Design Spaces and EEG Frequency Band Power in Constrained and Open Design

Design space is a common abstraction in design research used in the investigation of design cognition. Characteristic properties of design spaces and how they change are underexplored. Design spaces can vary with the design task and the task constraints, which are assumed to result in differences in relevant neuro-cognitive processes. This paper presents the results of analyzing the brain activity, measured using EEG, of 32 professional mechanical engineers and industrial designers while performing constrained and open design tasks. The neurophysiological activations during three stages, namely, reading the task, earliest reaction, and open externalization while designing in constrained and open design tasks are compared based on EEG frequency band power. Results indicate significant differences between constrained and open tasks for the beta frequency bands in the earliest reaction stage, in areas of the brain associated with the cognitive functions of semantic associations, planning and executive control. The first reaction in the open design request results in higher and significantly different brain activations from the first reaction produced in the constrained design task. Significant differences were also found in the alpha 2 and beta frequency bands of higher brain activation in the open externalization stage, for areas of the brain associated with visual mental imagery, search for originality, goal-intensive processing, planning and executive control. We show that EEG brain activation is sensitive to the level of constraints in designing, in particular alpha 2 and beta bands can act as proxies of the change and expansion of design spaces.

Keywords: *design spaces, constrained and open design, electroencephalography, mechanical engineers, industrial designers, design spaces index*

1. INTRODUCTION

Constrained and open design tasks are often used in experiments on the basis that they evoke different design behaviors framing distinct design spaces. In this paper we test this claim by using electroencephalography technique (EEG) measurements to explore frequency band power associated with brain activation of professional designers, while designing in constrained and open design tasks, and use these measurements as a proxy for constrained and open design spaces.

The notion of design spaces has its origin in the formation of the problem space and has been a subject of investigation and debate for the last 60 years. In the problem space theory of problem-solving (Newell & Simon, 1972) new constraints, subgoals and design alternatives evoked from long-term memory 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 (General Problem Solver, Newell, Shaw & Simon, 1959), whether a human or computer, would continually modify and characterise the problem space while searching for solutions. The use of methods and techniques available for tackling ill-structured problems (Simon, 1973) would vary within the extent of the designer's limited capacities, and according to the problem's goals, constraints and generated alternatives. An alternative approach to problem solving later emerged as reflective practice (Schön, 1983; 1987). The designer, by thinking and doing (knowing in action), 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 (Argyris et al., 1985; Schön, 1992). The situated cognition research approach (Clancey, 1997) elaborated the idea that learning takes place when an individual is doing something. The term s*ituated* emphasized that perceptual mechanisms causally relate human cognition to the environment and action. Being situated involved a causal coupling in the moment within internal organizing and between internal and external organizing, while changing things in the world. As a research approach, situated cognition was suitable to investigate design cognition (Gero, 1990). Design, seen as a temporal activity that generates appropriate solutions to situated and open requests framing the designer's mental space, would require constructs such as problem finding (Simon, 1995) before problem-solving takes place (Runco, 1994; Runco & Nemiro, 1994). In the last 40 years, alternative views to the problem-solving space emerged with the focus on the ultimate purpose for change, the solution space.

1.1 Design Spaces

The notion of design space, where designers explore an abstract space of possibilities, has been a useful abstraction in understanding designing (Amstel et al., 2016; MacLean et al., 2011). The problem-solving view of design claims that the designing process commences with an exploration within the problem space (Goel, 1994; Goel & Pirolli, 1992; 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). Perspectives on the dynamics of designing and how it unfolds such as co-evolution between the problem space and the solution space (Dorst, 2019; Dorst & Cross, 2001; Maher & Poon, 1996) has been another view consistent to the notion of design as situated cognition (Gero & Kannengiesser, 2004).

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 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. The design space expands, or a new solution space emerges (Gero & Kumar, 1993; Mose, Biskjaer & Halskov, 2013).

The problem-solving space view was shown to be incomplete with Schön's work (Schön, 1983) and later when in creativity research problem finding was identified as an important component of creative performances, and distinct from problem-solving (Abdulla et al., 2020; Runco, 1994). Problem finding was considered related to skills such as problem identification, problem definition, and also problem expression, problem construction, problem generation and eventually problem discovery (Runco & Nemiro, 1994). Similar characteristics were identified in protocol studies of design and non-design problem spaces, such as problem finding and problem forming (Simon, 1995) and problem structuring (Goel, 1994). In the last three decades, other constructs with a focus on the solution, concept and ideation were proposed but the modelling of design spaces has received less attention.

These views have helped thinking about one of the central design research questions, when and whether designing, as a cognitive process, is distinct from problem-solving (Goel & Pirolli, 1989; 1992; Vieira, 2021; Visser, 2009). Distinctive brain activity between design tasks, based on problem-solving and layout design (Alexiou et al., 2009; 2010; Vieira et al., 2020a) and problem-solving and open design (Vieira et al., 2020a; 2020b) have provided preliminary answers to this core design research question.

As part of a larger experiment, this study integrates a research project with the goal to distinguish designing from problem-solving across design domains. Studies have so far provided results for domains of expertise (Vieira et al., 2019; Vieira et al., 2020b), degree of professional experience (Vieira et al., 2020c), and gender effect (Vieira et al., 2021, 2022). Here, by comparing two prototypical tasks, we extend our motivation and investigate whether and how the neurophysiological activation of professional designers while designing in constrained and open design tasks (Vieira et al. 2020b) translate into frequency band power and may be used as measures of the change of design spaces. One of our aims and motivation of the study is to stimulate discussion about the creation and development of a novel index to characterise design spaces, the Design Spaces Index (DSI). EEG measures can constitute indices (Shan et al., 2019), in addition to other task-related and design-related measures of individual performance, but also teamwork (Perišić, Storga & Gero, 2021). Temporal analysis of networks based on frequency bands and networks of task-related and design-related measures can constitute such indices measuring the dynamics of design spaces. The DSI would not just give feedback on design spaces expansion but also on its pliability. By pliability we mean not just the change, expansion or contraction but also the flexibility of the design space. Such indices can be used as metrics for pattern recognition methods in real-time feedback mechanisms (e.g., indoor environment, Shan et al., 2019). The ultimate motivation for the creation of a DSI feedback tool is the possibility to inform learning and education models, to enhance design creativity and innovation processes, and to support design management and design research.

1.2 Neuroscience of Creative Cognition and Design Neurocognition

Research on brain activity has been developed in the fields of cognitive science and neuroscience. In the last 50 years, cognitive science (Collins, 1977; Boden, 2006) has contributed to the understanding of memory, emotional and cognitive processing, attentional demands, associative mechanisms, inhibition, and cognitive control of general cognition. 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 understanding the underlying role of executive functions, memory, attention and cognitive control of creative performance (Benedek & Fink, 2019). Design cognition (Akin, 2001; Cross, 2001; Eastman, 1970; Eastman, 2001; Hay, Cash & McKilligan, 2020; Lloyd, Lawson & Scott, 1996; Oxman, 2001) has been investigated based on macro perspectives by distinguishing phases or stages of designing from grounded theory approaches or theoretical models (Hatchuel & Weil, 2009; Kannengiesser & Gero, 2019; Kan & Gero, 2017) mostly based on protocol analysis, for the last 50 years.

While general cognition requires the ability to adjust modes of thought to match the demands of each situation (Gabora, 2002), creative cognition encompasses special combinations and patterns of the same cognitive processes seen in other non-creative endeavors (Finke, Ward & Smith, 1992). Research in each area has followed different paths. Although creativity and design are drivers of innovation and social and cultural progress, crucial for economic sustainability and well-being, they are not identical. Design, in its broad definition, is the generation of a plan for a change, as such, it is high-level cognition involving multimodal behaviour (Park & Alderman, 2018). 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). Creative thinking is traditionally associated with conceptual expansion implying a creative change in the approach to the request (Abraham, 2019). The creative problem-solving process involves the integration of creativity and intelligence of requests that ask for appropriate solutions (Benedek, Jung & Vartanian, 2018; Jaarsveld et al., 2015).

Design as a temporal pursuit involves complex activities of concurrent and entangled cognitive processes occurring while designing. Recent paradigm shifts in creativity assessment in neuroscience research highlight those neural responses of cognitive processes cannot be observed in isolation from other ongoing processes (Benedek et al., 2018). These ideas supported pairing neuroscience methods with behavioral paradigms during ecologically valid, real-world design tasks to improve the understanding of design cognition (Chrysikou & Gero, 2020; Goel 2014; Vieira et al., 2020b) and design creativity (Gero, 2020; Goldschmidt. 2018). Design neural processes studies emerged in the last two decades (Alexiou et al., 2009) originating the field of design neurocognition (Vieira, 2018; Gero, 2019). Design neurocognition (Vieira et al., 2019b), emerged as the field that provides the convergence of research methods from design cognition and neuroscience. Literature reviews (Borgianni & Maccioni, 2020; Gero & Milovanovic, 2020) have recently highlighted the research endeavour in this field. For the purpose of this paper, we focus on the literature using the electroencephalographic (EEG) technique for assessing brain activation in general cognition, creativity and design research.

