 2018) and functional near-infrared spectroscopy (fNIRS) design studies (Shealy, Hu & Gero 2018; Shealy & Gero 2019) have been used to understand acts of designing from a neurophysiological perspective. Design is a temporal activity. EEG has started to play a role in design research because of its high temporal resolution, readily available software, reduction in the cost of portable equipment and relatively little need for specialized training. This has made the collection and analysis of EEG signals a viable option for design researchers. The limitations of low-cost EEG equipment when compared to medical grade systems, include low number of channels, physical stability, lower signal to noise ratio, lower sampling rate and serial measurement of electrodes (lasting a quarter of a second for the equipment used in this experiment). These are addressed by scalp preparation prior to electrode fixing, contact quality, artifact removal and filtering of the measurement to increase the signal to noise ratio, and outlier analysis that reduces variability. The sampling rate of the low-cost EEG device used in this study is higher than the cognitive activation rate found in previous cognitive studies (Gero and McNeil 1998; Goldschmidt 2014). The cognitive actions of interest while designing span multiple seconds (Kan & Gero 2017). Typical design sessions of 45 min generate between 600 and 1200 segments using protocol analysis, where each segment codes a cognitive action. This results in an average between 2.25 and 4.5 s per action. This is well within the capacity of a low-cost EEG device. Although low-cost EEG equipment has lower signal to noise ratio potentially resulting in a higher variability of the results and higher standard deviation than medical-grade equipment, the statistical approaches we describe in Section 2.6, compensate for the potential effects on the results due to the limitations of the equipment. Low-cost EEG non-invasive portable equipment becomes a viable measuring tool for the level of resolution we are interested in and for achieving preliminary results (Badcock *et al.* 2013; Badcock *et al.* 2015; Bashivan *et al.* 2016; Hashemi *et al.* 2016; Krigolson *et al.* 2017).

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1.3. Electroencephalography temporal resolution

Electroencephalography records electrical brain activity with electrodes placed along the scalp according to a standard distribution. Neurons transmit signals down the axon and the dendrites via an electrical impulse. EEG activity reflects the summation of the synchronous activity of thousands or millions of neurons that have similar spatial orientation. When cells have similar spatial orientation, their ions line up and create waves that can be detected. Pyramidal neurons of the cortex are thought to produce the most EEG signal because they are well-aligned and fire together (Sawyer 2011; Dickter & Kieffaber 2014). EEG measures electromagnetic fields generated by this neural activity. Activity from deep sources of the brain is more difficult to detect than currents near the skull, thus EEG is more sensitive to cortical activity (Dickter & Kieffaber 2014; Hinterberger *et al.* 2014). Despite EEG's limited spatial resolution, it can offer high temporal resolution in the order of milliseconds in a portable device. EEG's high temporal resolution makes it a more suitable tool than fMRI to investigate designing as a temporal activity. However, fMRI offers both whole brain scans and a very high spatial resolution.

1.4. EEG results in design research

In design research, results from controlled experiments have identified neurophysiological EEG signals in which more visual thinking is spent during solution generation than in solution evaluation of a layout task (Nguyen & Zheng 2010). Further EEG bands associated with the design activities have been identified, namely beta 2, gamma 1 and gamma 2 (Liu, Zeng & Ben Hamza 2016), higher alpha power conducive for open ended tasks and divergent thinking, and theta and beta power associated to convergent thinking in decision-making and constraints tasks (Liu *et al.* 2018). EEG has been used in the study of visual attention and association in expert designers (Liang *et al.* 2017), visual communication during idea incubation in expert and novice designers (Liang *et al.* 2018), the study of effort, fatigue and concentration in conceptual design (Nguyen, Nguyen & Zeng 2017), and in the study of the neurophysiological correlates of embodiment and motivational factors during the perception of virtual architecture (Vecchiato *et al.* 2015).

This paper describes a study from a larger research project whose goal is to investigate neurophysiological activation of designers across multiple design domains, namely mechanical engineering, industrial design, graphic design and architecture (Vieira *et al.* 2019*a*, 2019*b*, 2020*a*). The study reported in this paper is based on the analysis of mechanical engineers' and industrial designers' neurophysiological activations using an EEG headset in the context of performing problem-solving and design tasks in a laboratory setting. The aims of the study are to:

(i) distinguish neurophysiological activations between designing and problem-solving for both mechanical engineering and industrial design domains.
(ii) distinguish neurophysiological activations between mechanical engineering and industrial design domains.

In the research reported in this paper we test the following hypotheses:

(i) *Hypothesis 1*: the neurophysiological activations of mechanical engineers when problem-solving and designing are significantly different.

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(ii) *Hypothesis 2*: the neurophysiological activations of industrial designers when problem-solving and designing are significantly different.
(iii) *Hypothesis 3:* the neurophysiological activations of mechanical engineers and industrial designers are significantly different for problem-solving and designing.
(iv) *Hypothesis 4:* the neurophysiological temporal distributions of activations of problem-solving and designing are significantly different for mechanical engineers.
(v) *Hypothesis 5:* the neurophysiological temporal distributions of activations of problem-solving and designing are significantly different for industrial designers.
(vi) *Hypothesis 6:* the neurophysiological temporal activations of mechanical engineers and industrial designers are significantly different for problem-solving and designing.

2. Methods

The research team of this study consisted of seven researchers including design scientists, a data analyst, a statistician, a cognitive psychologist and a neurophysiologist. For the present study the analysis focussed on a subset of 55 experiment sessions of mechanical engineering and industrial design professional participants. The tasks and experimental procedure were piloted prior to the full study, through five different sessions each of which produced changes resulting in the final experiment.

The hypotheses are tested by using a problem-solving task as the control/reference and statistically comparing an open design task with the reference task. We compare: absolute values known as transformed power (Pow) and task-related power (TRP) described in Section 2.5. This study was approved by the local ethics committee of the University of Porto.

2.1. Participants

The participants were a convenience sample, the subset of 55 experimental sessions comprises 26 mechanical engineers and 29 industrial designers. Results are based on 36 right-handed participants, 18 mechanical engineers, aged 25–40 ($M = 28.9$, $SD = 4.2$), 10 males (age $M = 29.0$, $SD = 5.3$) and 8 females (age $M = 28.7$, $SD = 2.5$); and 18 industrial designers, aged 25–43 ($M = 31.7$, $SD = 7.3$), 10 males (age $M = 35.1$, $SD = 7.2$) and 8 females (age $M = 27.5$, $SD = 5.1$). The participants are all professionals (experience $M = 5.9$, $SD = 6.0$). The sample has 20 participants with experience in designing of 5 years or less, and 16 participants with experience in designing of more than 5 years. The experience of the industrial designers compared to the mechanical engineers is statistically different. However, the analysis of covariance (ANCOVA) indicates no significant effect of domain on the EEG scores after controlling for experience, $F(1, 33) = 2.3$, $p = 0.15$.

2.2. Experiment tasks design

We adopted and replicated the problem-solving and layout design tasks described in the Alexiou *et al.* (2009) fMRI-based study. We matched Tasks 1 and 2 with the problem-solving and design tasks (Alexiou *et al.* 2009) in terms of requests, number of constraints, stimuli and number of instructions (Appendix A). Task

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Table 1. Description of the problem-solving, basic design and open design tasks.

Task 1 Problem-solving	Task 2 Basic layout design	Task 3 Open layout design	Task 4 Open sketching 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.	In the free-hand sketching Task 4, the participants are asked to: propose and represent an outline design for a future personal entertainment system.

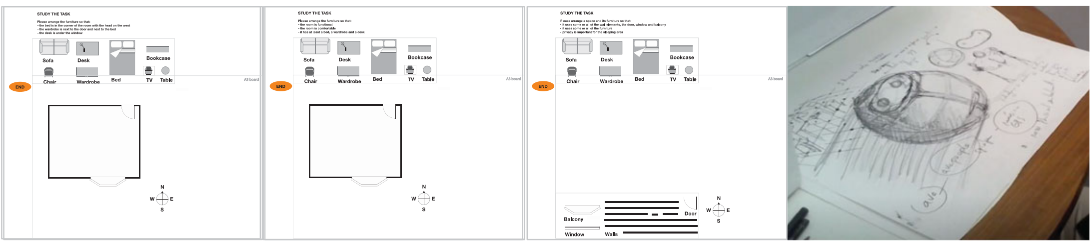

Figure 1. Depiction of the problem-solving Task 1, layout design Task 2, open layout design Task 3 and open free hand sketching design Task 4.

