Design Spaces: Neurophysiological Activations in Constrained and Open Design Tasks

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Design space is a common abstraction in design research used in the investigation of design cognition. Although its usefulness has been alleged and has contributed to the knowledge about designing, characteristics and properties of design spaces and how they change while designing are underexplored. Creativity has been recognized as an essential skill for changing the design space from constrained to open spaces. We analyzed the brain activity of designers while performing constrained and open design tasks. This study investigates the neurophysiological activations of professional mechanical engineers and industrial designers in two prototypical design tasks, a problem-solving constrained layout task and an open design sketching task. The analysis focused on comparing the neurophysiological activations of the cognitive demand in three stages of categorical similarity of designing in constrained and open design spaces. Results indicate significant differences of frequency bands activations between stages of the design spaces across and between domains. In particular, the stage of reflecting evoked visual imagination and associative reasoning modes and revealed significant differences in beta bands from the problem-solving stage leading to expanded activation in the sketching stage, which translates in higher activation in the open design task with significant differences in upper alpha and beta bands. We propose the neurophysiological activations as a measure of the pliability of design spaces.

Keywords: *Design space, open space, constrained space, mechanical engineers, industrial designers*

1. INTRODUCTION

The notion of design spaces has its origin in the formation of the problem space and it has been subject of investigation and debate for the last 60 years. In the problem space theory of problem-solving (Newell & Simon, 1972) developed in the field of information processing theory and based on the General Problem Solver computer program (1957), new constraints, subgoals and design alternatives evoked from long-term memory in the problem space leading to shifts in external memory representations, such as models and drawings, would be considered as changes of the problem space. The problem solver retrieval system, whether a human or a system of computational capacities, would continually modify and characterise the problem space while searching for solutions. By then, the distinction between well and ill-defined problems (Reitman 1964), or well and ill-structured problems (Newell 1969) were thought to be dependent on the problem-solving methods and techniques available to the problem solver. This dependency on the problem solver capacities gave origin to the notion that there are no well-structured problems, only ill-structured problems formalized for problem solvers (Simon 1973) within the extent of their limited capacities, and according to the problem's goals, constraints and generated alternatives.
An alternative approach to cognitive design theory, later emerged as reflective practice (Schön 1983; 1987). In this approach the designer by thinking and doing, therefore by knowing in action (Argyris et al. 1985), would construct the design world and set the dimensions of the problem space and the moves by which he/she would attempt to find solutions (Schön, 1992). The situated cognition research approach (Clancey 1997) then emerged spanning many disciplines and objectives related to social sciences, behavioural and dynamic neural processes to perspectives of knowledge and action, supporting the idea that learning takes place when and individual is doing something. The term situated emphasized that perceptual mechanisms causally relate human cognition to the environment and action. Being situated involves a causal coupling in the moment within internal organizing and between internal and external organizing, changing things in the world. New ways of seeing and ways of making changes to the world develop together in time. As a research approach, situated cognition disclosure emerged as appropriate to investigate human cognition in design (Gero 1990). Design is a temporal and multimodal activity that asks for appropriate solutions to requests, which are situated, and when these requests are open, asks for problem finding and problem framing (Runco 1994; Runco and Nemiro, 1994) before the problem-solving stage takes place. In the last 40 years alternative views to the problem-solving space emerged with focus on the ultimate purpose for change, the solution-space.

1.1 Design Spaces

A useful abstraction in understanding designing has been the notion of design space, where designers explore an abstract space of possibilities (Amstel et al. 2016; MacLean et al. 2011) of which the problem-solving view of design claims that the designing process commences with an exploration within the problem space (Goel & Pirolli, 1992; Goel 1994; Goldschmidt, 1997) while others claim that designing commences by generating the solution space (Dorst, 2019; Dorst & Cross 2001; Gero, 1990; Gero & Kumar, 1993; Kruger & Cross 2006; Visser 2009; Yoshikawa, 1981). Both views have been used in design cognition studies based on methods such as protocol analysis (Goldschmidt, 2014; Kan & Gero, 2017). Another view is the notion that the design space can be constrained or open, depending on the design request's level of constraint and openness to creative exploration and that is the focus of the research reported in this paper. While a constrained design space is usually confined by specific requirements, an open design space expands by the introduction of new design variables leading to solutions which may not have been possible earlier. This can occur where constraints are in conflict and hence there are no feasible solutions and a better design is desired or when the designer introduces new variables as part of the design process. In both cases a new solution space emerges (Gero & Kumar, 1993; Mose Biskjaer & Halskov, 2013). These views have helped thinking about one of the core design research questions, when and whether designing, as a cognitive process, is distinct from problem-solving (Goel and Pirolli, 1989; 1992; Visser 2009).

Some perspectives support that intrinsically motivated creative performances rely on problem finding an important component of creativity, and distinct from problem-solving (Runco 1994). Problem finding involves related skills such as problem identification, problem definition, and also problem expression, problem construction, problem generation and eventually problem discovery (Runco and Nemiro, 1994). These are characteristic stages of designing in open design spaces. In problem finding, the generation of problems, though related to ideation is distinct from the ideation in problem-solving. Recursive interactions occur more often in problem finding. Other perspectives on the dynamics of designing and how the problem-finding process unfolds have been studied. The notion of co-evolution between the problem space and the solution space (Maher & Poon 1996; Dorst & Cross 2001; Dorst, 2019) has been another view consistent to the notion of design as situated cognition.

In design research, constrained and open design tasks are often used in experiments on the basis that they evoke different design behaviors. As part of a larger experiment, we test this claim by studying the brains neurophysiological activations of professional designers' while designing for constrained and open design tasks. By comparing two prototypical tasks, we used methods from the neurosciences to measure and test how far the neurophysiological activations may possibly be used as a measure of the change and expansion in design spaces.

1.2 Neuroscience of Creative cognition and Design neurocognition

Recent paradigm shifts in creativity assessment in neuroscience research highlight that neural responses of cognitive processes cannot be observed in isolation from other ongoing processes (Benedek et al. 2018). These ideas support pairing neuroscience methods with well-established behavioral paradigms during ecologically-valid, real-world design tasks to improve the understanding of design cognition (Chrysikou & Gero, 2020) and design creativity (Goldschmidt 2018; Gero 2020).

Creative cognition (Finke, Ward & Smith, 1992; Smith, Ward & Finke, 1995) has been investigated in several fields of science (i.e. Psychology, Cognitive Science, Design, Neuroscience) for the last 30 years with relevant developments in the understanding of executive functions, memory, attention and cognitive control (Benedek & Fink, 2019).

Both creativity and design are drivers of innovation, social and cultural progress, crucial for economic sustainability and well-being, but they are not identical. Design is high-level cognition involving multimodal behaviour (Park & Alderman (2018) and as a thinking process influences activities across multiple domains within and beyond design. Creativity is defined as the ability to generate novel and effective ideas (Runco & Jaeger, 2012), or artifacts that are new, surprising, and valuable (Boden 2004).

Design cognition (Eastman 1970; Lloyd, Lawson & Scott, 1996; Eastman 2001; Cross 2001; Akin 2001; Oxman 2001), has been investigated based on macro perspectives (Hay, Cash & McKilligan, 2020), by distinguishing phases or stages of designing from theoretical models (i.e Kannengiesser & Gero, 2019; Kan & Gero 2017). Investigations of design related neural processes have emerged in the last two decades originating the recent field of design neurocognition (Vieira 2018; Gero 2019). Comprehensive (Borgianni & Maccioni, 2020) and synthetic (Gero & Milanovich 2020) literature reviews have recently enlightened the research contributions. For the purpose of this paper, we focus on the literature using the electroencephalographic (EEG) technique for assessing neurophysiological measurements in design and creativity research.