Neurocognitive creativity studies using EEG started more than 40 years ago, by investigating cortical activation during multiple creative tasks (Martindale & Hines, 1975), and differences as a function of creativity, stage of the creative process and originality (Martindale & Hasenfus, 1978). Other studies compared the brain activation of experts and novices (Göker, 1997), a topic recently revisited from other perspectives (Liang, Chang & Liu, 2019; Vieira et al., 2020d). Investigations focused either on single domain studies (Liang et al., 2017; Liu et al., 2016; Liu et al., 2018; Nguyen & Zeng, 2010; Vieira et al., 2019a; Vieira et al., 2020e), or domain comparisons between mechanical engineers and architects (Vieira et al., 2019b), and industrial designers (Vieira et al., 2020b).

In the neuroscience of creative cognition, comprehensive literature reviews have focused on topics relevant to design research, such as visual creativity, visual mental imagery (Aziz-Zadeh, Liew & Dandekar, 2013; Pidgeon et al., 2016), gender, creative potential and cognitive strategy (Abrahams 2016; Baer and Kaufman, 2008), creativity assessment (Benedek et al. 2019), and brain networks (Beaty et al., 2016; Beaty & Kennett, 2020). Neural processes associated with general creativity have been widely investigated (Abraham, 2019; Benedek & Fink, 2019; Benedek et al., 2018; Dietrich & Haider, 2017; Goel & Vartanian, 2005; Sawyer, 2011). We highlight results relevant to the understanding of constrained and open design spaces.

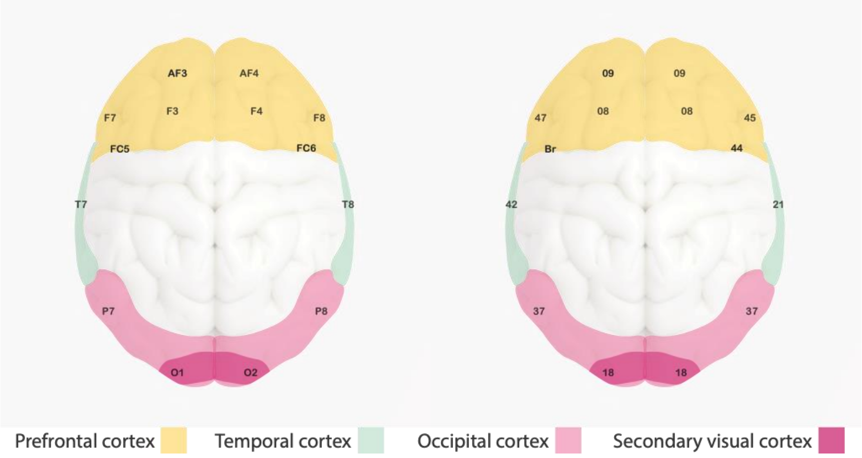
Studies using the EEG technique are usually based on the analysis of activation in specific frequency bands (Benedek & Fink, 2020; Stevens & Zabelina, 2019). About 20 years ago, the oscillatory neuroelectric activity of delta, theta, alpha, beta and gamma frequency bands were proposed to act as resonant communication networks through large populations of neurons, with functional relations to memory and integrative functions. Complex stimuli would elicit superimposed oscillations of different frequencies (Başar et al., 1999). Although neglected in the early 1990's, in the last decades most studies focus on the alpha frequency band. Higher alpha band activity is thought to be more sensitive to specific task-related requirements, while the lower alpha band activity is associated with attention processes such as vigilance and alertness (Klimesch, 1999). Increased alpha activity at prefrontal sites is considered to be an indication of the complex cognitive processes implicated in ill-defined problem spaces (Fink & Benedek, 2014; Fink et al., 2009a), reflecting high internal attention demands (e.g., imagination) or the inhibition of task-irrelevant sensory processes (Benedek, 2018; Fink & Benedek, 2014). Increased alpha activity in temporal and occipital areas are associated with visualization processes (Jaarsveld et al., 2015). Relevant studies of frequency bands of interest to the present study (theta, alpha and beta waves) on general cognition, creative cognition and design neurocognition from the last 35 years are summarized in Table 1.

Table 1. EEG findings in general cognition, creative cognition and design neurocognition by frequency band.

Frequency Band	**General Cognition**	**Creative Cognition**	**Design Neurocognition**
Beta 3 (20-28 Hz)	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 rhythms depend on creative ability and gender in creative figural tasks (Volf & Tarasova, 2010) predominant increases in visual creativity (Sviderskaya, 2011)	visual attention (Liang et al., 2018) increased beta 3 in open design tasks of layout and sketching (Vieira et al., 2020b) *increased beta 3 in reflecting and design sketching in open design spaces across mechanical engineers and industrial designers (this study)* increased beta 3 across hemispheres in open design spaces for both gender (Vieira et al., 2022)
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)	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., 2020a) *increased beta 2 in design sketching in open design spaces across mechanical engineers and industrial designers (this study)* increased beta 2 across hemispheres in open design spaces for both gender (Vieira et al., 2022)
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 layout and sketching design tasks (Vieira et al., 2020a) *increased beta 1 in reflecting and design sketching in open design spaces (this study)* increased beta 1 in constrained and open design spaces for female designers abd across hemispheres in open design spaces for both gender (Vieira et al., 2022)
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., 2015) top-down processing (Benedek et al., 2011) increases in right parietal cortex reflects focused internal attention (Benedek et al., 2014a) controlled memory retrieval induces bilateral synchronization (Klimesch, 2012) long-term (semantic) memory demands (Klimesch 1996, 1999) alpha oscillations facilitate association mechanisms in several brain structures (Başar et al., 1999)	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 & Benedek, 2014; Stevens & 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 creativity in high and low-creative groups (Volf, Tarasova & Razumnikova, 2010) increased alpha in mental elaboration of drawings (Rominger et al., 2018) insightful solvers show higher alpha activity (Erickson et al., 2018) 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. (Vieira et al., 2020b) alpha oscillations in alternate processing of demanding visual imagery tasks of graphic artists (Sviderskaya, Taratynova & Kozhedub, 2006) *increased alpha 2 in design sketching in open design spaces across mechanical engineers and industrial designers(this study)* increased alpha 2 in constrained and open design spaces for female designers and across hemispheres in open design spaces for both gender (Vieira et al., 2022)
Alpha 1 (7-10 Hz)	attention processes such as vigilance, alertness and expectancy (Klimesch et al., 1998; Klimesch, 1999) spatial attention (Cohen, 2017) information processing, inhibition and timing, attention and semantic orientation (Klimesh, 2012) inhibition-time hypothesis (Klimesh, 2007) attentional demands (Ray & Cole, 1985)	oscillations in the temporal dynamics of divergent thinking (Agnoli et al., 2020) increased alpha (1 and 2) in creative thinking interpreted as a sign of active cognitive processes rather than cortical idling (Fink et al., 2009) lower alpha power for reading and planning the solution in ill-defined problems (Jausovec, 1997).	increased alpha 1 in the right hemisphere in open design spaces for both gender (Vieira et al., 2022)
Theta (4-7 Hz)	increased theta in short-term (episodic) memory demands (Klimesch, 1996; 1999) and encoding new information (Klimesch,1999) theta oscillations related to cognitive processing and cortico-hippocampal interaction (Başar et al., 1999) selective attention (Başar-Eroglu et al., 1992) theta oscillations related to alertness, arousal and motor behavior (Başar et al., 1998a; Başar 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) theta greater power for art students (Sviderskaya et al., 2006) increased coherence in high visual creativity (Volf, Tarasova & Razumnikova, 2010)	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) increased theta in constrained and open design spaces for female designers (Vieira et al., 2022) increased theta in the right hemisphere in open design spaces for both gender (Vieira et al., 2022)

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

In this study, we look at the cognitive demands associated with constrained and open design tasks and how these translate into brain activation and specifically changes in frequency bands. These aspects are further described in the analysis of frequency bands and we suggest comparing the results with selected cognitive functions associated with the respective Brodmann areas (BA) that can be inferred from the literature and have potential connections to design cognition in constrained and open design. Brodmann's studies (1909) on the brain's structure, function and connectivity have been refined and correlated to various cortical functions and cognitive activities (Glasser et al., 2016). The electrode placement of the EEG device and their associated Brodmann area is shown in Figure 1. The relation between cognitive functions and Brodmann areas is listed in Table 2.