1 is considered a problem-solving task as the problem itself is well-defined, and the set of solutions is both limited and unique (Alexiou *et al.* 2009). 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 2 (Table 1). Both design tasks have no predetermined final state and the tasks are open-ended. Thus, the block experiment consisted of a sequence of three tasks: problem-solving layout design, basic layout design and open layout design (Figure 1). We added a fourth completely open design task that uses free-hand sketching after Task 3. Task 4 is an ill-defined and fully unconstrained task unrelated to formal problem-solving. Each participant was given two sheets of paper (A3 size) and three instruments, a pencil, graphite and a pen (Figure 1). The three design tasks (Tasks 2–4) require defining the problem and the solution spaces in a successive order of complexity. A neurophysiological subtraction between the problem-solving Task 1 and the design tasks will reveal brain magnetic fields more strongly involved in designing.

The set of four tasks was preceded by a pre-task so that participants could get used to the interface and headset. In the pre-task, the participant had to place a set

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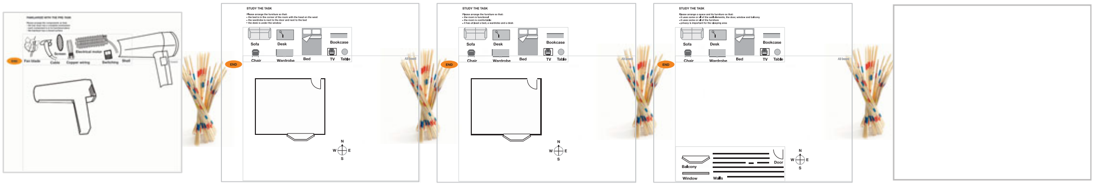

Pretask

Reference Task 1 Problem-solving

Task 2 Basic layout design

Task 3 Open layout design

Task 4 Open free hand sketching

Figure 2. Schematic sequence of the tasks' procedure given to the participants.

of components for the design of a hair dryer. As with all block experiments, each subsequent task was potentially primed by the previous task. The Mikado pick-up-sticks game was given to the participants to play in the breaks between tasks (Figure 2). Results across the tasks were previously reported on single and two-domain studies (Vieira *et al.* 2019*a*, 2019*b*, 2020*a*). For this paper, the focus is only on Tasks 1 and 4. Task 4 is an open design task while Task 1 is a well-defined, highly constrained problem, these are the two extremes of the way requirements of design tasks are presented. Task 4 has been selected because it has been used in previous protocol analysis studies of mechanical engineers and industrial designers and results about designers' cognition are available (e.g. Jiang 2012).

2.3. Setup and procedure

A tangible interface for individual task performance was built based on magnetic material for easy handling (Figure 3). Differently from the original tasks (Alexiou *et al.* 2009), the magnetic pieces were placed at the top of the vertical magnetic board to reduce signal noise due to eye and head horizontal movements. The pre-task was designed so that participants could 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, Task 1. This pre-task was also intended to familiarize participants with postural and facial movements and allowed the researcher to correct and fine-tune necessary adjustments before advancing to the block experiment.

Participants are instructed to wash their hair prior to attending the experiment session to improve contact quality. One researcher was present in each experiment session to instruct the participant and to check for recording issues. A period of 10 min for setting up and a few minutes for a short introduction was necessary for informing each participant, reading and signing of the consent agreement and setting the room temperature. Each participant was reminded to use the bathroom, spit out any gum and asked to untie their hair before the start of the experiment. The researcher checked metallic accessories for electromagnetic interference and contact lenses. The researcher sat at the desk and checked posture of each participant. In order to reduce excessive signal artifacts, the researcher asked each participant as far as possible to avoid neck movements, blinking, muscle contractions as well avoid rotating their head, horizontal eye movements, pressing the lips and teeth together during the tasks. The researcher followed a script to conduct the experiment so that each participant was presented with the same information and

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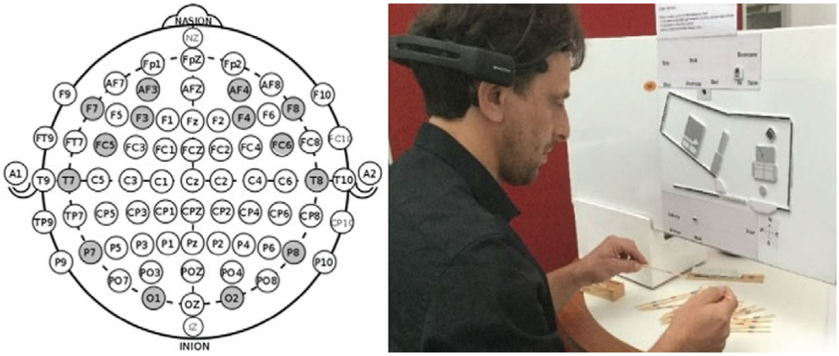

Figure 3. Emotiv Epoc+ electrodes highlighted in grey against the 10–10 I.S. layout and experiment setup using the headset.

stimuli. Before each task, participants were asked to start by reading the text describing the task which took an average of 10 s. Then the participants performed the sequence of tasks (Figure 2). The participants were asked to stay silent during the tasks and use the breaks for talking and clarifications. If needed, extra time was given to the participants, in particular in Task 4, so they could find a satisfactory solution. Instructions given to the participants are reported in Appendix A.

2.4. Data collection methods

EEG activity was recorded using a portable 14-channel system Emotiv Epoc+. Electrodes are arranged according to the 10–10 I.S standard (Figure 3).

Electromagnetic interference of the room was checked for frequencies below 60 Hz. Each of the Emotiv Epoc+ channels collects continuous signals of electrical activity at their location. The participants performed the tasks on the physical magnetic board, with two video cameras capturing the participant's face and activity and an audio recorder. All the data captures were streamed using Panopto software (https://www.panopto.com/) that also allows for direct screen capture, Figure 4.

A total of 100 experimental sessions constitute our major dataset of which 90 took place at the University of Porto, between March and July of 2017, and June and September of 2018. Ten sessions took place in the Design Hub of Mouraria, Lisbon, during August 2018 in rooms with the necessary conditions for the experiment, such as natural lighting sufficient for performing experiments between 9:00 and 15:00 and no electromagnetic interference. Only the 55 that involved either mechanical engineers or industrial designers are considered in this paper.

2.5. Data processing methods

The 14 electrodes were disposed according to the 10–10 I.S. (Figure 3) 256 Hz sampling rate, low cutoff 0.1 Hz, high cutoff 50 Hz. Several methods in the literature (Mannan *et al.* 2018) 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

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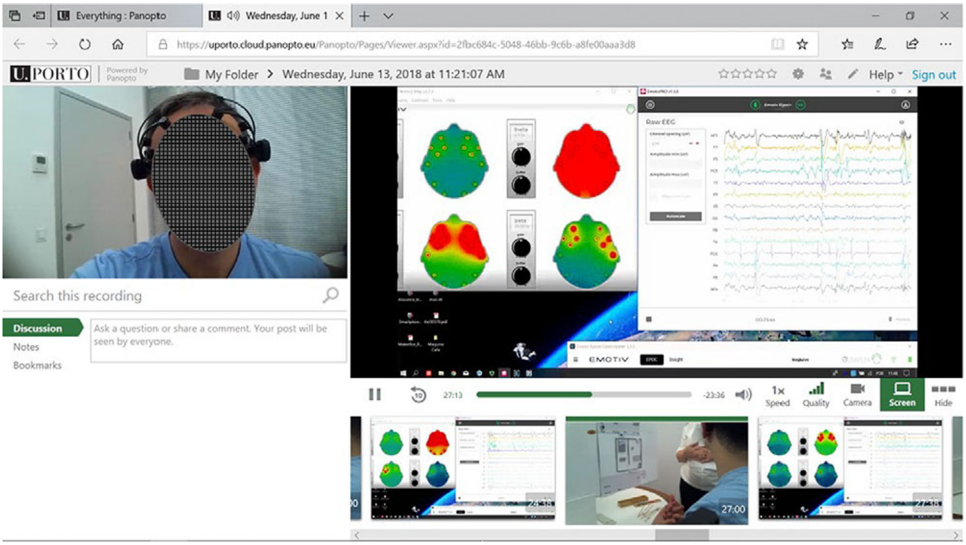

Figure 4. Screen capture depicting audio, video and screen captures streaming in Panopto.