Neurocognitive studies using EEG started more than 40 years ago, by investigating cortical activation during multiple creative tasks (Martindale & Hines, 1975), differences as a function of creativity, stage of the creative process and originality (Martindale & Hasenfus 1978), and then 20 years later a study on experts and novices (Göker, 1997), a topic recently revisited from other perspectives (Liang, Chang & Liu, 2019; Vieira et al. 2020a). Single domain-related design studies (Nguyen & Zeng, 2010; Liu et al., 2016; Liang et al., 2017; Liu et al., 2018; Vieira et al. 2019a), and domain effect comparative studies of mechanical engineers and architects (Vieira et al, 2019b), and mechanical engineers and industrial designers (Vieira et al. 2020b) were developed.

In the neuroscience of creative cognition comprehensive literature reviews have focus on topics relevant to design research, such as, visual creativity, the generation of novel and useful mental visual imagery, which may lead to the production of novel and useful visual forms (Dietrich & Kanso, 2010; Pidgeon et al. 2016; Aziz-Zadeh, Liew & Dandekar, 2013); gender, creative potential and cognitive strategy (Abrahams 2016), creativity assessment ((Benedek et al, 2019), executive functions (Benedek & Fink, 2019) and brain networks (Beaty et al. 2016; Beaty & Kennett, 2020).

Neural processes associated with general creativity have been widely investigated (Goel & Vartanian, 2005; Dietrich & Haider, 2017; Benedek et al. 2018; Benedek & Fink, 2019; Abrahams, 2019). We highlight results relevant to the investigation of constrained and open design spaces. Higher neurophysiological activation is traditionally associated with conceptual expansion implying a creative change in the approach to the request (Abrahams, 2019). The integration of creativity and intelligence in the evolving creative problem-solving process of requests that ask appropriate solutions in open problem spaces (Jaarsveld et al. 2015; Benedek, Jung & Vartanian, 2018). Cognition requires the ability to adjust modes of thought to match the demands of each problem situation (Gabora, 2002).

Neuroscience of creative cognition studies using the EEG technique are usually based on the analysis of frequency bands. About 20 years ago, oscillatory neuroelectric activity of delta, theta, alpha and gamma frequency bands were proposed to act as resonant communication networks through large populations of neurons, with functional relations to memory and integrative functions (Bas ̧ar et al. 1999). Complex stimuli would elicit superimposed oscillations of different frequencies (Bas ̧ar 1998). Although neglected in the early 90’s, in the last decades most studies focus on the alpha frequency band. Increased alpha at prefrontal sites is considered to be an indication of the cognitive processes implicated in ill-defined problem spaces (Fink & Benedek, 2014; Fink et al., 2009a). Higher alpha band is thought to be more sensitive to specific task-related requirements, while the lower alpha band is associated with attention processes such as vigilance and alertness (Klimesch, 1999). Increased alpha in temporal and occipital areas and over prefrontal sites are associated with visualization processes and complex information processing, respectively (Jaarsveld et al. 2015). Increases in prefrontal alpha have been interpreted as reflecting high internal processing demands or the inhibition of task- irrelevant processes enfolding within ill-defined problem spaces (Fink & Benedek, 2014). Relevant studies of frequency bands of interest to the present study (theta, alpha and beta waves) andlts on cognition, creative cognition and design neurocognition from the last 35 years are summarized, Table 2.

Table 2. Functions associated to brain waves in cognition, creative cognition and design neurocognition

Brain wave	**Cognition**	**Creative cognition**	**Design neurocognition**
Beta 3 (20-28 Hz)	Beta oscillations reflect a default state interrupted by encoding and decoding (of primates) in memory tasks (Lundqvist et al. 2016) Emotional and cognitive processing (Ray & Cole 1985)	Beta rythms depend on creative ability and gender in creative figural tasks (Volf & Tarasova, 2009)	Visual attention (Liang et al. 2018) Increased beta 3 in open design tasks of layout and sketching (Vieira et al. 2020b)
Beta 2 (16-20 Hz)	Higher beta 2 in emotional and cognitive processing (Ray & Cole 1985) analytic problem solvers show greater frontal beta-band activity (Erickson et al. 2018)	Beta 2 oscillations associated to creativity in men and women in verbal creative tasks (Razumnikova, Volf & Tarasova, 2010) Decreased beta 2 in men with high originality scores (OS) and increased beta 2 in women with high OS, in creative figural tasks (Volf & Tarasova, 2009; 2010) insightful problem solvers show greater left parietal beta 2 (Erickson et al. 2018)	Increased beta 2 in open design tasks of layout and sketching (Vieira et al. 2020 dcc)
Beta 1 (13-16 Hz)			Increased beta 1 in decision-making of constrained tasks and convergent thinking (Nguyen & Zeng, 2010) Increased beta 1 in open design tasks of layout and sketching (Vieira et al. 2020b)
Alpha 2 (10-13 Hz)	sensitive to specific task-related requirements (Fink & Benedek, 2014) visualization processes in temporal and occipital areas and complex information processing, over prefrontal sites (Jaarsveld et al. 2015a) top-down processing in convergent and divergent thinking (Benedek et al. 2011) increases in right parietal cortex reflects focused internal attention (Benedek et al. 2014) controlled memory retrieval induces bilateral synchronization (Klimesch, 2012) desynchronization in long-term (semantic) memory demands (Klimesh 1996, 1999) alpha oscillations facilitate association mechanisms in several brain structures (Basar et al. 1999) divergent cognitive processing (Fink et al. 2007; Jauk et al. 2012)	higher prefrontal alpha reflects high internal processing or the inhibition of task irrelevant processes in ill-defined problem spaces (Fink & Benedek, 2014) in creative ideation (Fink and Benedek, 2014; Stevens and Zabelina, 2019) U-shaped function of task-related alpha power reflects distinct stages of the creative thinking process (Schwab et al. 2014) increased top-down control in occipital areas during imagination of spatial features before transferring mental conceptualization into a physical drawing (Jaarsveld et al. 2015) ***Decreased alpha in visual mental imagery in high and low-creative groups (Pidgeon et al. 2016)*** ***Increased alpha in mental elaboration of drawings (Rominger et al. 2018)*** insightful solvers show higher alpha-band activity (Erickson et al. 2018) Alfa oscillations in temporal dynamics of divergent thinking (Agnoli et al. 2020)	open ended tasks and Divergent thinking (Nguyen & Zeng, 2010) Visual association (Liang et al. 2018) Increased alpha 2 in open design tasks of layout and sketching. Key role from problem-solving to designing (Vieira et al. 2020b) Alpha oscillations in alternate processing of demanding visual imagery tasks of graphic artists (Sviderskaya, Taratynova & Kozhedub 2006)
Alpha 1 (7-10 Hz)	Attention processes such as vigilance and alertness (Klimesh 1999) Internally directed attention (Cohen 2017) Information processing, inhibition and timing, attention and semantic orientation (Klimesh 2012) Inhibition-time hypothesis (Klimesh 2007) Attentional demands (Ray & Cole 1985)	Alfa oscillations in the temporal dynamics of divergent thinking (Agnoli et al. 2020) Increased alpha in creative thinking interpreted as a sign of active cognitive processes rather than cortical idling (Fink et al. 2009) -For both alpha-	
Theta (4-7 Hz)	Increased theta in short-term (episodic) memory demands (Klimesh 1996; 1998) Increased theta in encoding new information (Klimesh 1999) theta oscillations related to cognitive processing and cortico-hippocampal interaction (Basar et al. 1999) selective attention (Basar et al. 1992) theta oscillations related to alertness, arousal and motor behavior (Basar et al. 1998a; Basar et al. 1998b) error monitoring and cognitive control (Cohen 2017)	Decreased mid-frontal theta power in lower levels of top-down control (Wokke, Ridderinkhof & Padding 2018) insightful solvers show increased left-temporal theta-band (Erickson et al. 2018)	Increased theta in decision-making of constrained tasks and convergent thinking (Nguyen & Zeng, 2010) Increased theta in open design tasks of layout and sketching (Vieira et al. 2020b)

In design research, frequency bands have been used as a measurement tool to compare visual thinking spent during solution generation with solution evaluation (Liu et al. 2018), and associate with design activities, in particular, beta 2, gamma 1 and gamma 2 (Liu, Zeng & Hamza, 2016). Higher alpha power has been found to be associated with open ended tasks and divergent thinking, while theta and beta power have been found to be associated to convergent thinking in decision-making and constraints tasks (Nguyen & Zeng, 2010). Higher beta power has been associated with visual attention and higher alpha power with visual association in expert designers (Liang et al. 2018). Higher alpha, theta and beta frequency bands have been found to play a key role in open design tasks (Vieira et al. 2020c).