(a) (b)

Fig. 1 (a) Electrodes placement related to each cortex of the brain and (b) corresponding Brodmann areas.

Table 2. Brodmann areas (BA) and design relevant associated cognitive functions for each hemisphere.

BA	Left hemisphere	Right hemisphere	BA
09	deductive reasoning (Goel et al., 1997) metaphoric comprehension (Shibata et al., 2007)	coordinating visual spatial memory (Slotnick & Moo. 2006) planning (Fincham et al., 2002) decision-making (Rogers et al., 1999)	**09**
08	executive control (Kübler, Dixon & Garavan. 2006) inductive reasoning (Goel et al., 1997) planning (Crozier et al., 1999)	executive control (Kübler, Dixon & Garavan .2006) planning (Crozier et al., 1999) selective memory retrieval (Rugg et al., 1996)	**08**
47	deductive reasoning and semantic processing (Goel et al., 1997)	response inhibition (Marsh et al., 2006)	**45**
Broca (Br)	complex verbal functions, reasoning processes (Goel et al., 1997; 1998) metaphor processing (Rapp et al., 2004)	goal-intensive processing (Fincham et al., 2002) search for originality (Nagornova, 2007)	**44**
42	visual word recognition (Pekkola et al., 2005)	observation of motion (Rizzolatti et al., 1996)	**21**
37	deductive reasoning (Goel et al., 1998) metaphor comprehension (Rapp et al., 2004) semantic categorization (Gerlach et al., 2000) semantic relations (MacDermott et al., 2003)	drawing (Harrington et al., 2007) monitoring shape (Le, Pardo & Hu, 1998) visual fixation (Richter et al., 2004)	**37**
18	visual mental imagery (Platel et al., 1997) visual word form (Vorobyev et al., 2004)	visuo-spatial information processing (Waberski et al., 2008)	**18**

Each Brodmann area is increasingly associated with more and more cognitive functions and most researchers are cautious about relating specific electrode positions with higher cognitive functions, although such associations are commonly used when discussing brain regions of main findings.

Through the comparison of frequency band power between the two prototypical tasks, we connected the results to the literature on associated cognitive functions and present an overview of hypothetical inferences and interpretation. These inferences are not intended to claim the presence of cognitive processes from observed brain activation (reverse inference, (Poldrack, 2006; 2011)). This would ask for other concurrent sources of data such as think-aloud design protocols, and infer the cognitive processes from the verbalisations.Instead, we highlight selected studies of cognitive functions associated with channels that reveal statistical differences in the present study and infer potential associations that relate to design cognition, in particular to these stages of design cognition that can inspire future design experiments.

1.3 Research Question and Approach

We investigate constrained and open design spaces through the analysis of the neurophysiological activation differences of mechanical engineers and industrial designers, in line with the studies in the right column of Table 1, when addressing two prototypical tasks, a constrained problem-solving layout design task and an open sketching design task. We use frequency bands power from the constrained and open design tasks as proxies for constrained and open design spaces. The experiment design from which we report results here included four different tasks, as previously detailed in Vieira et al. (2020b). Among the different tasks proposed to the subjects, for this study we selected those clearly presenting the traits of the intended comparison: a constrained layout design task and an open design task.

In the present paper, we divided the two tasks into three stages of categorical similarity: Stage 1, *reading the task*; Stage 2, *earliest reaction*; Stage 3, *open externalization*. Distinguishing the three stages is motivated by the assumptions that:

a) designing starts by reading the task request, whether the request is constrained or open and may evoke different levels of conceptual expansion prompting designers to construct different design spaces.
b) protocol analyses usually address only the third stage as they rely on the externalizations by the designer, we use the potential of the EEG neurophysiological measurements to investigate what comes before the externalization of the idea and immediately after reading the task request.
c) protocol studies have identified problem finding and problem forming (Simon, 1995) and problem structuring (Goel, 1994) as invariants of design problem spaces and how these differ from problem solving in non-design problem spaces (Goel, 1994). We explore if such difference takes place between design spaces of constrained and open tasks, by examining brain activity.

The analysis focuses on the frequency bands power 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 within design sessions across the three stages. We use these activations from constrained and open design tasks as proxies for constrained and open design spaces. We investigate the following research questions:

- *What are the similarities and differences in frequency band power in constrained and open tasks associated with reading the task, earliest reaction and open externalisation?*

- *What are the similarities and differences in frequency band power in constrained and open tasks associated with reading the task, earliest reaction and open externalisation between mechanical engineers and industrial designers?*

2. METHODS

The research questions are investigated by using the constrained design task as the reference task for the open design task. We analyze frequency power (Pow) across distinct frequency bands. The tasks and experimental procedure were piloted prior to the full study, which produced changes resulting in the final experiment design (Vieira et al., 2020b).

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 result of the unpaired t-test controlling for experience between cohorts revealed no statistically significant difference, $t(30)=1.8$, $p=.08$. The participants are all professionals (years of experience $M = 6.4$, $SD = 6.2$). This study was approved by the local ethics committee of the University of Porto.

2.2 Experiment Tasks

All participants completed two experimental tasks, a constrained and an open design task. The constrained task was adopted from the problem-solving layout design described in the Alexiou et al. (2009) fMRI study. This task is considered a constrained 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 that consisted of a sequence of tasks previously reported (Vieira et al., 2020b). We added an open design task that included free-hand sketching. This task is an ill-defined and fully unconstrained task (see Figure 2).

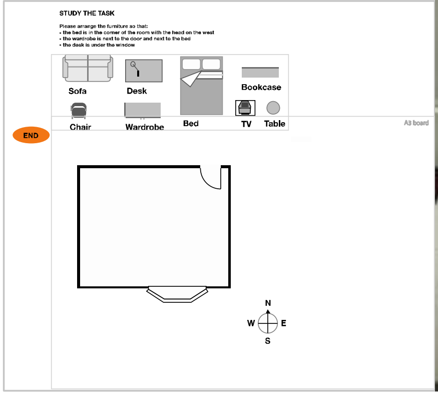
Constrained design task based on problem-solving	**Open design task based on design sketching**
In the constrained layout task, the design of a set of furniture is available and three conditions are given as requirements. The task consists of meeting three given restrictions and they freely complete the design afterwards.	In the free-hand sketching, the participants are asked to propose and represent an outline design for a future personal entertainment system.
 STUDY THE TASK Please arrange the furniture so that: - the bed is in the corner of the room with the head on the west - the wardrobe is next to the door and next to the bed - the desk is under the window 	

Fig. 2 Depiction and description of the constrained design task based on problem-solving and the open design sketching task.

In both tasks the subject received the description of the assignment in the form of written text. Moreover, the interaction is based on the visualization of the layout/sketch and on the application of design modifications through manual actions on the furniture elements or hand-sketching. In turn, the most significant difference between the two tasks is the degree of openness. We explore the observable and measurable differences of the frequency bands power between the constrained and the open design task.

To understand brain activity in constrained and open design tasks we took a macro perspective, by distinguishing three stages as follows:

- Stage 1, *Reading*, is the stage in which the designers read the task request.
- Stage 2, *Earliest reaction*, is the stage in which the designers take the earliest reaction after reading the request. In the constrained design task, it starts when the participant takes action to locate the three strict requests and ends when these are accomplished. This stage is labelled *problem-solving.* All the 32 participants immediately take this action after reading, by locating the three requests in one sequence. Two participants of each cohort ended the task here. In the open design task, a stage of *reflecting* is the earliest reaction after reading the request and ends when the participant initiates sketching or notation activities. All the 32 participants exhibited the stage of *reflecting.*
- Stage 3, *Open externalization*, is the stage in which the designers have more freedom to externalise their design solutions. In the constrained design task, after the *problem-solving* stage, the participants freely complete the *layout* design. In the open design task, the open externalization stage starts with the beginning of sketching or notation activities and ends when the design is concluded. This stage is labelled *sketching* and was performed by all the participants.

By taking the *problem-solving* stage of the constrained task, we know that participants cognitive effort is focused on solving well-defined instructions. By narrowing the *problem-solving* stage of the task we consider this a suitable segment for comparison with the other stages, in particular the stages of the open design task (Vieira et al. 2021).

2.3 Setup and Procedure

The setup and complete procedure have been previously described in Vieira et al. (2020b). A brief outline is presented here. Electromagnetic interference of the room was checked including the 50Hz power line contamination. 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 the consent agreement and setting 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 constrained design task, participants received a tangible interface based on magnetic material for easy handling. In the open design task, each participant was given two sheets of paper (A3 size) and three instruments, a pencil, graphite and a pen (see Figure 1).