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 (Borga & Knutsson 2001; De Clercq *et al.* 2006) adapted to remove the short EMG bursts due to articulation of spoken language, attenuating the muscle artifacts contamination on the EEG recordings (Vos *et al.* 2010). 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 lowest correlated sources represent noise. By systematically eliminating a subset of the bottom sources, the EEG signals from all subjects used in this study were cleaned. More specifically, by turning the last four 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 the EEGLab open source software. All the EEG segments of the recorded data were used for averaging throughout the entire tasks, from beginning to end. Unpublished results testing the BSS–CCA procedure's efficacy on EEG signals from participants performing sketching tasks in three conditions including pen and paper confirm its 99% efficacy. The statistical approach we describe in Section 2.6, compensates for the potential effects on the procedure due to the limitations of the equipment. As Task 4 involves muscular activity given that participants sketched, the procedure described in De Clercq *et al.* (2006) was used. All the tasks of this experiment involve thinking and motion. The motor actions involved in the tasks using the tangible interface versus the free hand sketching and their corresponding EEG signals are of the same source, thus we claim that the BSS–CCA procedure filters the signal.

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Each of the Emotiv Epoc+ channel's continuous electrical signal is processed to produce multiple measures. Here, we report only on two: 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's processed signal per task. This measure tells us about the amplitude of the signal per channel, per participant magnified to absolute values. We present Pow values on aggregates of participants' individual results, for each domain cohort, per total task and for each task deciles for the temporal analysis. The TRP is the task-related power, typically calculated taking the resting state as the reference period per individual (Dickter & Kieffaber 2014; Schwab *et al.* 2014; Rominger *et al.* 2018). This method that is normally time-locked to fractions of seconds. In this study, we time-locked on a scale of multiple seconds to allow for the design activity to unfold. We make a shift of the focus on time-locking the experiments equally for all participants, to the unfolding of the designing and problem-solving cognitive activities until the solution is produced. Thus, our experiment is time-locked for the complete unfolding of the cognitive activities involved in each task.

Of the 55 sessions recorded, 7 had recording problems that rendered them unsuitable for further analysis and were excluded from further analysis. These problems ranged from failing to switch on all the equipment, equipment failures, participants' handedness and failure to complete the experiment. We processed the Pow and the TRP measurements for each participant per total task and temporal deciles per task, then after determining the outliers, we calculated the mean and standard deviation of each measure for each cohort. A z-score was conducted in the analysis of Pow across tasks for each of the remaining 48 participants data to determine outliers. The criteria for excluding participants were based on the evidence of 6 or more channel threshold z-score values above 1.96 or below -1.96 and individual measurements above 2.81 or below -2.81. This resulted in a further eight sessions being excluded leaving 40. After the division of the Pow into time deciles (which provides the basis for the analysis of temporal stages) amplitude leading to 2.5 standard deviations from the mean as threshold values were excluded per channel, 4 experiments were further excluded leaving 36, 18 per domain.

2.6. Data analysis methods

As the focus of the study is to determine how well neurophysiological activations during designing can be distinguished from those during problem-solving, we take the problem-solving task, Task 1 as the control/reference period for the TRP calculations. Thus, for each electrode, the following formula was applied taking the log of the Pow of the corresponding electrode i (of 14), 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 (per participant), according to the formula:

$$TRP_i = log\,(Pow_i, activation)_j - log\,(Pow_i, reference)_j \tag{1}$$

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 indicate a power increase (Pfurtscheller & Lopes da Silva 1999) (power and activation refer to brain wave amplitude).

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2.7. Statistical approach

We performed standard statistical analyses based on the design of the experiment: always a mixed repeated-measures design with pairwise comparisons to follow up on specific differences with task, hemisphere, electrode and decile as within-subject factors and domain as the between-subjects factor. These analyses were performed for the dependent variable of Pow and for all the within-subject variables. The threshold for significance in all the analyses is $p \leq 0.05$. We further describe each statistical comparison performed in relation to the hypotheses and the methods used. To compare the Pow of the tasks within domain we performed an analysis by running a $5 \times 2 \times 7$ repeated-measurement ANOVA, with the within-subject factors of task, hemisphere and electrode (Appendix B). We then compared the Pow of the tasks between domains and performed an analysis by running a $5 \times 2 \times 7$ repeated-measurement ANOVA, with the between-subjects factor domain and the within-subject factors of task, hemisphere and electrode (Appendix B). To investigate the temporal behaviour within each domain, we performed an analysis by running a $5 \times 2 \times 7 \times 10$ repeated-measurement ANOVA, with the within-subject factors of task, hemisphere, electrode and decile (Appendix C). To compare the Pow for the temporal analysis in deciles across domains, we performed an analysis by running a $5 \times 2 \times 7 \times 10$ repeated-measurement ANOVA, with the between-subject factors of task, hemisphere, electrode and decile (Appendix D). We used only the results for the two tasks of interest from the analyses of the full data set.

3. Analysis of results

3.1. Task-related power across domains

The TRP results for the two domains and tasks are depicted in Figure 6. The radar plot simulates the two hemispheres by distributing the electrodes (10–10 I.S.) symmetrically around a vertical axis. Total TRP scores per electrode can be considered by comparing with the vertical scale and across the tasks (Figure 5). Once the problem-solving Task 1 (reference task) is subtracted from itself to produce the reference, it shows up as an orange circle with a value of zero for all electrode measurements. The difference is shown as higher or lower activation of the electrodes/regions for Task 4 within or beyond the orange circle border. The sketching Task 4 shows higher neurophysiological activation compared to the Task 1 in both domains.

3.2. Analysis of transformed power within domains

Pow results for each domain cohort are depicted in Figures 6 and 7. Pow scores per electrode (average of entire task) can be considered by comparing the vertical scale values and across the two tasks. The open sketching design Task 4 shows higher neurophysiological activation from Task 1 in both domains, Figure 6. Mechanical engineers show higher activations in the problem-solving Task 1. Detailed analysis results from running the $5 \times 2 \times 7$ repeated-measurement ANOVA for each domain are presented in Appendix B. Below, we report on significant ($p \leq 0.05$) differences, the channels of significant differences between the two tasks within domain are shown highlighted with a solid circle. The circles indicate significant

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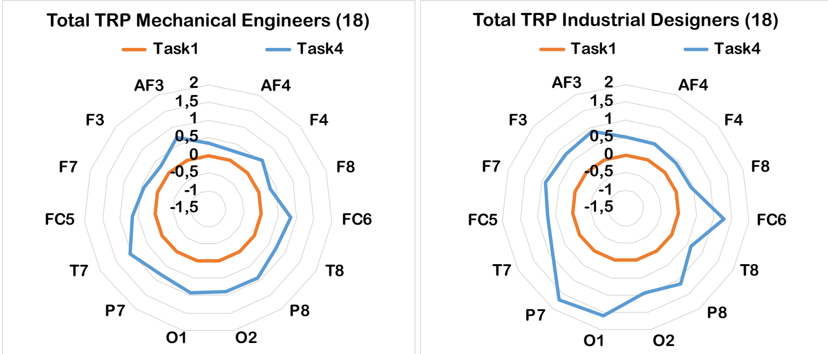

Figure 5. Radar plot of task-related power (TRP) for the 14 electrodes by taking the problem-solving Task 1 as the reference period for Task 4 for the industrial designers and mechanical engineers. The electrode labels are distributed such that all the electrodes on the left hemisphere are on the left and all those on the right hemisphere are on the right. Their labelling uses the standard 10–10 I.S.

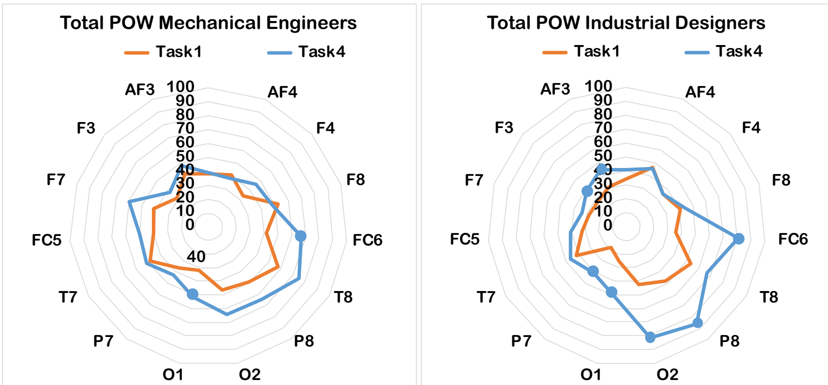

Figure 6. Transformed power (Pow) of the two tasks for each domain. The solid circles indicate channels where there are significant differences between the tasks within each domain.

differences from the pairwise comparisons that were conducted to follow up on the main effects and interaction effects.

From the analysis of the mechanical engineers the pairwise comparisons revealed that the open design sketching Task 4 does not show significantly different neurophysiological activations from problem-solving Task 1 ($p = 0.10$).