1.3 Research Question and Approach

This paper describes a study on constrained and open design from a larger research project whose goal is to investigate EEG neurophysiological activation of designers across multiple design domains (Vieira et al. 2019). The aim of the study is to investigate the neurophysiological activation differences of mechanical engineers and industrial designers when designing for constrained layout task and designing for an open task using an EEG headset in the context of performing the tasks in a laboratory setting. The experiment was previously reported (Vieira et al. 2020) in a comparative study on domain effect, based on total signal of the tasks, and temporal analysis of deciles. In this paper, we divide the two tasks on three stages and perform the analysis of the EEG signal frequency bands. To understand brain activity in constrained and open design spaces we took a macro perspective, by distinguishing stages of categorical similarity between the two tasks, namely:

- Reading, the stage in which the designers read the request in both tasks.
- Problem-solving, the stage in which participants strictly answer to the request of locating three pieces of furniture in the constrained task, and reflecting, the stage in which the designers think about the request of the open design task.
- Layout, the stage in which the designers completing the layout design in the constrained design task, and sketching, the stage in which the designers can unrestrictedly sketch and generate the outline designs for the open design task,.

We explore the observable and measurable differences of the neurophysiological activations between the problem-solving request and the open design task. The analysis focuses on the neurophysiological activation differences observed along the three different stages of the execution of the tasks. By temporally segmenting these activations for each participant, it is possible to distinguish brain activation across design sessions and between the three stages. We investigate the following research question:

- *What are the differences in the neurophysiological activations of the cognitive demand of mechanical engineers and industrial designers when reading, problem-solving and layout in a constrained design task, and reading, reflecting and sketching in an open design sketching task?*

2. METHODS

The research question is investigated by using the constrained problem-solving task as the control and statistically comparing the open design task with the reference task. In this study we compare absolute values known as transformed power (Pow) further described. The tasks and experimental procedure were piloted prior to the full study, which produced changes resulting in the final experiment design (Vieira et al. 2020).

2.1 Participants

Results are based on 32 right-handed participants, 15 mechanical engineers, aged 25-43 (M = 28.4, SD = 4.7), 10 men (age M = 29, SD = 5.5) and 5 women (age M = 27.2, SD = 2.7); and 17 industrial designers, aged 25-50 (M = 33.1, SD = 8.9), 9 men (age M = 35.7, SD = 8.6) and 8 women (age M = 30.4, SD = 8.8). The participants are all professionals (experience M = 6.4, SD = 6.2). The result of the unpaired t-test controlling for experience between cohorts revealed not statistically significant, $F(1.0, 30)=2.1$, $p=.08$. This study was approved by the local ethics committee of the University of XXX.

2.2 Experiment Tasks Design

We adopted and replicated the constrained task based on problem-solving layout design described in the Alexiou et al. (2009) fMRI-based study. We matched the constrained task in terms of requests, number of constraints, stimuli and number of instructions. This task is considered a problem-solving task as the problem itself is well-defined, and the set of solutions is unique (Alexiou et al., 2009). We designed a block experiment which consisted of a sequence of tasks previously reported (Vieira et al., 2020). We added an open design task that included free hand sketching. This task is an ill-defined and fully unconstrained task unrelated to formal problem-solving. For this paper the focus is on the neurophysiological activations of frequency bands of the three stages of both the constrained design task based on problem-solving and the open design task based on free hand sketching, Table 1.

Table 1. Description of constrained and open design spaces.

Constrained design Task based on Problem-solving	**Open design Task based on design sketching**
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 the free-hand sketching Task 4, the participants are asked to: propose and represent an outline design for a future personal entertainment system

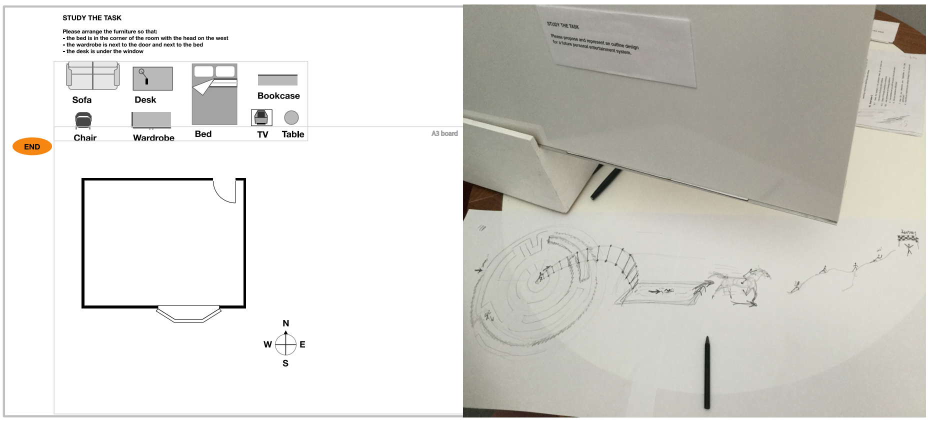


Fig. 1 Depiction of the problem-solving Task 1and open free hand sketching design Task 4.

2.3 Setup and Procedure

A tangible interface for individual task performance was built based on magnetic material for easy handling. The setup, full sequence of tasks and complete procedure is described elsewhere (Vieira et al. 2020). Electromagnetic interference of the room was checked for frequencies below 60Hz. One researcher was present in each experiment session to instruct the participant and to check for recording issues. A period of 10 minutes for setting up and a few minutes for a short introduction were necessary for informing each participant, reading and signing of the consent agreement and to set the room temperature. The researcher followed a script to conduct the experiment so that each participant was presented with the same information and stimuli. The participants were asked to start by reading the task request which took an average of 10s. The participants were asked to stay silent during the tasks and use the breaks for clarifying questions. In the open sketching task, each participant was given two sheets of paper (A3 size) and three instruments, a pencil, graphite and a pen.

2.4 Equipment

The present study uses a low-cost EEG device for measuring the neurophysiological activations during constrained and open design tasks of the experiment session of each participant. When compared to medical grade systems, the limitations of low-cost systems, namely physical stability, multiplexed acquisition of electrodes, lower space resolution and more data loss do not have significant effects on what we are measuring, where we are interested not in specific episodes but average behavior over time while performing certain activities. This device requires proper setup, reliable and good enough to report results. Although the low-cost EEG devices have lower signal to noise ratio potentially resulting in lower quality of the signals, the signal processing and artifacts removal methods, and statistical approach used in post-processing, compensate for these potential effects.

2.5 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. Each of the Emotiv Epoc+ channel collects continuous signals of electrical activity at their location.