The average stage duration for the constrained design task was: *reading*, M = 11.1s (SD = 7.1), *problem-solving*, M = 30.5s (SD = 17.8), and *layout*, M = 56.1s (SD = 31.5), for the mechanical engineers; and *reading*, M = 12.5s (SD = 8.5), *problem-solving*, M = 30.2s (SD = 13.1), and *layout*, M = 53.1s (SD = 37.1), for the industrial designers.

The average stage duration for the open design task was: *reading*, *M* = 8.2s (*SD* = 3.6), *reflecting*, *M* = 51.6s (*SD* = 67.8), and *sketching*, *M* = 522.7s (*SD* = 290.0), for the mechanical engineers; and *reading*, *M* = 7.6s (*SD* =2.9), *reflecting*, *M* = 54.7s (*SD* = 53.1), and *sketching*, *M* = 519.1s (*SD* = 266.6), for the industrial designers.

2.4 Equipment and Data Collection Methods

EEG activity was recorded using a portable 14-channel system Emotiv Epoc+. Each of the Emotiv Epoc+ channels collects continuous signals of electrical activity at their location with a 256 Hz sampling rate. The fourteen electrodes were positioned according to the 10-10 I.S, Figure 3.

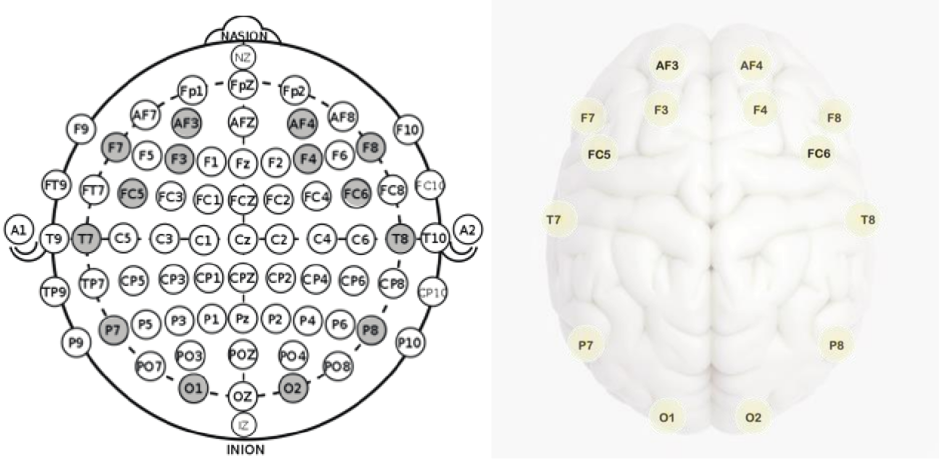


Fig. 3 Electrodes placement according to the 10-10 I.S in the brain cortex.

The participants performed the tasks, with two video cameras capturing the participants' face and activity. All the data captures were streamed using the 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.

2.5 Data Processing Methods

The signal was band pass-filtered with a low cutoff of 3.5 Hz and a high cutoff of 28 Hz to maintain only oscillatory brain activity between the theta and beta frequency range. As both tasks involved motor activity, we applied methods to attenuate the muscle artifact contamination of the EEG recordings. 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 any short EMG bursts. Data processing included the removal of Emotiv specific DC offset with the Infinite Impulse Response (IIR) filter and BSS-CCA. The BSS-CCA procedure successfully filters most 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 the 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 adopting lower and upper alpha boundaries, and beta sub-bands, we ensured that our findings 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 power (Pow) of each frequency band. The Pow was obtained by band-pass filtering the EEG signal at each electrode for specific frequency bands (see above) and computing the mean of the squared values of the resulting signal. This measure tells us about the amplitude of the frequency power per channel and per participant. 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 band. 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. The valid EEG data corresponding to each stage of the constrained and open design tasks were averaged, respectively. The segmentation of each task in three stages followed a time-stamping procedure according to the criteria presented in the methods section and then computed in MatLAB. The divisions into Stage 1, *reading the task*, Stage 2, *earliest reaction*, and Stage 3, *open externalization*, were visually checked through the observation of the two videos captured per session. We present frequency bands Pow values on aggregates of the 32 participants' individual results, for each stage of each task and cohort.

2.6 Statistical Approach

We performed standard statistical analyses based on the design of the experiment: a mixed measures design (2x2x3x2x7) with domain (mechanical engineers, industrial designers) as the between-subjects factor and task (constrained design task and open design task), stage (reading, earliest reaction, open externalization), hemisphere (left, right) and electrode (O1/2, P7/8, T7/8, FC5/6, F7/8, F3/4, AF3/4) as within-subject factors Analyses were performed for the dependent variable of Pow for each frequency band. The threshold for significance in all the analyses is $p \leq .05$.

3. ANALYSIS OF RESULTS

The analysis of transformed power (Pow) of each frequency band indicates that the constrained and open design tasks can be distinguished from each other. Results from running the 2x2x3x2x7 mixed repeated-measurement ANOVA are presented in Table 3.

Significant main effects

From the analysis of the 32 participants, we found significant main effects and significant interaction effects between multiple factors (see Table 3).

A main effect of *task* was found for four frequency bands. Industrial designers and mechanical engineers show significant differences for alpha 2 and the beta bands between the two tasks. Of particular interest for this study is the absence of a significant main effect of *stage,* and the interaction effect between *task* and *stage* for alpha and beta frequency bands. No differences were found between stages within the same task, but differences were found between tasks within the same stage.

No significant main effect was found for the between-subjects factor domain across the six frequency bands. Interaction effects with the between-subjects factor domain were found for alpha 1 and beta 3. Mechanical engineers show higher prefrontal alpha 1, (and alpha 2, Figure 7) in the constrained task, possibly due to dominant attentional processes (Klimesch, 1999; Klimesch et al., 1998). Industrial designers show higher prefrontal beta 3 (Figure 8) in the constrained task. These two significant interaction effects provide initial answers to the research question on differences and might be partly due to how these groups differ in expertise/experience and thus approach these tasks. While differences characterizing the abilities of mechanical engineers and industrial designers of relevance to perform these tasks can be discriminated, such as different use of sketching, and sketching abilities, the results reveal major similarities between these cohorts from the two domains. The almost complete absence of main effects and interaction effects may indicate prospective similarities or a lack of statistical power to detect those differences in the current study."

Table 3. Significant main effects and interaction effects from the ANOVA (2x2x3x2x7) for each frequency band

Main and Interaction effects	**Theta**	**Alpha 1**	**Alpha 2**	**Beta 1**	**Beta 2**	**Beta 3**
Between-subjects factor of domain	.66	.06	.11	.17	.20	.74
Task and domain	.69	.21	.70	.93	.77	.43
Stage and domain	.94	.69	.58	.64	.18	.11
Hemisphere and domain	.25	.79	.49	.38	.22	.01*
Electrode and domain	.41	.32	.19	.58	.36	.46
Hemisphere, electrode and domain	.16	.57	.08	.12	.50	.08
Task, stage and domain	.80	.63	.80	.88	.61	.89
Task, hemisphere and domain	.57	.70	.81	.49	.25	.09
Task, electrode and domain	.74	.04*	.61	.28	.61	.41
Task, stage, hemisphere and domain	.85	.16	.41	.72	.83	.47
Task, stage, electrode and domain	.45	.42	.74	.36	.61	.23
Task, hemisphere, electrode and domain	.19	.06	.39	.49	.63	.84
Stage, hemisphere and domain	.19	.47	.41	.65	.67	.88
Stage, hemisphere, electrode and domain	.47	.81	.45	.17	.09	<.01*
Stage, electrode and domain	.73	.39	.44	.84	.18	.28
Task, stage, hemisphere, electrode and domain	.53	.85	.82	.17	.66	.36
Within-subjects factor						
Task	.94	.54	.02*	<.01*	<.001*	<.001*
Stage	.20	.17	.36	.18	.49	.73
Hemisphere	<.001*	<.001*	<.001*	<.001*	<.001*	<.001*
Electrode	<.001*	<.001*	<.001*	<.001*	<.001*	<.001*
Task and Stage	.10	.04*	.02*	<.01*	<.01*	<.001*
Task and hemisphere	.02*	<.01*	<.01*	<.001*	.19	.27
Task and electrode	.07	.03*	<.001*	<.01*	.02*	.11
Stage and hemisphere	.04*	.34	.03*	.61	.29	.28
Stage and electrode	.62	.12	.24	.25	<.05*	.08
Hemisphere and electrode	<.001*	<.001*	<.001*	<.001*	<.001*	<.001*
Task, stage and hemisphere	.70	<.01*	<.05*	.12	.14	.37
Task, stage and electrode	.41	.09	.14	.18	.54	.26
Stage, hemisphere and electrode	<.05*	.08	<.01*	.20	.06	.12
Task, hemisphere and electrode	<.001*	<.001*	<.001*	<.001*	.001*	.001*
Task, stage, hemisphere and electrode	.26	.09	.08	.23	.20	.06
Pairwise contrasts for task effects at each stage						
Stage 1: *Reading*	.21	.22	.64	.22	.92	.29
Stage 2: *Earliest reaction*	.22	.11	.09	<.001*	<.01*	<.001*
Stage 3: *Open externalization*	.25	.06	<.001*	<.01*	<.001*	<.001*