3.2.1. Significant main effects

From the analysis of the industrial designers, the pairwise comparisons revealed that the open design sketching Task 4 shows significantly different neurophysiological activations from problem-solving Task 1 ($p < 0.001$). From the analysis of each cohort, we found significant main effects per domain (Table 2).

These significant main effects related to different tasks provide evidentiary support for Hypothesis 2, as all the factors show main effects for the industrial

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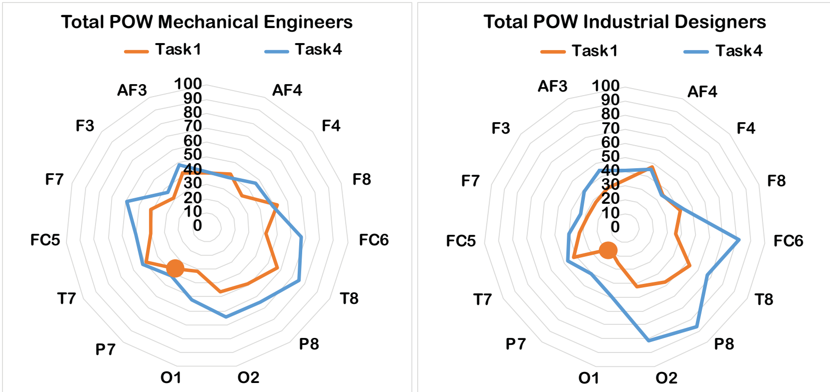

Figure 7. Transformed power (Pow) of the two tasks per domain. The solid circles indicate channels and task where there are significant differences across domains.

Table 2. Significant main effects from the ANOVA for each domain

Mechanical engineers	Industrial designers
• task ($p = 0.10$) • hemisphere ($p \leq 0.001$) • electrode ($p = 0.01$)	• task ($p < 0.001$) • hemisphere ($p < 0.001$) • electrode ($p < 0.001$)

designers, but not to Hypothesis 1, as only hemisphere and electrode show main effects for the mechanical engineers but not task. Task, hemisphere and electrode are further investigated in the temporal analysis, presented in Section 4.

3.3. Analysis of transformed power across domains

Detailed analysis results from running the $2 \times 5 \times 2 \times 7$ mixed repeated-measurement ANOVA are presented in Appendix B· We conducted pairwise comparisons to check for differences comparing the seven electrodes per hemisphere and task across domains. Below, we report on significant ($p \leq 0.05$) differences (Figure 7). The channels of significant differences per task between domains are shown highlighted with a solid circle. The circles indicate significant differences from the pairwise comparisons that were conducted to follow up on the main effects and interaction effects. The pairwise comparisons revealed that the open design sketching Task 4 shows significantly different neurophysiological activations from problem-solving Task 1 ($p < 0.01$).

3.3.1. *Significant main effects*

From the analysis of the 36 participants, we found significant main effects and significant interaction effects between multiple factors (Table 3). Of particular interest is the significant main effect related to the tasks. No significant main effect was found for the between-subjects factor domain ($p = 0.67$).

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Table 3. Significant effects from the ANOVA based on the 36 participants

Significant main effects	Significant interaction effects
• task ($p < 0.01$) • hemisphere ($p < 0.001$) • electrode ($p < 0.001$)	• domain and hemisphere ($p = 0.02$) • hemisphere and electrode ($p < 0.01$)

These significant main effects provide evidentiary support for Hypothesis 3 concerning differences between problem-solving and designing across the two domains.

4. Temporal analysis results

Designing is a temporal activity, a single value based on aggregating across an entire session hides how designing unfolds over time. Different cognitive behaviours exhibited when design sessions are divided into deciles show this temporal activity in designing (Jiang *et al.* 2014; Kan & Gero, 2017). The division of each design session's data into temporal deciles allows a more detailed analysis of the temporal dimension stages.

4.1. Problem-solving and design tasks of mechanical engineers

To compare the Pow scores for the deciles by domain, we performed an analysis by running a $5 \times 2 \times 7 \times 10$ repeated-measurement ANOVA, with the within-subject factors of task, hemisphere, electrode and decile, for each domain (Appendix C).

4.1.1. Significant main effects

From the analysis of the 18 mechanical engineers we found significant main effects and significant interaction effects between the factors shown in Table 4.

In addition, we conducted pairwise comparisons for hemisphere, electrode, decile and task.

The significant main effects for mechanical engineers relate to task and to decile and the significant interaction effect relates to task + decile. These provide evidentiary support for Hypothesis 4. For a more detailed analysis, we carried out pairwise comparisons that showed differences comparing hemispheres for the seven electrodes and tasks within each decile.

The significant ($p \leq 0.05$) pairwise comparisons found between Task 1 (problem-solving task) and Task 4 (open free hand sketching task) across the deciles (Appendix C) are shown in Figure 8. Solid circles represent the channels with activation of statistically significant differences in Task 4 from Task 1. Problem-solving Task 1 shows increased general activation in some deciles (1, 2 and 5), Task 4 shows higher variation of temporal distributions of activations across deciles.

The placement of the electrodes related to each cortex of the brain is shown in Figure 9. Higher activations of channels of the right occipitotemporal cortex and secondary visual cortex occur in Task 4. Statistically significant differences between the open sketching design Task 4 and problem-solving task, Task 1 occur in the prefrontal cortex, right temporal and visual cortices. The channels of significant differences with decreased activation from Task 4 to Task 1 are located in the prefrontal cortex.

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Table 4. Significant effects from the ANOVA based on the 18 mechanical engineers

Significant main effects	Significant interaction effects
• task ($p = 0.03$) • hemisphere ($p < 0.001$) • electrode ($p = 0.01$) • decile ($p = 0.02$)	• hemisphere and electrode ($p < 0.001$) • task and decile ($p = 0.01$) • electrode and decile ($p < 0.01$)

4.2. Problem-solving and design tasks of industrial designers

To compare the Pow scores for the deciles we performed the same analysis as for the mechanical engineers by running a 5 × 2 × 7 × 10 repeated-measurement ANOVA, with the within-subject factors of task, hemisphere, electrode and decile (Appendix C).

4.2.1. Significant main effects

From the analysis of the 18 industrial designers we found significant main effects and significant interaction effects between the factors as shown in Table 5.

In addition, we conducted pairwise comparisons for hemisphere, electrode, decile and task. The pairwise comparisons indicate that Task 4 differs significantly from:

- problem-solving Task 1 ($p < .01$)

The significant main effects for industrial designers relate to task and the significant interaction effect relates to task + decile. These provide evidentiary support for Hypothesis 5.

The pairwise comparisons showed differences comparing hemispheres for the seven electrodes and tasks within each decile. In Figure 10, we show significant ($p \leq 0.05$) pairwise comparisons found between Task 1 (problem-solving task) and Task 4 (open free hand sketching task) across the deciles (Appendix C).

Generally, higher activations of channels of the right occipitotemporal cortex and secondary visual cortex are shown in Task 4. Statistically significant differences between Task 4 and problem-solving Task 1 occur bilaterally in the dorsolateral prefrontal, temporal and visual cortices. All the channels of significant differences show increased activation from Task 1 to Task 4.

4.3. Problem-solving and design tasks across domains

Detailed analysis results from running the 2 × 5 × 2 × 7 × 10 mixed repeated-measurement ANOVA are presented in Appendix D· We conducted pairwise comparisons to check for differences comparing the 7 electrodes per hemisphere, task and decile across domains. Below we report on significant ($p \leq .05$) differences.