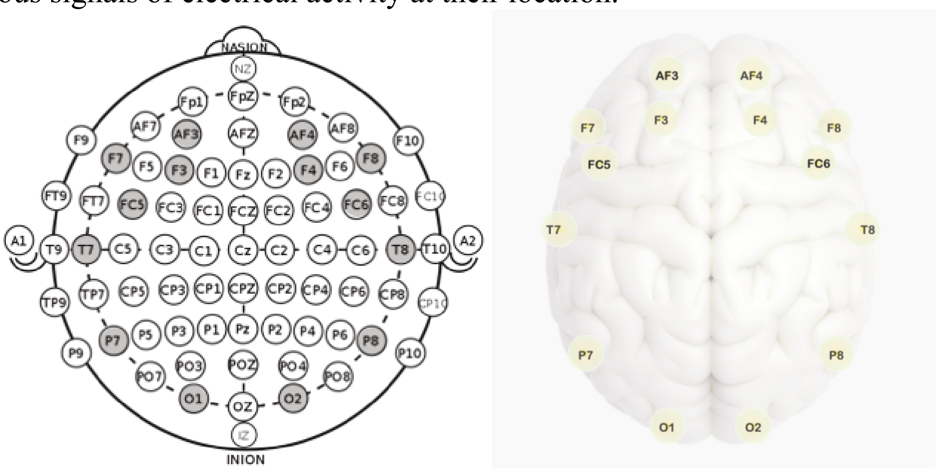


Fig. 2 Electrodes placement according to the 10-10 I.S in the brain cortex.

Electroencephalography records electrical brain activity with electrodes placed along the scalp. 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 by having similar spatial orientation their ions line up and create waves to 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). EEG measures electromagnetic fields generated by this neural activity. EEG offers high temporal resolution in the order of milliseconds in a portable device which makes it a highly suitable tool to investigate designing as a temporal activity.
The participants performed the tasks, with two video cameras capturing the participant's face and activity. All the data captures were streamed using Panopto software

(https://www.panopto.com/). Sessions took place at the University of Porto, between March and July of 2017 and June and September of 2018 in the Design Hub of Mouraria, Lisbon, during August 2018 between 9:00 and 15:00.

2.6 Data Processing Methods

The fourteen electrodes were disposed according to the 10-10 I.S, 256 Hz sampling rate, low cutoff 3.5 Hz, high cutoff 28 Hz. We adopted the blind source separation (BSS) technique based on canonical correlation analysis (CCA) for the removal of muscle artifacts from EEG recordings (De Clercq, 2006; Vos et al. 2010) adapted to remove the short EMG bursts, attenuating the muscle artifact contamination of the EEG recordings. Data processing includes the removal of Emotiv specific DC offset with the Infinite Impulse Response (IIR) filter and BSS-CCA. The BSS-CCA procedure successfully filters 90% of the signal from artefacts. The data were visually checked for the remaining artifacts, and artifactual epochs caused by muscle tension, eye blinks or eye movements were excluded from further analysis. A z-score was conducted in parallel to this procedure and applied to each frequency band. The decomposition of the EEG signal followed tthe typical component frequency bands and their approximate spectral boundaries, theta (3.5–7 Hz), alpha 1 (7–10 Hz), alpha 2 (10–13 Hz), beta 1 (13–16 Hz), beta 2 (16–20 Hz) and beta 3 (20–28 Hz). By the adoption of lower and upper alpha boundaries, and the beta waves, we expect to find results that can be related to the literature in other domains.

Data analysis included power values of frequency bands on individual and aggregate levels using MatLab and EEGLab open-source software. All the EEG segments of the recorded data were used for averaging throughout the segments corresponding to each of the stages in analysis. We report on one measurement, the transformed power (Pow) for each frequency band. 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 stage, frequency band and participant. This measure tells us about the amplitude of the signal per channel and per participant magnified to absolute values. After a z-score 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 below -2.81 for each stage of the two tasks and each frequency bands. To avoid extreme outliers in the EEG data only stages with activation periods of at least 2s artifact-free EEG recording were used for statistical analyses. We present frequency bands Pow values on aggregates of the 32 participants' individual results, per each stage of each task.

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 stage, hemisphere and electrode as within-subject factors and domain as the between-subjects factor. These analyses were performed for the dependent variable of Pow, for all the within-subject variables, and participants (N=32). The threshold for significance in all the analyses is $p \leq .05$. To compare the Pow of the six stages of the two domains we performed an analysis by running a 2x6x2x7 repeated-measurement ANOVA, with the within-subject factors of stage, hemisphere and electrode and with the between-subjects factor domain for each frequency band. To compare the Pow of the six stages of each task within domain we performed an analysis by running a 6x2x7 repeated-measurement ANOVA, with the within-subject factors of stage, hemisphere and electrode for each frequency band. Results are based on the analyses of the three sets of stages of categorical similarity.

3. ANALYSIS OF RESULTS AND DISCUSSION

Results from the analysis of transformed power (Pow) of each frequency band indicate that stages of the constrained and open tasks can be distinguished from each other. We look at the cognitive demand of each stage and how it translates in brain activation. These aspects are further described in the analysis of frequency bands and Brodmann areas. Brodmann's studies (1909) on brain cells' neuron structure, function and connectivity have been refined and correlated to various cortical functions and cognitive activities (Glasser et al. 2016). Through the analysis of the stages of categorical similarity across and within domains we connect the results to the literature on cognitive functions identified in studies using fMRI and positron emission tomography (PET).

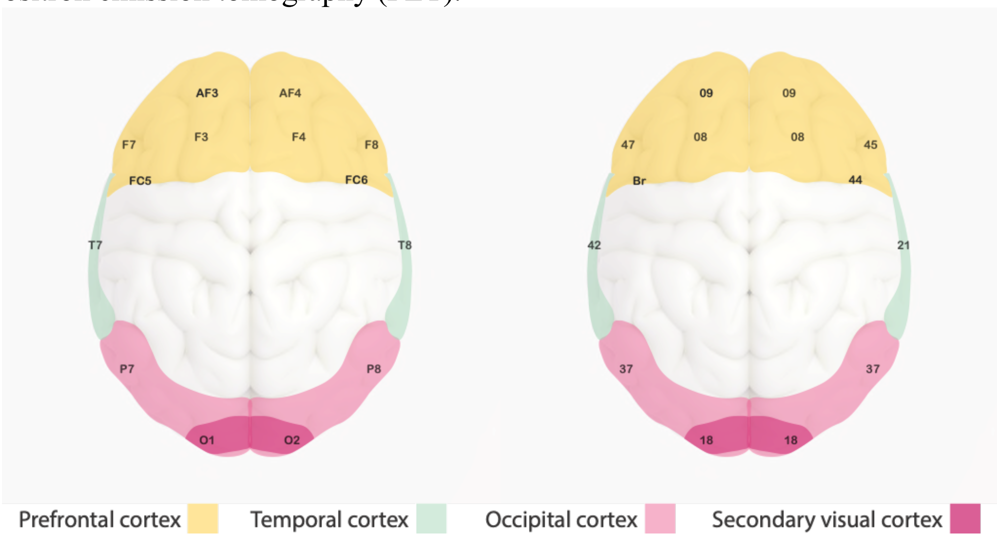


Fig. 3 (a) Electrodes placement related to each cortex of the brain and (b) corresponding Brodmann areas.

3.1 Stages of Categorical Similarity across Domains

Results from running the 2x6x2x7 mixed repeated-measurement ANOVA revealed no significant main effect for the between-subjects factor domain (Table 2). An interaction effect is found between hemisphere and domain for beta 3. Main effects for the within subjects' variables of stage, are found for upper alpha and beta bands and for hemisphere and electrode across all the six bands.

From the analysis of the three stages of categorical similarity across domains the pairwise comparisons revealed significant differences between the problem-solving stage of the constrained design and the reflecting stage of the open design for lower and upper beta frequency bands. The pairwise comparisons also revealed significant differences between the layout stage of the constrained design and the sketching stage of the open design, across all frequency bands except theta. No significant differences were found between the reading stages of both tasks for the considered range of frequency bands.

Total transformed power (Pow), for each comparison across the 14 channels and frequency bands of significant differences between stages are further described and illustrated.