* p≤.05

Stage and electrode are further investigated with detailed analyses. We perform electrode-based comparisons to check for differences comparing the 7 electrodes per task, stage and hemisphere. Through the analysis of the electrode positions, we connect the results to the literature on selected cognitive functions identified in studies using fMRI and positron emission tomography (PET) (Figure 1, Table 2 of section 1.2.), in general cognition and creative cognition research (Table 1), relevant to understanding design cognition and the change between the design spaces of the two tasks within and across domains.

3.1 Analysis of Stages between Constrained and Open Design across Domains

From the temporal analysis of the EEG full signal of the same tasks, significant differences were found for both domains between these two prototypical tasks (Vieira et al. 2020b). The present results augment the significant differences based on frequency band power, and similar changes in brain activity for both cohorts. The statistical analyses of stages revealed significant differences between two of the three stages across domains. The pairwise comparisons revealed significant differences for: Stage 2, *earliest reaction*, between the two tasks corresponding to the *problem-solving* and *reflecting* stages, for the three beta bands; and Stage 3, *open externalization*, between the two tasks corresponding to the *layout* and sketching *stages*, for upper alpha and beta bands.

No significant differences were found between the reading stages of both tasks for the range of frequency bands. We further describe detailed analysis of Stages 2 and 3 based on shared significant differences of frequency bands for both cohorts. This is followed by electrode-based comparisons and hypothetical associations to selected cognitive functions. From the results on significant differences in the two stages between tasks for specific frequency bands, we infer that prioritising some cognitive functions seems to play a role in mechanical engineers' and industrial designers' approaches to constrained and open design tasks. Hence, we connect the discussion of the results to the literature on selected cognitive functions associated with channels of statistical significance, relevant to understanding design cognition. These inferences based on results from studies using fMRI and positron emission tomography (PET), should not be understood as absolute reverse inference (Poldrack, 2006; 2011), but exploratory and hypothetical inferences by selecting studies of cognitive functions that related to these stages of design cognition. By doing so, we open possibilities for insights on hypotheses building, new studies and experiments.

3.1.1 Stage 2 - Earliest Reaction: Problem-solving and Reflecting

This section focuses on the comparison of the constrained and open design tasks in the *earliest reaction* stage (i.e., *problem-solving* vs *reflecting*).

Significant differences in beta 1, beta 2 and beta 3 frequency bands were observed between the *problem-solving* and *reflecting* stages for both domains, Figures 4 and 5. The plots show the two hemispheres by distributing the electrodes (10-10 IS) symmetrically around a vertical axis. Pow scores per electrode (average of the entire stage) can be considered by comparing using the vertical scale. With the exception of channel AF4 for beta 2 of the mechanical engineers cohort, all the channels of significant differences for beta 1, beta 2 and beta 3 show higher activation in the reflecting stage of the open design task for both domains.

Beta 1

The analysis revealed common significant differences across the two domains for beta 1 in the channels T8, mapped onto the right hemisphere, and the channels P7 and F3, mapped onto the left hemisphere, Figure 6. Potential cognitive functions associated with each channel, relevant for designing are presented. Channel T8 is associated with the cognitive functions of Brodmann Area (BA) 21, such as observation of motion (Rizzolatti et al., 1996), possibly related to designing as participant are about to sketch. Channel P7 is associated with the cognitive functions of BA 37, such as semantic categorization (Gerlach et al., 2000) semantic relations (MacDermott et al., 2003), metaphor comprehension (Rapp et al., 2004) and deductive reasoning (Goel et al., 1998). Channel F3 is associated with the cognitive functions of BA 08, such as inductive reasoning (Goel et al., 1997), planning (Crozier et al., 1999) and executive control (Kübler, Dixon & Garavan, 2006).

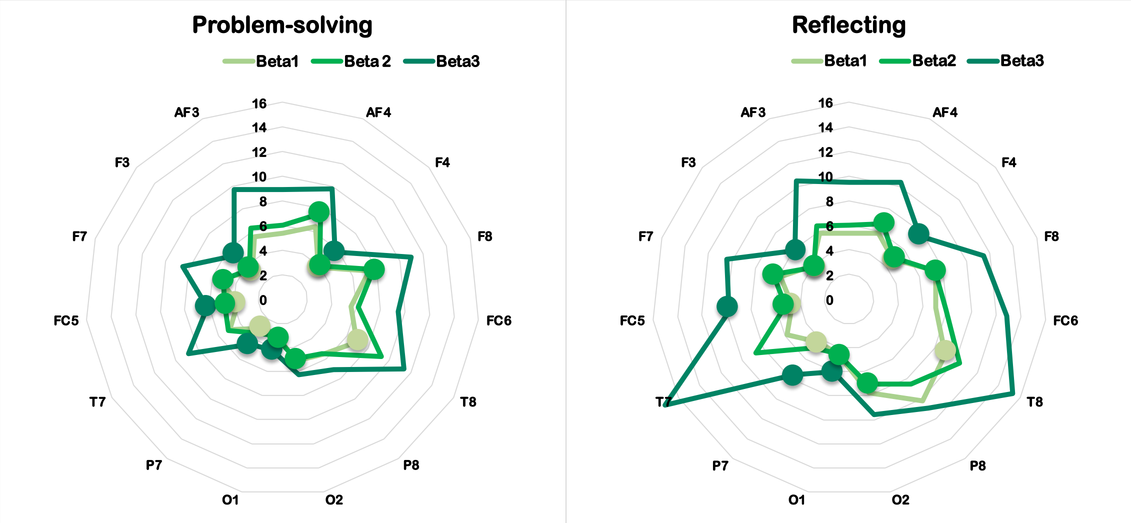


Fig. 4 Transformed power (Pow) across channels of beta 1, beta 2 and beta 3 frequency bands of mechanical engineers. The solid circles represent the channels of significant differences between stage, task and domain (p≤.05).

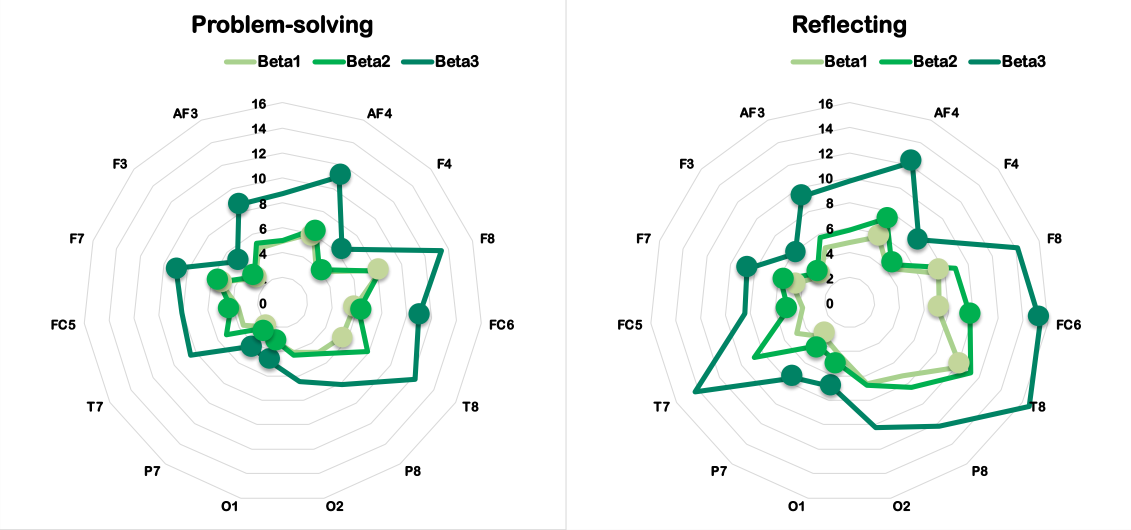


Fig. 5 Transformed power (Pow) across channels of beta 1, beta 2 and beta 3 frequency bands of industrial designers. The solid circles represent the channels of significant differences between stage, task and domain (p≤.05).