4.3.1. Significant main effects

From the analysis of the 36 participants we found significant main effects and significant interaction effects between multiple factors, Table 6. Of particular

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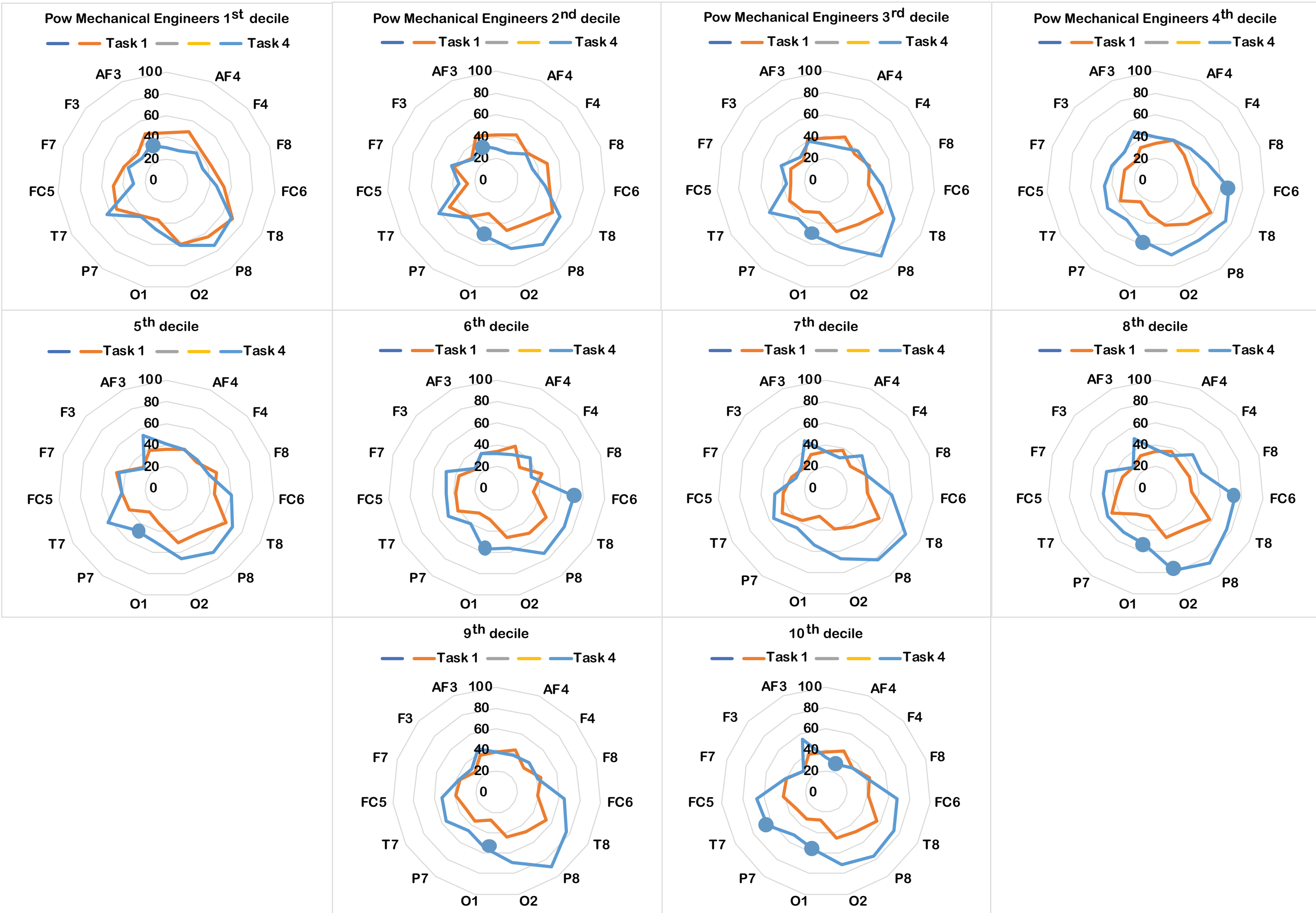

Figure 8. For mechanical engineers, channels with significant differences from Task 1 to Task 4 by decile, shown as solid circles.

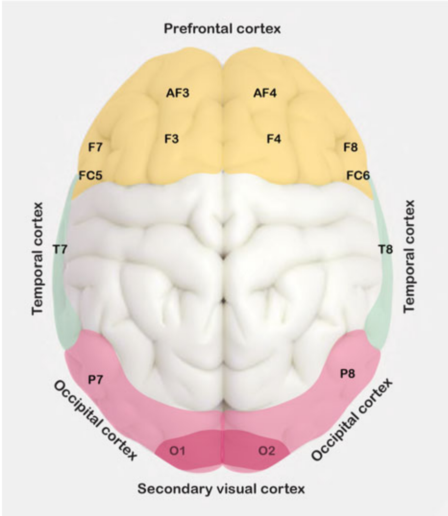

Figure 9. Electrodes placement related to each cortex of the brain.

Table 5. Significant effects from the ANOVA based on the 18 industrial designers.

Significant main effects	Significant interaction effects
• task ($p < 0.001$) • hemisphere ($p < 0.001$) • electrode ($p = 0.001$)	• hemisphere and electrode ($p < 0.01$) • task and decile ($p < 0.001$) • task and electrode ($p < 0.001$) • task and hemisphere ($p = 0.01$)

interest is the significant main effect related to deciles, task, significant interaction effects related to task + deciles and task + domain. No significant main effect was found for the between-subjects factor domain ($p = .28$).

These significant main effects relate to task and decile and the significant interaction effects relate to task and domain and task and decile provide evidentiary support for Hypothesis 6 concerning differences in temporal distributions of activations between problem-solving and designing, between tasks and across domain.

5. Discussion and conclusion

With this controlled experiment we showed evidence for significant differences between two prototypical problem-solving and open design tasks, between two cohorts from the domains of mechanical engineering and industrial design. The neurophysiological differences of task-related power between problem-solving Task 1 and the sketching Task 4, support a number of inferences:

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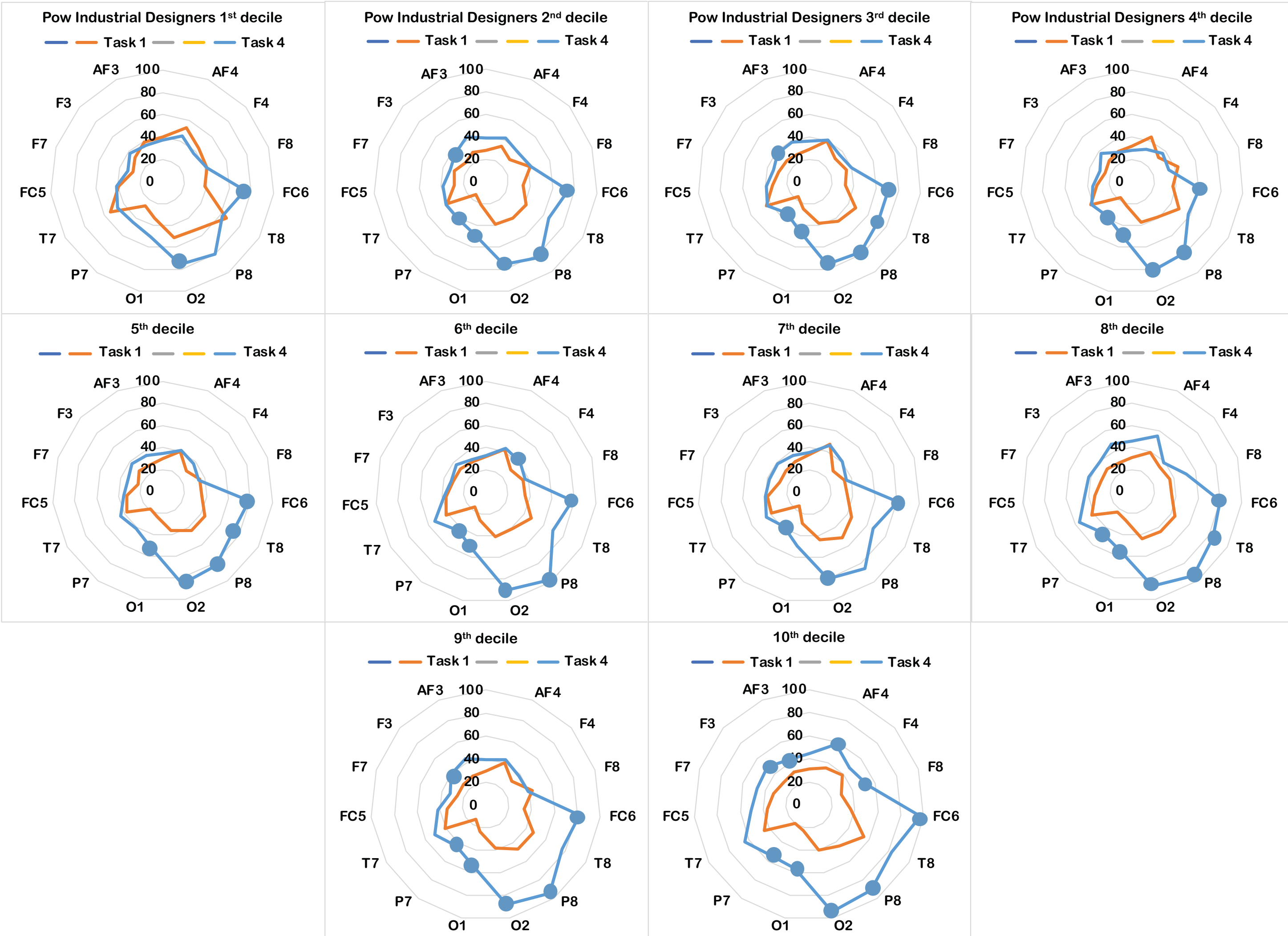

Figure 10. For industrial designers, channels with significant differences from Task 1 to Task 4 by decile, shown as solid circles.