Table 2. Significant main effects from the ANOVAs (2x6x2x7)

Frequency band	Theta	Alpha 1	Alpha 2	Beta 1	Beta 2	Beta 3
Between-subjects factor	.657	.058	.113	.167	.168	.732
Domain interaction effect	-	-	-	-	-	*Domain + hemisphere <.01**
stage	.194	.081	*.02**	*<.001**	*<.001**	*<.001**

hemisphere	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**
electrode	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**
stage and hemisphere	*.010**	*<.001**	*<.01**	*<.01**	.594	.308
stage and electrode	.362	*.029**	*<.01**	*.018**	.080	.078
hemisphere and electrode	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**
Reading constrained design differs from open design	.214	.218	.644	.221	.915	.291
Problem-solving differs from Reflecting	.217	.111	.086	***<.001****	.080	***<.001****
Layout differs from Sketching	.250	***.045****	***<.001****	***.001****	***<.001****	***<.001****

* p≤.05

3.1.1 Problem-solving and Reflecting

The two cohorts share significant differences in beta 1 and beta 3 frequency bands between the problem-solving stage of the constrained design space and the reflecting stage of the open design space. The plots show the two hemispheres by distributing the electrodes (10-10 IS) symmetrically around a vertical axis, (Figures 4 and 5). Pow scores per electrode (average of entire stage) can be considered by comparing with the vertical scale and across stages and domain. All the channels of significant differences show higher activation in the reflecting stage of the open design task (Figures 4 and 5).

The two cohorts share significant differences in the channels O1, O2 and P8 in beta 1, and P7 and O1 in beta 3. The channel O1, is associated with the cognitive functions of BA 18 such as visual mental imagery (Platel et al. 1997) inherent to open designing and reflected in beta 1 and beta 3. Significant differences in beta 1 are also revealed in the channel O2, also associated with the cognitive functions of BA 18 such as visuo-spatial information processing (Wabersky et al. 2008) and channel P8, associated with the cognitive functions of BA 37, such as monitoring shape (Le, Pardo & Hu 1998) and drawing (Harrington et al. 2007). Significant differences in beta 3 are revealed in the channel P7 associated with the cognitive functions of BA 37, of 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).

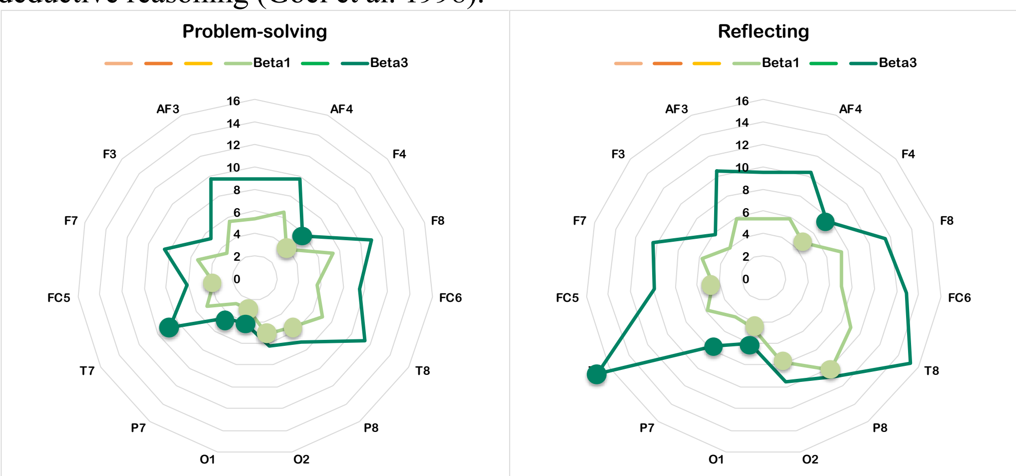


Fig. 4 Transformed power (Pow) across channels of beta 1 and beta 3 frequency bands of the stages problem-solving and reflecting of mechanical engineers. The solid circles represent the channels of significant differences (p≤.05).

The cohort of mechanical engineers also revealed significant differences in beta 1 and Beta 3, for the channel F4 associated with the cognitive functions of BA 08, of executive control (Kübler, Dixon & Garavan 2006) and planning (Crozier et al. 1999). The channel FC5 associated with the cognitive functions of Broca’s area, BA 45, known for being involved in complex verbal functions, reasoning processes (Goel et al. 1997; 1998) and metaphor processing (Rapp et al. 2004) in beta 1.

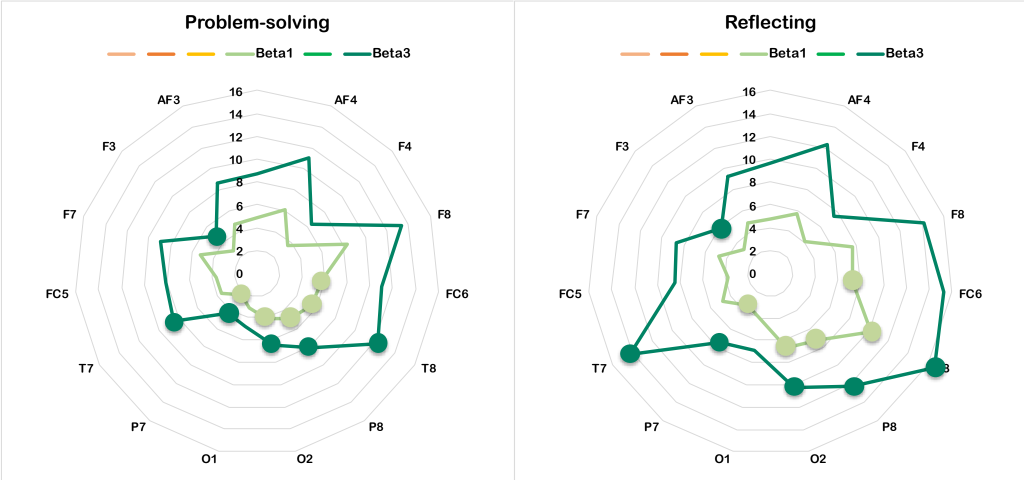


Fig. 5 Transformed power (Pow) across channels of beta 1 and beta 3 frequency bands of the stages problem-solving and reflecting of industrial designers. The solid circles represent the channels of significant differences (p≤.05).

The cohort of industrial designers also revealed significant differences in the channel F3 associated with the cognitive functions on BA 08, as inductive reasoning, F3 (Goel et al. 1997) and in the 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) in beta 1 and beta 3. Significant differences in beta 1 are also revealed in the channel FC6, and for beta 3 in the channels O2 and P8. The channel FC6 is associated with the cognitive functions of Ba 44, namely goal-intensive processing (Fincham et al. 2002) and search for originality (Nagornova 2007). Significant differences occur in channels of the occipitotemporal cortices, and specific channels of the prefrontal and dorsolateral cortices for each cohort (Figure 6).

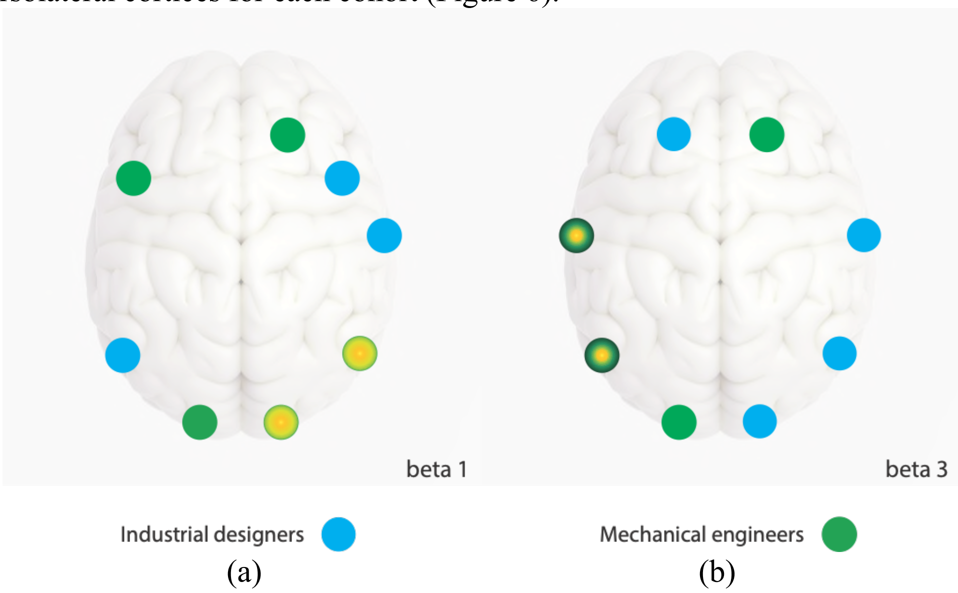


Fig. 6 Channels of significant differences (p≤.05) between the stages of problem-solving and reflecting, of beta 1 (a), and beta 3 (b) frequency bands, for both domains. Solid blue and green circles represent channels specific to industrial designers and mechanical engineers respectively.