Beta 2

The analysis also revealed common significant differences for beta 2, in the channels AF4 and F4, mapped onto the right hemisphere, and the channels O1, FC5, F7 and F3, mapped onto the left hemisphere, Figure 6. Potential cognitive functions relevant for designing are associated with each channel. Channel AF4 is associated with the cognitive functions of

BA 09, namely planning (Fincham et al., 2002) and decision-making (Rogers et al., 1999). Channel F4 is associated with the cognitive functions of BA 08, such as selective memory retrieval (Rugg et al., 1996), executive control (Kübler, Dixon & Garavan, 2006) and planning (Crozier et al., 1999). Channel O1 is associated with the cognitive functions of BA 18, such as visual mental imagery (Platel et al. 1997), and visual word form (Vorobyev et al., 2004).

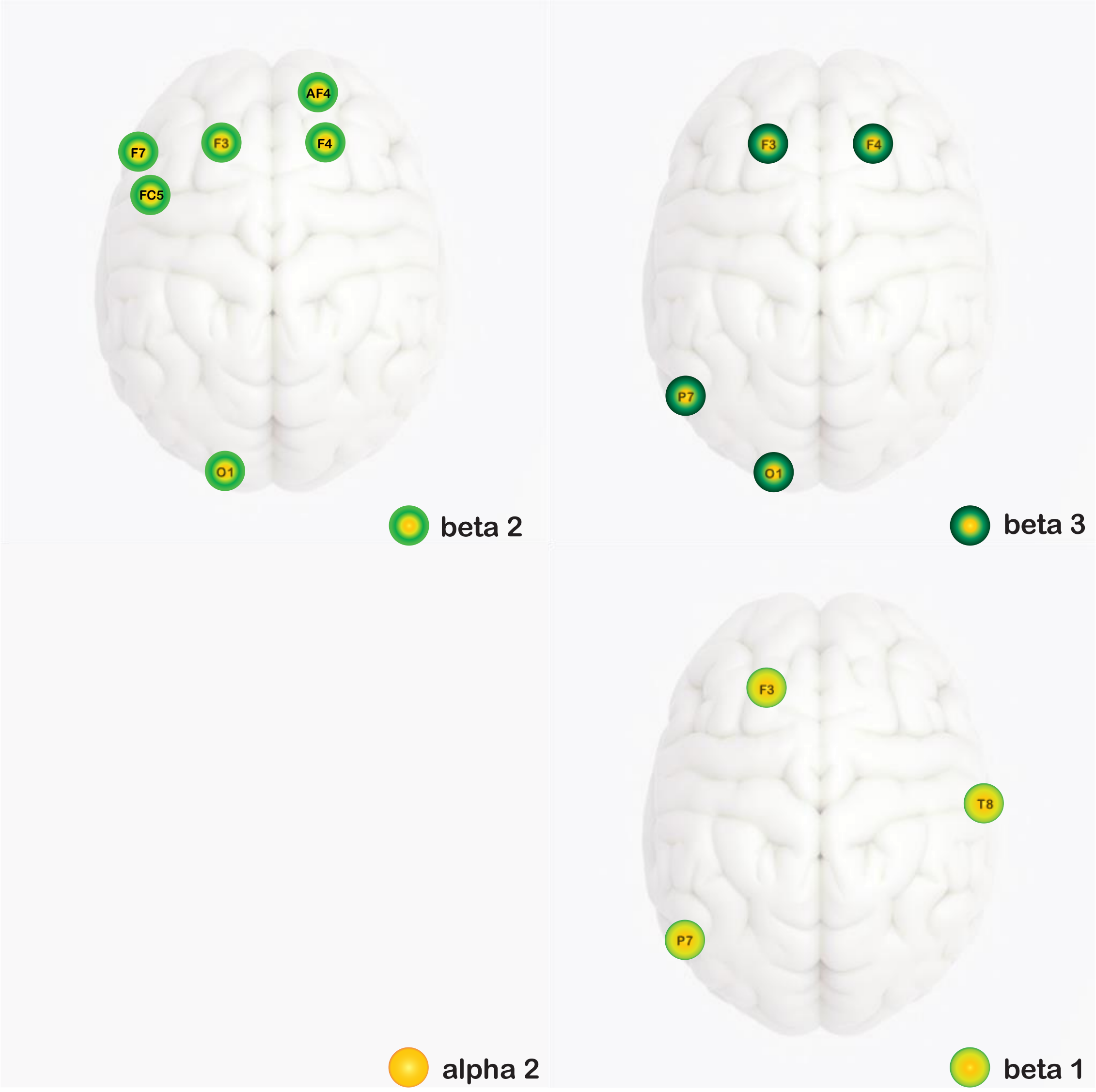


Fig. 6 Channels of significant differences ($p \leq .05$) between problem-solving and reflecting, in beta 1, beta 2 and beta 3 frequency bands that were observed for both domains.

In the left hemisphere, channel FC5, is associated with the cognitive functions of Broca's area BA 45, known for being involved in complex verbal functions and reasoning processes (Goel et al., 1997; 1998) and metaphor processing (Rapp et al., 2004). Channel F3 as previously described and Channel F7 associated with the cognitive functions of BA 47, deductive reasoning and semantic processing (Goel et al., 1997).

Beta 3

The analysis also revealed significant differences for beta 3 in the channels F4 and T8 mapped onto the right hemisphere, and the channels O1, P7 and F3 mapped onto the left hemisphere whose associated cognitive functions were previously mentioned, Figure 6.

In Stage 2 of the open design task, the cognitive demand in the *reflecting* stage is translated in distinct brain activations from the *problem-solving* stage of the constrained design task. We hypothesize that the designers' search relies to a certain extent on problem finding, distinct from problem-solving and an essential component of creative thinking (Abdulla et al., 2020; Runco & Nemiro, 1994; Simon, 1995). While reflecting in the open design space designers conceivably required other constructs, such as framing, defining, and generating the solution, concepts and ideation. In the last 30 years, useful cognitive constructs have been formalized in design research with focus not just on the problem, but also on the solution, likely to occur in *reflecting* stages, of high iterative recurrence and possibly extended to the next stage of *open externalization*.

3.1.2 Stage 3 - Open Externalization: Layout and Sketching

This section focuses on the comparison of the constrained and open design tasks in the *open externalization* stage (i.e., *layout* vs *sketching*). Significant differences in alpha 2 and beta frequency bands were observed between the *layout* and *sketching* stages for both domains, Figures 7 and 8.