Table 6. Significant effects from the ANOVA based on the 36 participants

Significant main effects	Significant interaction effects
• task ($p < 0.001$) • hemisphere ($p < 0.001$) • electrode ($p < 0.001$) • decile ($p < 0.01$)	• task and domain ($p < 0.01$) • task and electrode ($p = 0.01$) • task and decile ($p < 0.001$) • hemisphere and electrode ($p < 0.001$)

(i) Significant higher amplitudes in the open sketching design Task 4 for both cohorts were measured, meaning that from this study open design sketching, as expected, is the most distinguishable design activity from problem-solving thinking mode. The relevance of sketching while designing has been studied (Goldschmidt 1994; Scrivener, Ball & Tseng 2000; Kavakli & Gero 2001; Bilda, Gero & Purcell 2006). Our preliminary results show higher amplitude for sketching at the aggregate level. Further analysis of the data might reveal other aspects when comparing novices and experienced designers (Vieira *et al.* 2020*a*), categorical stages (Vieira *et al.* 2020*b*) and the conceptual categories of the participants' sketching solutions.

(ii) Dissimilar amplitude results found in the open sketching design Task 4 between domains could involve differences in the confidence in sketching, as sketching skills might differ between these mechanical engineers and industrial designers. This could have influenced the results in particular, of the channel P8, whose cognitive functions are associated with drawing (Harrington *et al.* 2007).

(iii) Dissimilar adaptive approaches can be inferred as the constraints of the magnetic elements and physical solution space of Task 1 disappeared in Task 4. Industrial designers showed higher change of activations implying a greater adaptation to the open design task. This supports prior cognitive results that show mechanical engineers do not necessarily change nor adapt their approach when constraints are reduced, and more freedom of choice is given (Jiang *et al.* 2014). Probably due to their education, mechanical engineers show higher amplitudes in channels related to deductive reasoning, F7 (Goel *et al.* 1997) and lower amplitudes in channels associated with inductive reasoning, F3 and P7 (Goel *et al.* 1997).

(iv) Hemisphere and electrode significant differences were found between the two tasks for both cohorts for all of the within-domain analyses. Channels of significant differences between Task 1 and Task 4 were found in the occipitotemporal and prefrontal cortices.

We further discuss these channels associated with Brodmann areas' specific cognitive functions and the hypotheses of this study. EEG measures electromagnetic fields generated by neural cortical activity, as a consequence no direct inferences can be made in relation to cognitive functions activity from deep sources of the brain (Sawyer 2011; Dickter & Kieffaber 2014; Hinterberger *et al.* 2014). However, we can infer that each channel is associated with the cognitive functions of the Brodmann area onto which it is mapped in the brain hemispheres. Brodmann's studies on brain cells' neuron structure and its cytoarchitecture (Brodmann 1909) have been refined

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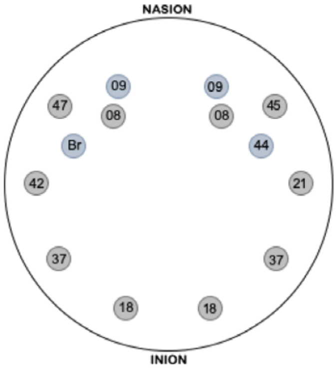

Figure 11. Approximate Brodmann areas (numbered) of the 10–10 I.S. placement system.

and correlated to various cortical functions and cognitive activities by measuring blood flow in response to different mental tasks, Figure 11.

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 (Dickter & Kieffaber 2014). Multiple magnetic resonance imaging measurements have resulted in an extended map (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).

5.1. Hypotheses

Statistically significant differences were found indicating preliminary evidence for some of the hypotheses. The results of the analysis of the EEG data of the 36 participants showed differences in the neurophysiological activity of these cohorts of mechanical engineers and industrial designers across tasks and provide initial support for five of the six hypotheses.

- *Hypothesis 1*: the neurophysiological activations of mechanical engineers when problem-solving (Task 1) and designing (Task 4) are significantly different.

Results from the repeated-measurement ANOVA for this domain do not support Hypothesis 1. For these mechanical engineers, statistically significant differences were not found between the open sketching design Task 4 and problem-solving Task 1. However, main effects were found for hemisphere and electrode. This is consistent with recent results between open-ended and constrained tasks of product design engineers where no significant differences were found (Hay *et al.* 2020). However other aspects are revealed by the temporal analysis.

- *Hypothesis 2*: the neurophysiological activations of industrial designers when problem-solving (Task 1) and designing (Task 4) are significantly different.

Results from the repeated-measurement ANOVA for the industrial designers, show statistically significant differences between the open sketching design Task 4 and the problem-solving Task 1, providing support for Hypothesis 2.

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- *Hypothesis 3:* the neurophysiological activations of mechanical engineers and industrial designers are significantly different for problem-solving and designing.

From the results of the mixed repeated-measurement ANOVA across domains, no significant main effect was found for domain, meaning that a common design ground is shared by the cohorts. However, an interaction effect between domain and hemisphere was found. These hemispheric differences will be explored in a future paper.

Statistically significant differences between the open design sketching Task 4 and the problem-solving Task 1 were found. Although differences can be found from the analysis within domain, the two cohorts as a whole, show significant differences between designing and problem-solving prototypical tasks, providing support for Hypothesis 3.

The pairwise comparisons show significant differences between the tasks in channel P7 between domains. In the left hemisphere, channel P7 maps on Brodmann area 37 involved in lexico-semantic associations and semantic categorization (Gerlach *et al.* 2000), attention to semantic relations (MacDermott *et al.* 2003), metaphor comprehension (Rapp *et al.* 2004) and deductive reasoning (Goel *et al.* 1998). It could be inferred that mechanical engineer's specific domain training sets them to prioritize some of these cognitive functions over others. The open requests of the task might not correspond to the specific nature of the requests these mechanical engineers are used to responding to. They may not be using the metaphorical and associative nature of exploring within the problem space (Goel & Pirolli 1989, 1992), nor producing a solution-focussed primary concept (Darke 1979; Cross 2006; Dorst 2011, 2015) before carrying out an analysis of the proposal. Further research is needed to elucidate this potential explanation.

Pairwise comparisons within domains revealed significant differences in two channels between the tasks. The mechanical engineers exhibit higher amplitude of FC6 in Task 4, and industrial designers start with lower amplitude of this channel in Task 1 and progressively surpass in amplitude that of mechanical engineers in Task 4. The channel FC6 is associated with the cognitive functions of Brodmann area 44. In the right hemisphere onto which it is mapped, BA 44 cognitive functions of interest are associated with goal-intensive processing (Fincham *et al.* 2002) and search for originality (Nagornova 2007). The open design requests of Task 4 prompt them to explore and plan ahead within the problem and solution space (Dorst & Cross 2001). The mechanical engineers and the industrial designers also show significant differences in channel O1, associated with the cognitive functions of Brodmann area 18. In the left hemisphere onto which it is mapped BA18 is associated with the cognitive functions of visual mental imagery (Platel *et al.* 1997) and visual word form (Vorobyev *et al.* 2004), such cognitive functions are associated with open designing.

- *Hypothesis 4:* the neurophysiological temporal distributions of activations of problem-solving (Task 1) and designing (Task 4) are significantly different for mechanical engineers.

Results from the repeated-measurement ANOVA within domain, show statistically significant difference between the open sketching design Task 4 and the problem-solving task, Task 1, across deciles for the domain of the mechanical engineers. This provides initial support for Hypothesis 4.

In addition to the channels FC6, O1 and P7, the pairwise comparisons show significant differences between the tasks across deciles for the channels AF3 (deciles 1 and 2), O2 (decile 8) and AF4 and T7 (decile 10). Channel AF3, which maps onto the left prefrontal cortex, is associated with the cognitive functions of Brodmann area 09, such as deductive reasoning (Goel *et al.* 1997) and metaphoric comprehension (Shibata *et al.* 2007). Higher activation of these areas involves semantic and pragmatic processing which differ from those in literal comprehension. The mechanical engineers show significant differences and lower amplitude in channel AF3 in Task 4 for the first two deciles inverting the tendency from decile 4.

Channel O2, which maps onto the right occipitotemporal cortex, is associated with visuo-spatial information processing (Wabersky *et al.* 2008). The mechanical engineers show significant differences for this channel only in decile 8.