Significant differences in beta 1 are dominant in the right hemisphere, in particular for the industrial designers supporting the main effect revealed for stage and hemisphere (Table 2). While channels of significant differences in beta 3 have a mirror distribution.

3.1.2 Layout and sketching

The two cohorts share significant differences in alpha 2, beta frequency bands between the layout stage of the constrained design space and sketching of the open design space (Tables 3 and 4). All the channels of significant differences show higher activation in the open design task (Figures 7 and 8). Shared significant differences in alpha 2 are revealed in the channels P7, O1, O2, P8, T8 mapped onto the occipitotemporal cortices (Figure 9). Shared significant differences in alpha beta 1 are revealed in the channels FC6 and P8, beta 2, FC6, P8, O2, P7, T7, FC5, F7, and beta 3, T8, P8, O2, P7, T7, F7 and F3. In addition to the cognitive functions previously described, the channel F7 is associated with the cognitive functions of BA 47, deductive reasoning and semantic processing (Goel et al. 1997).

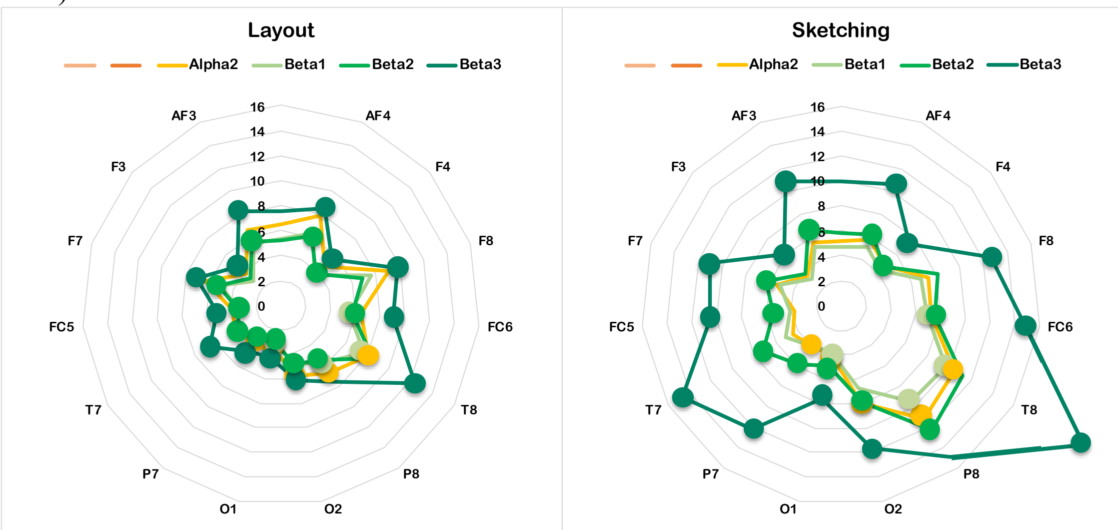


Fig. 7 Transformed power (Pow) across channels of alpha 2, beta 1, beta 2 and beta 3 frequency bands of the stages layout and sketching of the mechanical engineers. The solid circles represent the channels of significant differences (p≤.05).

The cohort of mechanical engineers also revealed significant differences in beta 1, for the channel T8 and O1, beta 2, O1, AF3, AF4 and F4, and beta 3, AF3, AF4, F4, F8 and FC6. The mechanical engineers reveal higher activation of alpha 2 in the right prefrontal cortex when compared with the industrial designers in the layout stage. The channel AF4 is associated with the cognitive functions of BA 09 of coordinating visual spatial memory (Slotnick & Moo 2006), planning (Fincham et al. 2002) and decision-making (Rogers et al. 1999).

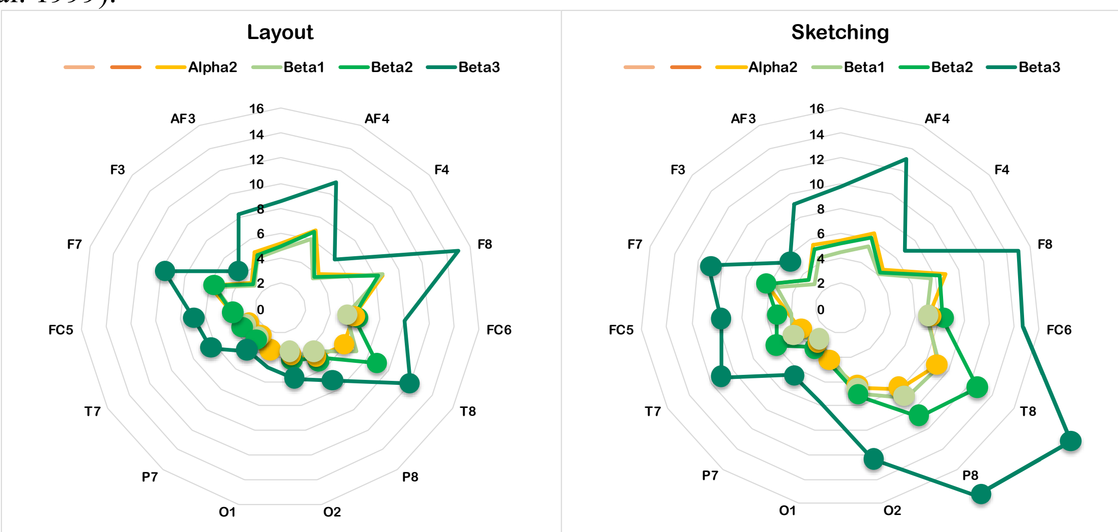
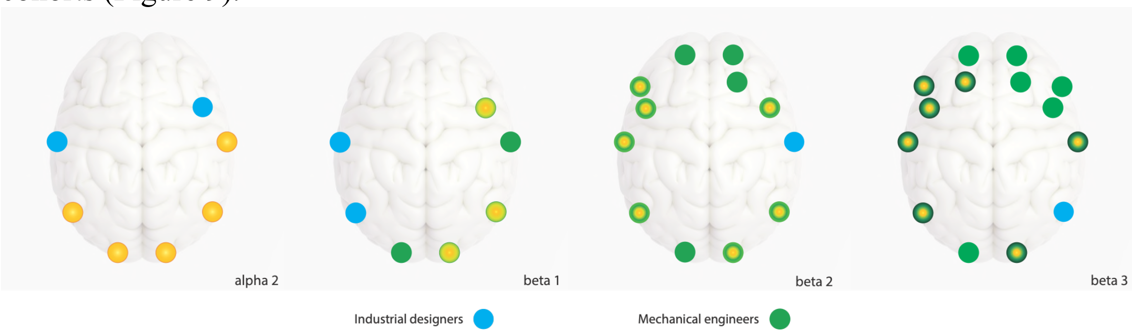


Fig. 8 Transformed power (Pow) across channels of higher alpha, beta 1, beta 2 and beta 3 frequency bands of the stages layout and sketching of the industrial designers. The solid circles represent the channels of significant differences (p≤.05).