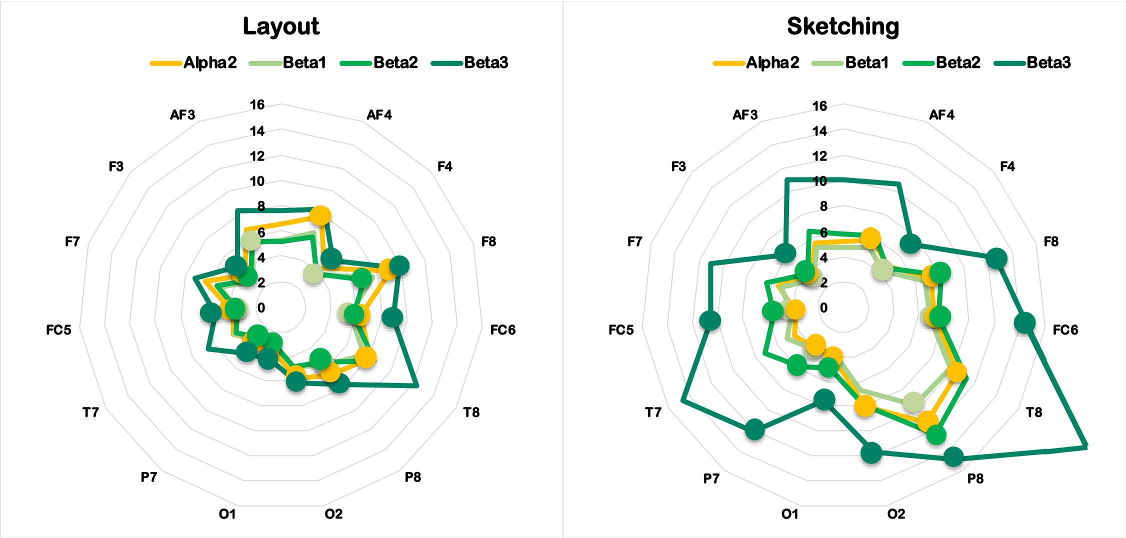

Layout
Sketching

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

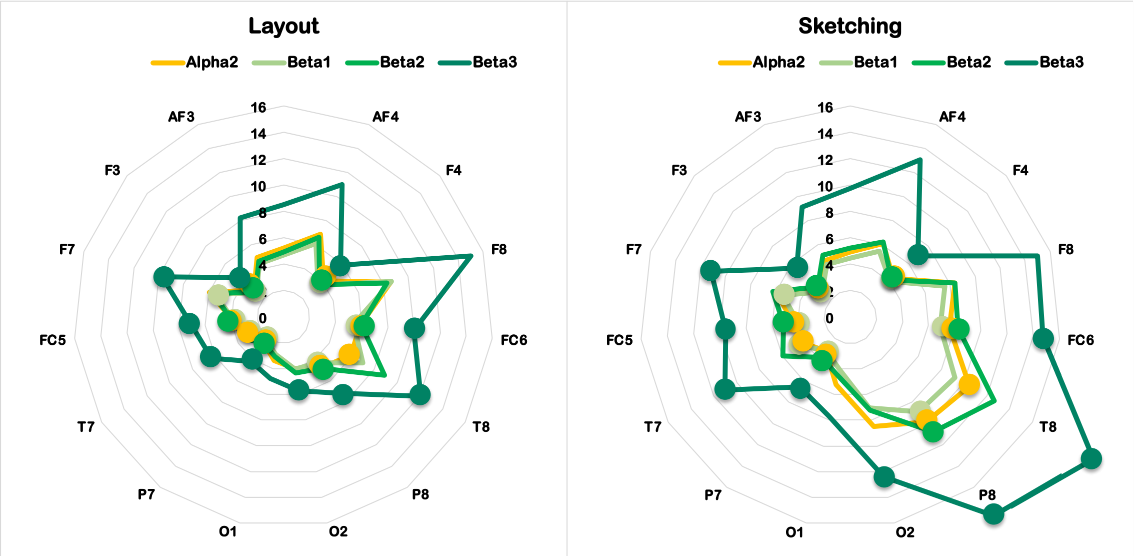

Layout
Sketching

Fig. 8 Transformed power (Pow) across channels of alpha 2, beta 1, beta 2 and beta 3 frequency bands of the industrial designers. The solid circles represent the channels of significant differences between stage, task and domain ($p \leq .05$).

All the channels of significant differences show higher activation in the open design task. The mechanical engineers reveal higher activation of alpha 2 in the prefrontal cortex in the *layout* stage and the industrial designers reveal higher activation of beta 3 in the right prefrontal cortex in the *layout* and *sketching* stages.

Alpha 2

The analysis revealed significant differences for alpha 2 in the channels T8, P7 and F3, previously mentioned, the channels FC6 and P8, mapped onto the right hemisphere, and the channel FC5, mapped onto the left hemisphere, figure 9. Channel FC6 is associated with the cognitive functions of BA 44 such as goal-intensive processing (Fincham et al., 2002) and search for originality (Nagornova, 2007).

Channel P8 is associated with the cognitive functions of BA 37, such as monitoring shape (Le, Pardo & Hu, 1998), visual fixation (Richter et al., 2004), and drawing (Harrington et al., 2007). Channel FC5, associated with the cognitive functions of Broca's area BA 45, is known for being involved in complex verbal functions and reasoning processes (Goel et al., 1997; 1998) and metaphor processing (Rapp et al., 2004).

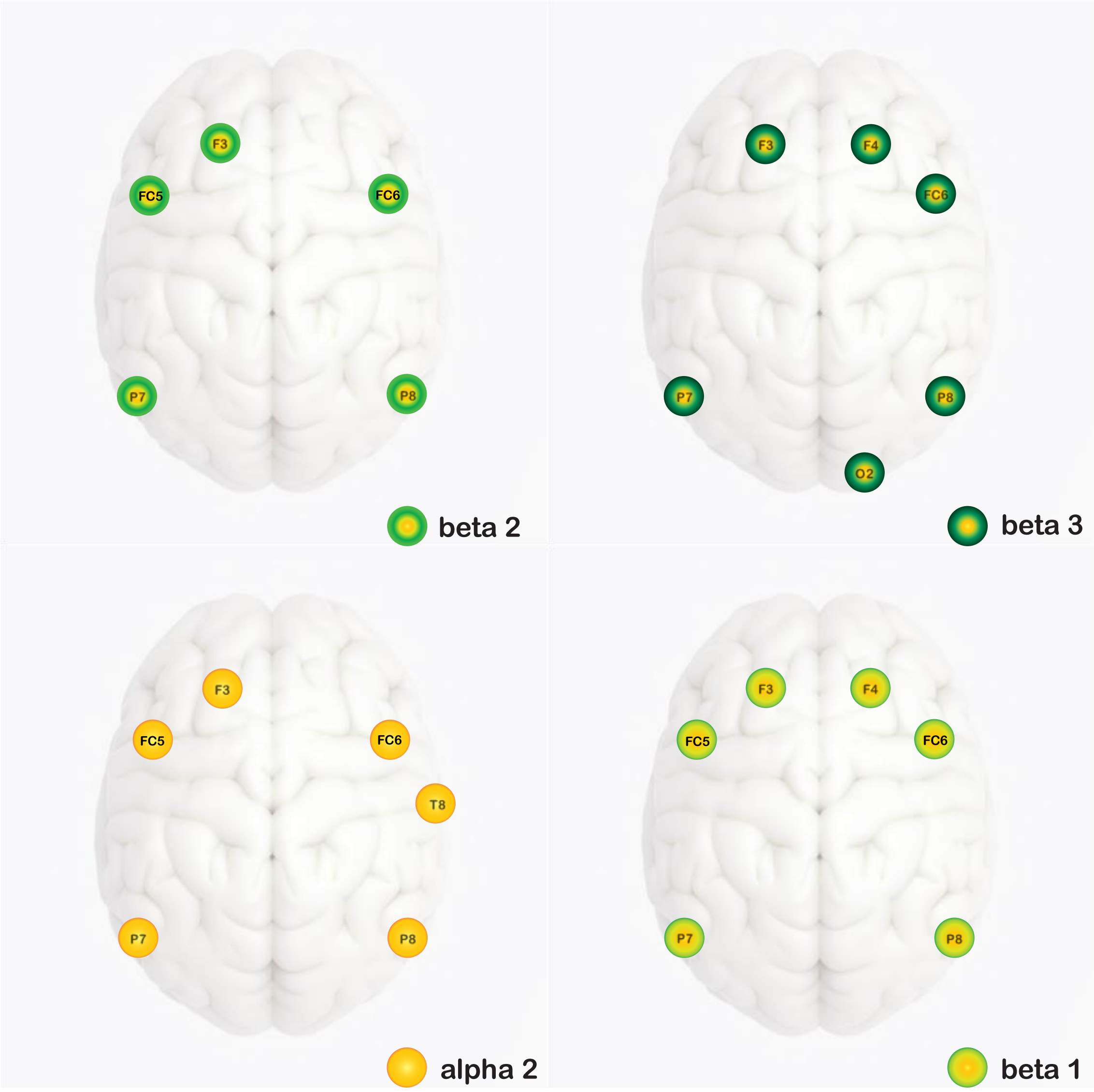


Fig. 9 Channels of significant differences ($p \leq .05$) between layout and sketching, in alpha 2, beta 1, beta 2 and beta 3 frequency bands that were observed for both domains.

Beta Bands

The analysis revealed significant differences for beta 1 in the channels F4, FC6, P8, P7, FC5 and F3 previously mentioned, mapped symmetrically in both hemispheres, figure 9.

The analysis revealed significant differences for beta 2 in the channels, FC6, P8, mapped in the right hemispheres and the channels P7, FC5 and F3 mapped in the left hemisphere, figure 9.

The analysis also revealed significant differences for beta 3 in the channels, F4, FC6, P8, P7 and F3 previously mentioned and the channel O2, figure 9. Channel O2 is associated with the cognitive functions of BA 18, such as visuo-spatial information processing (Waberski et al., 2008).

In Stage 3 of the open design task, the search for a creative and original solution in the *sketching* stage translates into distinct brain activations from the *layout* stage of the constrained task. We hypothesize that the designers' search relies on the co-evolution of problem and solution in the *sketching* stage of the open design space (Dorst, 2019; Dorst & Cross 2001; Maher & Poon 1996).

4. DISCUSSION

This controlled experiment provides evidence for the sensitivity of EEG brain activation for differences between constrained and open design tasks, carried out by two cohorts from the domains of mechanical engineering and industrial design. From the results of the analysis between the two tasks, we can infer the following similarities and differences in brain activation associated with the stages of *reading, earliest reaction* and *open externalisation* in constrained and open design tasks:

(i) No significant differences were found between the reading stages of both tasks for the range of frequency bands.