In the last deciles, mechanical engineers show significant differences for channel O1 previously mentioned, and channels T7 and AF4. Mapped onto the temporal cortex of the left hemisphere, channel T7's known associated cognitive functions are not easy to relate to design cognition. However, its higher activation during visual word recognition (Pekkola *et al.* 2005) may suggest that it relates to generating internal representations of speech from reading the design request.

Mapped on the right hemisphere, prefrontal cortex, channel AF4, which is associated with the cognitive functions of coordinating visual spatial memory (Slotnick & Moo 2006), planning (Fincham *et al.* 2002) and decision-making (Rogers *et al.* 1999), shows significant differences in the last decile.

- *Hypothesis 5:* the neurophysiological temporal distributions of activations of problem-solving (Task 1) and designing (Task 4) are significantly different for industrial designers.

Results from the repeated-measurement ANOVA within domain, show statistically significant difference between the open sketching design Task 4 and the problem-solving task, Task 1, across deciles for the domain of the industrial designers. This provides initial support for Hypothesis 5.

The pairwise comparisons show significant differences between the tasks for the industrial designers across deciles. Besides channels AF4, FC6, O2, O1, P7, T7, F3, AF3 with their cognitive functions, significant differences were also found for channels F4, F8, T8 and P8, which all map onto the right hemisphere.

Channels F4 and F8, which map onto the right prefrontal cortex, show significant differences in deciles 6 and 10. Channel F4 is associated with the cognitive functions of Brodmann area 08, of executive control (Kübler, Dixon & Garavan 2006) and planning (Crozier *et al.* 1999). Channel F8 is associated with the cognitive functions of Brodmann area 45, such as response inhibition (Marsh *et al.* 2006), probably reflecting preparing to finish the task. Channel T8, which maps onto the right temporal cortex, is associated with the cognitive functions of Brodmann area 21, such as observation of motion (Rizzolatti *et al.* 1996). Industrial designers' training skills in sketching develops attention to gestures, and this translates in higher activation. Channel P8, which maps onto the right occipitotemporal cortex, is associated with the cognitive functions of Brodmann area 37, such as monitoring shape (Le, Pardo & Hu 1998), visual fixation (Richter *et al.* 2004) and drawing (Harrington *et al.* 2007). Industrial designers show significant differences for this channel in 8 of 10 deciles in which we infer they prioritize some of these cognitive functions in open design requests.

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- *Hypothesis 6:* the neurophysiological temporal activations of mechanical engineers and industrial designers are significantly different for problem-solving and designing.

Results from the mixed repeated-measurement ANOVA, revealed no significant main effect for domain. However, an interaction effect between domain and task was found and this provides initial support for Hypothesis 6.

Results from this study, in particular the results from the industrial designers, provide preliminary evidence to the initial and core research question whether designing is distinct from problem-solving (Goel & Pirolli 1989, 1992; Visser 2009) at least on the level of neurophysiological activations between a problem-solving layout task and an open sketching design task. The differences found between mechanical engineers and industrial designers in terms of activations match differences found in cognitive studies of mechanical engineers and industrial designers, where mechanical engineers did not change their cognitive behaviour related to the openness of the task, but industrial designers did (Jiang *et al.* 2014). However, a common design ground was also found for these two design activities as the analyses show no effect for domain, and significant differences between the tasks across deciles were found for both. The results from this EEG study provide an alternate form of evidence than protocol studies to support differences between problem-solving and designing.

This paper has demonstrated, through a detailed analysis of EEG data, that a low-cost EEG device can be used to produce preliminary results in design research, results capable of being used to provide initial testing of hypotheses.

5.2. Limitations of the study

The data set is from a convenience sample of volunteers who responded to the call for participants. The participants' familiarity with layout tasks and their sketching ability have the potential to influence the results. The statistical approach we described reduced the potential effects on the results of the limitations of using a low-cost EEG device. Due to the low spatial resolution of EEG the results cannot support strong claims related to location, as fields extend across the brain (Sawyer, 2011). To better identify unique brain regions associated with neural activity a larger number of EEG channels is needed or techniques that provide a higher spatial resolution are required.

5.3. Further work

Analysis of the frequency bands and temporal analysis of the EEG data is in progress to produce a more detailed articulation of the neurophysiological activations of these cohorts of mechanical engineers and industrial designers and to relate them to published results (Nguyen & Zheng 2010; Vecchiato *et al.* 2015; Liu *et al.* 2016; Liang *et al.* 2017).The results we already have allow for the comparison between domains at multiple levels of details. These comparisons will be the subject of a future paper. More data needs to be collected to understand the extent of EEG data for design studies. Think-aloud protocols of individuals and design teams are being collected separately while measuring EEG responses. Further research is needed for the removal of artefacts due to speech and motor skeletal bursts without removing signals that result from cognitive actions. If successful, the cleaned data would allow for the direct temporal matching of design cognition, derived from think-aloud protocol, with neurophysiological measurements, opening up a new research direction for neurocognitive research in design studies.

More research connecting brain region activations and cognitive functions is needed to make design neurocognition a research tool that supersedes such cognitive research tools as protocol analysis.

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Appendix A

Instructions given to the participants for and in between tasks.

Pre-task

1.1 Ask participant to: “Please start by reading the text after I say OK.”
1.2 Ask participant to: “Please touch the orange end button in the board after concluding each task.”

Task request: Please arrange the components so that:

(i) the hairdryer has a complete mechanism,
(ii) each component is in its functional place and
(iii) the hairdryer has a closed surface.

First task break: “we have this game for you to play while I prepare the board for the next task.”

Task 1

1.3 Ask participant to: “Please start by reading the text after I say OK.”
1.4 Ask participant to: “Please touch the orange end button in the board after concluding each task.”

Task request: Please arrange the furniture so that:

(i) the bed is in the corner of the room with the head on the west,
(ii) the wardrobe is next to the door and next to the bed and
(iii) the desk is under the window.

Second task break: “please continue playing the game while I prepare the board for the next task.”

Task 2

1.5 Ask participant to: “Please start by reading the text after I say OK.”
1.6 Ask participant to: “Please touch the orange end button in the board after concluding each task.”

Task request: Please arrange the furniture so that:

(i) the room is functional,
(ii) the room is comfortable and
(iii) it has at least a bed, a wardrobe and a desk.

Third task break: “please continue playing the game while I prepare the board for the next task.”

Task 3

1.7 Ask participant to: “Please start by reading the text after I say OK.”
1.8 “Both boards are available.”
1.9 Ask participant to: “Please touch the orange end button in the board after concluding each task.”

Task request: Please arrange a space and its furniture so that:

(i) it uses some or all of the wall elements, the door, window and balcony,
(ii) it uses some or all of the furniture and
(iii) privacy is important for the sleeping area.

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Interview 1 – Ask participants the following questions:

1. How satisfied are you with the result of the third task?
2. Did you experience difficulties?
3. How did you determine your trajectories in each task performed?
4. How did you implement your design strategy if you used one?

Fourth task break: "please continue playing the game while I prepare the board for the next task."

Task 4

1.10 Ask participant to: "Please start by reading the text after I say OK."
1.11 Inform the participant: "You have 10 min for this task. I will let you know 3 min before the end with a hand sign."
1.12 Ask participant to: "Please touch the orange end button in the board after concluding each task."

Task request: Please propose and represent an outline design for a future personal entertainment system.

Interview 2 – Ask participants the following questions:

1. How satisfied are you with the result of the fourth task?
2. Did you experience difficulties?
3. How did you determine your trajectories in the task performed?
4. How did you implement your design strategy if you used one?

Appendix B

To compare the Pow of mechanical engineers we performed an analysis by running a $5 \times 2 \times 7$ 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: *hemisphere*, $F(1, 17) = 16.88$, $p \leq 0.001$, $\eta^2_{\text{partial}} = 0.50$; and electrode, $F_{GG}(2.85, 48.44) = 3$, $p < 0.01$, $\eta^2_{\text{partial}} = .15$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.89$). The pairwise comparisons revealed that Task 4 does not differs significantly from Task 1 ($p = 0.11$). In addiction the pairwise comparisons revealed that some electrodes were significant between Task 1 and Task 4, namely, in the left hemisphere electrode O1($p = 0.02$) and in the right hemisphere electrode FC6($p = 0.04$).

To compare the Pow of industrial designers we performed an analysis by running a $5 \times 2 \times 7$ 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*, $F(4, 68) = 5.95$, $p < 0.001$, $\eta^2_{\text{partial}} = .26$; hemisphere, $F(1, 17) = 43.25$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.72$; and electrode, $F(6, 102) = 4.51$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.21$. The pairwise comparisons revealed that Task 4 differs significantly from Task 1 ($p < 0.001$). In addiction the pairwise comparisons revealed that some electrodes were significant between Task 1 and Task 4, namely, in the left hemisphere electrodes AF3 ($p = 0.03$), F3 ($p = 0.03$), P7 ($p < 0.001$) and O1 ($p < 0.001$) and in the right hemisphere electrodes FC6 ($p = 0.03$), P8 ($p = 0.01$) and O2 ($p < 0.001$).