The cohort of industrial designers also revealed significant differences in the channel T7 for alpha 2 and beta 1. The channel FC6 also shows significant differences in the upper alfa band. The channels P7 and O2 also shows significant differences in lower beta band, and the channel T8 in beta 2. The industrial designers reveal higher activation of beta 3 in the right prefrontal cortex when compared with the mechanical engineers in the layout and sketching stages. Expanded general activation of alpha 2, and beta bands are consistent for both cohorts, from constrained to open design spaces. Channels of significant differences are mapped onto the electrodes' placement in the scalp for both cohorts (Figure 9).



(a) (b) (c) (d)

Fig. 9 Channels of significant differences (p≤.05) between the stages layout and sketching, of alpha 2 (a), beta 1, beta 2 and beta 3 frequency bands, for both domains. Solid blue and green channels are specific of industrial designers and mechanical engineers.

Channels of significant differences in alpha 2 are dominant in the right hemisphere and in particular for the industrial designers. Shared significant differences in beta 1 are dominant in the right hemisphere, in particular for the mechanical engineers. Shared significant differences in beta 2 occur in 7 channels distributed in both hemispheres. Shared significant differences in beta 3 occur in 7 channels of which five are located in the left hemisphere. These hemispheric differences support the interaction effects between stage and hemisphere for alpha 2, beta 1 and beta 3 (Table 2).

3.2 Stages of Categorical Similarity within Domains

From the statistical analyses within each domain reveal no further results for the mechanical engineers and specific results further inform the design space expansion for the cohort of industrial designers.

3.2.1 Mechanical Engineers

Results from running the 6x2x7 mixed repeated-measurement ANOVA revealed significant main effects of the within subjects' variable of stage for beta bands (Table 3).

Table 3. Significant main effects from the ANOVAs (6x2x7)

Frequency band	Theta	Alpha 1	Alpha 2	Beta 1	Beta 2	Beta 3
stage	.601	.507	.266	.048*	<.01*	.001*
hemisphere	<.001*	<.001*	<.001*	<.001*	.001*	<.01*
electrode	<.001*	<.001*	<.001*	<.001*	<.001*	<.001*
stage and hemisphere	.310	.033*	.012*	.315	.986	.913
stage and electrode	.607	<.001*	<.01*	<.01*	.161	.055
hemisphere and electrode	<.001*	<.001*	<.001*	.011*	.001*	<.001*
Reading constrained design differs from open design	.374	.374	.709	.353	.888	.470

Problem-solving differs from Reflecting	.571	.652	.175	***.015****	.630	***.013****
Layout differs from Sketching	.585	.430	***.049****	***.02****	***<.001****	***<.001****

* *p≤.05*

Interaction effects were found between the within subjects' variables of stage and hemisphere on alpha bands, and between stage and electrode on beta bands and across all bands for hemisphere and electrode. The pairwise comparisons revealed significant differences between the problem-solving and the reflecting stages and the layout and the sketching stages between the constrained design and the open design tasks for the frequency bands previously described.

3.2.2 Industrial Designers

Results from running the 6x2x7 mixed repeated-measurement ANOVA revealed significant main effect for the within subjects' variable stage also for the beta bands (Table 4). Interaction effects between the within subjects' variables of stage and hemisphere are found for four theta, alpha 1, beta 1 and beta 3, between stage and electrode, for alpha 1, and between hemisphere and electrode across all frequency bands.

Table 4. Significant main effects from the ANOVAs (6x2x7)

Frequency band	Theta	Alpha 1	Alpha 2	Beta 1	Beta 2	Beta 3
stage	.369	.106	.110	***.050****	***<.01****	***<.001****
hemisphere	<.001*	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**
electrode	<.001*	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**
stage and hemisphere	*.035**	*<.01**	.071	*.013**	.080	.047*
stage and electrode	.618	.325	.098	.169	*<.01**	.088
hemisphere and electrode	*<.001**	*<.001**	*<.001**	*<.001**	*<.001**	*<.01**
Reading constrained design differs from open design	.377	.412	.781	.456	.659	.448
Problem-solving differs from Reflecting	.245	***<.01****	.283	***<.01****	***<.01****	***<.01****
Layout differs from Sketching	.132	***.025****	***<.01****	***.012****	***.001****	***<.001****

* *p*≤.05

The pairwise comparisons revealed significant differences between the problem-solving stage of the constrained design and the reflecting stage of the open design space, for alpha 1 and beta 2, in addition to the differences reported in 3.1.1. Channels of significant differences mostly in the occipitotemporal cortices are known for visual imagery and associative cognitive functions as previously mentioned.

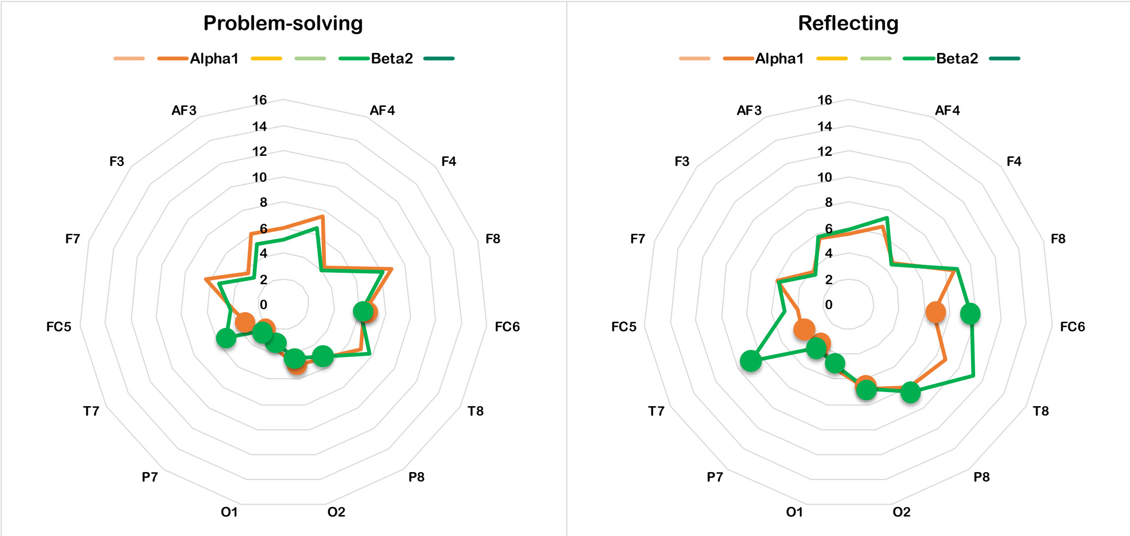
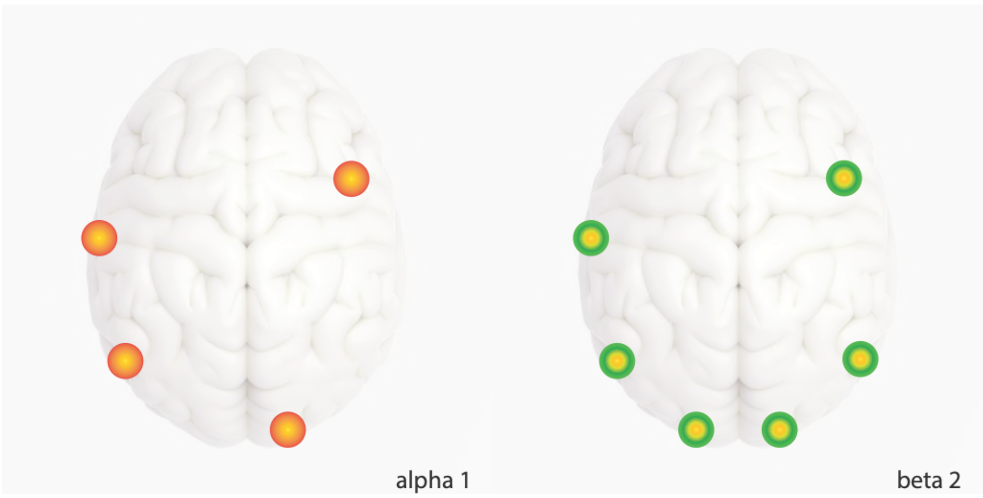


Fig. 10 Transformed power (Pow) across channels of beta 1 and beta 3 frequency bands of the stages problem-solving and reflecting of the industrial designers. The circles represent the channels of significant differences (p≤.05).