(ii) Significant differences were found for Stage 2, earliest reaction, in the three beta bands between the two tasks. We infer that *reflecting* about the open design request evokes different levels of semantic associations, metaphor comprehension, deductive and inductive reasoning, observation of motion, planning and executive control than in the *problem-solving* stage, prompting designers to change their design space, which results in increased activation in the open design task.

(iii) Significant differences were found for Stage 3, *open externalization,* in alpha 2 and beta bands between the two tasks. We infer that design *sketching* evokes a more complex network of cognitive functions potentially related to visual mental imagery, search for originality, monitoring shape, goal-intensive processing, deductive, inductive and complex reasoning, planning and executive control than the *layout* stage in the constrained design task. We hypothesize that designers' higher activations while freely producing creative and original solutions expand their design spaces.

Together, these findings highlight the sensitivity of EEG to the brain activity and potential cognitive functions associated with design-related tasks and stages, but also its specificity as differences were only observed in more active designing stages (stage 2 and 3) but not during initial reading (stage 1). The results are partially consistent with the literature in design neurocognition studies. Beta 2 is found to play a role in searching for originality and goal-intensive processing in open design (Vieira et al., 2020a) and has been associated with design activities (Liu, Zeng & Hamza, 2016). Alpha 2 has been found to be associated with open tasks (Vieira et al., 2020a) and divergent thinking (Nguyen & Zeng, 2010) and visual association (Liang et al., 2018). While beta bands are found to play a role in reflecting and externalization in open design tasks, this is not consistent nor immediately plausible with results from the literature on beta power associated with convergent thinking in decision-making and constraints tasks (Nguyen & Zeng, 2010). Beta bands are related to active thinking, attention, or solving specific problems (Sanei & Chambers, 2007). Further studies are needed to disentangle the inconsistency of these results.

- The absence of significant differences in upper alpha, in Stage 2, between *problem-solving* and *reflecting* stages for both domains, is consistent with findings on decreased alpha in visual mental imagery in high and low-creative groups (Volf, Tarasova & Razumnikova, 2010). While other results show higher alpha in creative ideation (Fink & Benedek, 2014; Stevens & Zabelina, 2019), this seems to indicate that the different nature of the ideation process and stimuli in creative and design tasks translate into different brain activation of the upper alpha band.
- The significant differences in upper alpha, in Stage 3, between the *layout* and *sketching* stages for both domains are consistent with findings of increased alpha

in mental elaboration of drawings (Rominger et al., 2018). Higher alpha band activity is thought to be more sensitive to specific task-related requirements (Klimesch, 1999). The results on 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 and posterior alpha have been interpreted as reflecting high internal attention demands (e.g., imagination) or the inhibition of task-irrelevant sensory processes enfolding within ill-defined problem spaces (Benedek, 2018; Fink & Benedek, 2014).

- From the significant differences in beta bands in Stage 2, between the *problem-solving* and *reflecting* stages for both domains, we infer that the unrestrictedly open design task requires other constructs, distinct from problem-solving, such as problem finding (Abdulla et al., 2020; Runco & Nemiro, 1994; Simon, 1995), problem framing, problem generation, problem definition (Runco & Nemiro, 1994), problem structuring (Goel, 1994) and solution focused constructs, as well (Dorst, 2019; Dorst & Cross 2001; Gero, 1990; Gero & Kumar, 1993; Kruger & Cross 2006; Visser, 2009; Yoshikawa, 1981) while reflecting. From the present study we infer and therefore hypothesize that such constructs not just distinguish design from non-design problem spaces (Goel, 1994) but also constrained from open design tasks.
- While these same constructs are expected to develop in Stage 3, the significant differences between the *layout* and *sketching* stages for both domains are indicated by higher brain activity for alpha 2 and beta bands in the open design task. This leads us to infer that the nature of the constraints, whether by specific requirements in the constrained design task, or the absence of specific requirements in the open design task, prompted participants to engage additional and more complex networks of cognitive functions that translated into higher brain activity while sketching.

While in the past, protocol studies on design and non-design problem spaces revealed the distinction between problem structuring as a specific feature of design spaces (Goel, 1994) and distinct from problem solving (Goel 1994, Simon 1973), the present results raise the possibility that a constrained design space shares characteristics with a non-design space (Goel, 1994). Problem structuring was defined as the process of drawing upon knowledge to compensate for missing information and using this knowledge to construct the problem space (Simon, 1973). Whether the request is constrained or open prompts the designer to adopt a formal problem-solving mode or a design thinking approach, through the use of other constructs involved in the co-evolution of problem and solution. The first reaction to a task request produced by a formal problem-solving approach is a characteristic of non-design spaces (Goel 1994) and also of constrained design tasks. Instead, the design thinking approach to the open request results in higher brain activity for upper alpha and beta bands. This we take to imply that the design space of the open design task further expands.

5. CONCLUSION

Taking the approach that design creativity is associated with opening the space of possible designs, amongst other changes, this experiment has shown that EEG frequency band power, may reflect the extent to which opening the design space of constrained and open design tasks may differ. The present results reveal significant differences based on frequency band power, and similar changes in brain activity for both cohorts that provide the basis for the development of indices constituted by EEG measures for the Design Spaces Index. Such EEG measures have the potential to constitute indices for pattern-recognition methods in real-time feedback tools, such as the Design Spaces Index. 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, we infer, results in a further expanded design space. Both tasks differently prompt ideational skills, self-expression and creative potential. The results contribute to the knowledge of oscillatory brain responses across frequency bands for the brain/body–mind functional dynamics (Başar & Karakas, 2006) and to the knowledge about neurocognitive measurements in design.

Limitations of the Research

The knowledge level of the participants and the variability of their EEG acquired signals are variables that we cannot fully control. Among the general limitations we might mention also the potential influence of other uncontrolled differences between the two proposed tasks (e.g. between the motor actions for moving magnets vs. motor actions for sketching). Although mechanical engineers might not be so familiar with free-hand sketching, this does not seem to have an impact in the results across both cohorts.

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 the EEG device used, the results cannot support strong claims related to location, as fields extend across the brain. By connecting the results to the literature on associated cognitive functions, we present an overview of exploratory and hypothetical inferences not intended to claim the presence of cognitive processes from brain activation (Poldrack, 2006; 2011), but to inspire hypothesis generation by selecting cognitive functions that relate to design cognition, in particular to each of the three stages considered in this study. These exploratory inferences can play an role in the early development of future and advanced work. To better identify unique brain regions associated with neural activity a larger number of EEG channels is needed.

The sketching activities have been related to a specific area of the right occipitotemporal cortex (Harrington et al., 2007) however its potential influence on brain activity needs further research. Higher activation of the magnetic field around this area revealed in subjects with planned sketching ability but also struggling with its representation asks for future disentanglement.

Since the comparison in this study involved 6 frequency band, the significance level of the comparison should be reduced to control the family-wise false positive rate. For instance, according to the Bonferroni method, significant results would be considered only if critical p ($p \leq .05$) is divided by 6 (frequency bands) => $p < .0083$. In such perspective, only highly significant results should be considered as consolidated, while the results on alpha 2, and some of the results for beta 1 and beta 3, need more caution and should be explored in larger data sets.

Future Work

The present results allowed the exploration of the neurophysiological activation across frequency bands as proxies for assessing design space. We infer that the designers' neurophysiological activation reflects the expansion or contraction of the design space from the analysis of two prototypical tasks. We hypothesize that alpha and beta frequency bands can be an effective approach for measuring change in design spaces. As the ultimate outcome from this study, we propose a shift in the analysis of design spaces, from external memory representations, such as models and drawings, to the inclusion of brain activation as predictors of design space pliability. Further experiments are necessary to test how far neurophysiological activation can work as an anchor and be correlated to other possible measures of design spaces, as items towards the development of a Design Spaces Index (DSI), a feedback system of the pliability of the design space created by the designers while designing. The ongoing analysis of think-aloud protocols of related experiments collected while measuring EEG responses can add support to this hypothesis. The development of the Design Spaces Index can be relevant to support neurocognitive, ideational and creative feedback and inspire methodological change in design thinking, design management, design education, and design research. More data needs to be collected to understand the extent of variation in EEG data of design studies necessary for the development of DSI datasets, of potential use in Artificial Biological Intelligence. This paper provides initial results and a foundation to support the development of the DSI.

Acknowledgements

To come

The 1st author plans to publish the data open access after completing the analyses of the experiment, and is available to provide data and details upon request.

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