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To compare the Pow of industrial designers and mechanical engineers, we performed an analysis by running a 2 × 5 × 2 × 7 mixed repeated-measurement ANOVA, with the between-subjects factor domain and the within-subject factors task, hemisphere and electrode. From the analysis of the 36 participants (18 industrial designers and 18 mechanical engineers) we found a significant main effect of: task, $F_{GG}(3.03, 102.87) = 5.50$, $p < 0.01, \eta^2_{partial} = 0.14$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.76$)' hemisphere, $F(1, 136) = 59.05$, $p < 0.001, \eta^2_{partial} = 0.64$ and for electrode, $F_{GG}(3.80, 129.35) = 6.49$, $p < 0.001, \eta^2_{partial} = 0.16$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.63$). Moreover, the ANOVA revealed a significant interaction effect between the factors: domain and hemisphere, $F(1, 136) = 5.92$, $p = 0.02, \eta^2_{partial} = 0.15$; and hemisphere and electrode, $F_{GG}(3.34, 113.56) = 4.36$, $p < 0.01, \eta^2_{partial} = 0.11$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.56$). In addition, we conducted pairwise comparisons to check for differences between industrial designers and mechanical engineers comparing the seven electrodes per hemisphere and task. Below we report on significant ($p \leq 0.05$) comparisons. The following comparisons were significant in the left hemisphere for Task 1, electrodes P7($p = .03$) and in the right hemisphere for Task 3, electrode FC6 ($p = 0.03$).

Appendix C

To compare the Pow scores for the deciles we performed an analysis by running a 5 × 2 × 7 × 10 repeated-measurement ANOVA, with the within-subject factors of task, hemisphere, electrode and decile, per domain. From the analysis of the 18 mechanical engineers we found a significant main effect of: task, $F(4, 68) = 2.95$, $p = 0.03$, $\eta^2_{partial} = 0.15$; hemisphere, $F(1, 17) = 48.64$, $p < 0.001$, $\eta^2_{partial} = 0.74$; electrode, $F(6, 102) = 2.89$, $p = 0.01$, $\eta^2_{partial} = 0.15$) and decile $F_{GG}(4.29, 72.94) = 3.09$, $p = 0.02$, $\eta^2_{partial} = 0.15$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.48$). Significant interaction effects were found between the factors: hemisphere and electrode, $F_{GG}(6, 102) = 6.59$, $p < 0.001$, $\eta^2_{partial} = 0.27$); task and decile, $F(36, 612) = 1.65$, $p = 0.01$, $\eta^2_{partial} = 0.09$; electrode and decile, $F(54, 918) = 1.58$, $p < 0.01$, $\eta^2_{partial} = 0.09$. In Table C1 we report on significant ($p \leq .05$) pairwise comparisons found between Task 1 and Task 4 (open free hand sketching design) across the deciles.

To compare the Pow scores for the deciles we performed an analysis by running a 5 × 2 × 7 × 10 repeated-measurement ANOVA, with the within-subject factors of task, hemisphere, electrode and decile, per domain. From the analysis of the 18 industrial designers we found a significant main effect of: task, $F_{GG}(2.56, 43.49) = 8.67$, $p < 0.001$, $\eta^2_{partial} = 0.34$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.64$); hemisphere, $F(1, 17) = 88.77$, $p < 0.001$, $\eta^2_{partial} = 0.84$; and electrode, $F_{GG}(3.86, 65.53) = 3.98$, $p = 0.001$, $\eta^2_{partial} = 0.19$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.64$). A marginally significant main effect was found for decile, $F(9, 153) = 1.83$, $p = 0.07$, $\eta^2_{partial} = 0.10$. Significant interaction effects were found between the factors: task and hemisphere, $F_{GG}(2.12, 35.98) = 5.09$, $p = 0.01$, $\eta^2_{partial} = 0.23$) (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.53$); task and electrode, $F(24, 408) = 3.44$, $p < 0.001$, $\eta^2_{partial} = 0.17$; task and decile, $F(36, 612) = 2.31$, $p < 0.001$, $\eta^2_{partial} = 0.12$); and hemisphere and electrode, $F(6, 102) = 3.26$, $p < 0.01$, $\eta^2_{partial} = 0.16$. In Table C2, we report on significant ($p \leq 0.05$) pairwise

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Table C1. Pow significant differences for electrodes between Tasks 1 and 4 per decile of mechanical engineers (p value)

Decile	AF4	F4	F8	FC6	T8	P8	O2	O1	P7	T7	FC5	F7	F3	AF3
1														
2				<0.01										
3								0.02						
4							0.03	0.05	0.05					
5									0.02					
6				0.03				0.02						
7														
8		0.04		0.04				<0.01						
9						0.02	<0.01	<0.01						
10	0.04			0.05			0.03	<0.01	0.03					

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Table C2. Pow significant differences for electrodes between Tasks 1 and 3 and Tasks 1 and 4 per decile of industrial designers (p value).

Decile	AF4	F4	F8	FC6	T8	P8	O2	O1	P7	T7	FC5	F7	F3	AF3
1				<0.01			0.01							
2				<0.01	0.03	<0.01	<0.01	<0.01	<0.01				0.01	
3				<0.01		0.02	<0.01	0.02	<0.01				0.04	
4				0.05		<0.01	<0.01	<0.01	<0.01					
5				<0.01	<0.01	<0.01	<0.01	<0.01	<0.01					
6		0.05		0.02		<0.01	<0.01	<0.01	<0.01					
7				<0.01			<0.01	<0.01	<0.01					
8				<0.01	0.03	<0.01	<0.01	<0.01	<0.01					<0.01
9				<0.01		<0.01	<0.01	<0.01	<0.01				0.03	
10	<0.01		<0.01	<0.01		<0.01	<0.01	<0.01	<0.01					

comparisons found between Task 1 (problem-solving) and Task 4 (open free hand sketching design) across the deciles.

Appendix D

To compare the Pow scores for the deciles of industrial designers and mechanical engineers, we performed an analysis by running a 5 × 2 × 7 × 10 repeated-measurement ANOVA, with the between-subjects factor domain and the within-subject factors of task, hemisphere, electrode and decile. From the analysis of the 36 participants (18 industrial designers and 18 mechanical engineers) we found a significant main effect of: task, $F_{GG}(3.01, 102.41) = 7.07$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.17$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.75$); hemisphere, $F(1, 34) = 134.64$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.80$; electrode, $F_{GG}(4.53, 153.88) = 6.06$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.15$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.75$); and decile $F_{GG}(6.29, 213.79) = 2.91$, $p < 0.01$, $\eta^2_{\text{partial}} = 0.08$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.70$). No significant main effect was found for domain, $F(1, 34) = 1.16$, $p = 0.29$,$\eta^2_{\text{partial}} = 0.03$. Moreover, the ANOVA revealed a significant interaction effect between the factors: task and domain, $F(4, 136) = 4.39$, $p < 0.01$, $\eta^2_{\text{partial}} = 0.11$; task and electrode, $F_{GG}(9.02, 306.80) = 2.40$, $p = 0.01$, $\eta^2_{\text{partial}} = 0.07$ (corrected for Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.38$); task and decile, $F(36, 1224) = 2.33$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.06$; and hemisphere and electrode, $F(6, 204) = 8.62$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.20$. No other significant main effect nor interaction effect between the factors was found. There was no adjustment for multiple comparisons.

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Table D1. Transformed power (Pow) significant differences for electrodes between Tasks 1 and 4 per decile (p value) for the 36 participants.

Decile	AF4	F4	F8	FC6	T8	P8	O2	O1	P7	T7	FC5	F7	F3	AF3
1	0.03													
2				0.02		<0.01	<0.01	<0.01						
3				<0.01		<0.01	<0.01	<0.01						
4				<0.01		0.04	<0.01	<0.01						
5				<0.01		0.04	<0.01	<0.01	<0.01					
6				<0.01		<0.01	<0.01	<0.01	<0.01					
7				<0.01			<0.01	<0.01	<0.01				0.05	
8				<0.01		<0.01	<0.01	<0.01	<0.01		0.03			<0.01
9				<0.01	0.05	<0.01	<0.01	<0.01	<0.01				0.05	
10				<0.01		<0.01	<0.01	<0.01	<0.01	0.03	0.02		0.04	

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