Significant differences in alpha 1 and beta 2 have bilateral hemispheric location and occur in channels of the dorsolateral, temporal and secondary visual cortices.



(b) (b)

Fig. 11 Channels of significant differences (p≤.05) between the stages problem-solving and reflecting, of alpha 1 (a), beta 2 frequency bands of industrial designers.

The pairwise comparisons also revealed significant differences between the layout stage of the constrained design and the sketching stage of the open design, for alpha 1 in addition to the differences reported in 3.1.2.

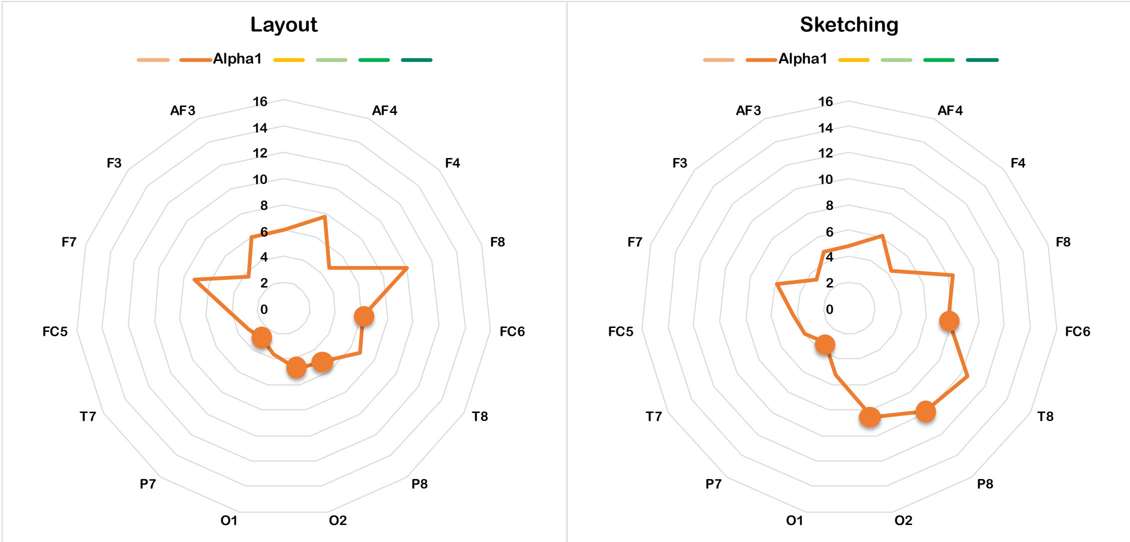


Fig. 12 Transformed power (Pow) across channels of alpha 1 and beta 2 frequency bands of the stages layout and sketching of the industrial designers. The solid circles represent the channels of significant differences (p≤.05).

Significant differences in alpha 1 are more dominant in the right hemisphere and occur in channels of the dorsolateral, temporal and secondary visual cortices. These channels show higher activation in the stage of the open design task.

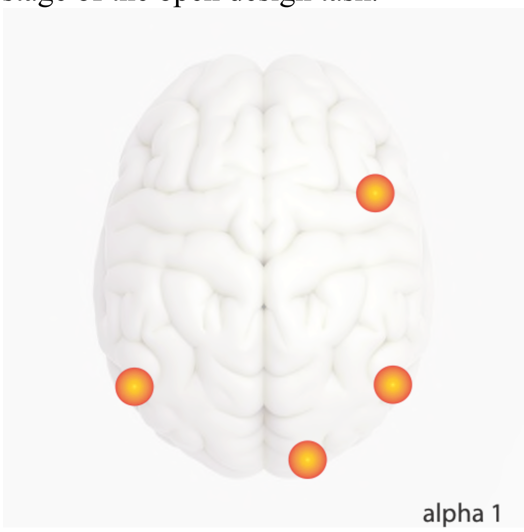


Fig. 13 Channels of significant differences (p≤.05) between the stages layout and sketching of alpha 1 frequency band of industrial designers.

4. CONCLUSION

Results show significant differences between the neurophysiological activations of the constrained and the open design spaces shared by both cohorts. The neurophysiological activations in the brains of these 32 designers showed expanded activations in the open design task compared to the constrained design task. From the results of the analysis of the categorical stages between the tasks, we can infer the following:

- In the constrained design task, all the participants followed the three conditions in the request. While in the open design task, some participants infringed the request, by considering entertainment a social activity rather than personal and by substantiating their solutions on preferred activities rather than future ones. The infringement of these conditions in the open design task heightened the possible transformation and expansion of the open design space (Reitman 1964).

- Problem-solving a constrained request or reflecting on open requests can evoke different levels of conceptual expansion, prompting designers to change their solution space, which translates in expanded activation in the open design task. The way designers formulate their understanding of the problem and solution plays a significant role in shaping constrained and open design spaces.
- Problem-solving a constrained task and reflecting about an open task, revealed differences in channels associated with visual imagination and associative cognitive functions of the occipital and temporal cortices that seem to support designers expanding the design spaces.
- The absence of significant differences in upper alpha, between the problem-solving and reflecting stages, is consistent with previous findings on decreased alpha in visual mental imagery in high and low-creative groups (Pidgeon et al. 2016). Visual mental imagery, defined as an experience of sensory information without a direct external stimulus, relies heavily on the visual cortex (Stevens & Zebelina 2019; Pearson 2014; Sparing et al. 2002).
- Sketching in the open design task shows higher amplitudes when compared to the layout stage. Cognitive functions of channels of the temporal and occipital cortices with the highest activations seem to play a role in sketching along with significant differences in upper alpha and beta bands. The significant differences in upper alpha, between the layout and sketching stages is consistent with findings of increased alpha in mental elaboration of drawings (Rominger et al. 2018).
- Sketching in the open design task shows the highest amplitudes for the beta bands, in particular of beta 3, where channels of significant differences are noteworthy in the left prefrontal cortex. The process of idea generation has been generally understood as a state of focused internally-directed attention involving controlled semantic retrieval for which left prefrontal regions may subserve the flexible integration of previous knowledge for the construction of new and creative ideas (Benedek et al. 2014).

Results also show significant differences between the neurophysiological activations of the constrained and the open design spaces particular of the industrial designers, namely for alpha 1 in stages of the open task, and beta 2, in the stage of reflecting.

Taking the approach that creativity is associated with opening the space of possible designs, amongst other changes, this experiment has shown that neurophysiological activations can be used as a measure of the change and expansion in design spaces. We asked participants to design for a highly constrained task which, we infer, results in a constrained design space and then to design for an open task which results in an open design space. Both tasks differently prompt ideational skills, self-expression and creative potential. We postulate the neurophysiological activation as a measure of the plasticity of the design spaces.

The design neurocognition field emerges promises to further the understanding of the acts of designing and perhaps a more in-depth distinction of creativity in the mental processes associated with designing.

Limitations of the Research

The knowledge level of the participants and the variability of their EEG signals acquired are variables which we cannot fully control. The statistical approach we described and the signal processing treatment reduced the potential effects on the results of the limitations of the 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, PET or fMRI techniques that provide a higher spatial resolution are required.

Future Work

The results we have allowed the exploration of the neurophysiological activations of frequency bands as one of the possible dimensions for assessing design space. We infer that the designers' neurophysiological activations translate the expansion or contraction of the design space from the analysis of two prototypical tasks. Further experiments would be necessary to test and assess other possible measures of design spaces. More data needs to be collected to understand the extent of variation in EEG data for design studies. The ongoing analysis of think-aloud protocols of related experiments collected while measuring EEG responses can bring further enlightenment.

Acknowledgements

To come

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