INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED21
16-20 AUGUST 2021, GOTHENBURG, SWEDEN

BRAIN ACTIVITY OF INDUSTRIAL DESIGNERS IN CONSTRAINED AND OPEN DESIGN: THE EFFECT OF GENDER ON FREQUENCY BANDS

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ABSTRACT

In this paper, we present results from an experiment using EEG to measure brain activity and explore EEG frequency power associated with gender differences of professional industrial designers while performing two prototypical stages of constrained and open design tasks, problem-solving and design sketching. Results indicate no main effect of gender. However, among other main effects, a consistent main effect of hemisphere for the six frequency bands under analysis was found. In the problem-solving stage, male designers show higher alpha and beta bands in channels of the prefrontal cortices and female designers in the right occipitotemporal cortex and secondary visual cortices. In the design sketching stage, male designers show higher alpha and beta bands in the right prefrontal cortex, and female designers in the right temporal cortex and left prefrontal cortex, where higher theta is also found. Prioritising different cognitive functions seem to play a role in each gender's approach to constrained and open design tasks. Results can be useful to design professionals, students and design educators, and for the development of methodological approaches in design research and education.

Keywords: Human behaviour in design, Design cognition, Industrial design, Gender, frequency bands

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Cite this article: Vieira, S. L. d. S., Benedek, M., Gero, J. S., Cascini, G., Li, S. (2021) ‘Brain Activity of Industrial Designers in Constrained and Open Design: The Effect of Gender on Frequency Bands’, in *Proceedings of the International Conference on Engineering Design (ICED21),* Gothenburg, Sweden, 16-20 August 2021. DOI:10.1017/pds.2021.57

1 INTRODUCTION

Whether the practice of design is influenced by gender is of particular interest to understand methodological approaches in design research and education. Rooted in different professional activities the practice of design shows variable use of what makes the foundations of designing as a generic thinking process (Goel and Pirolli 1992; Visser, 2009). In this study we investigate if this variability extends to gender. Knowledge of gender differences while designing is underexplored. Neuroscience methods can contribute to our understanding of designing and to the improvement of design education. 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 tested this claim by studying the brain activation of professional designers while designing in constrained and open design tasks. In this single-domain study, we use measurements from EEG to explore frequency power associated with gender differences of professional industrial designers while performing two prototypical stages of constrained and open design tasks, a problem-solving stage and a design sketching stage.

The field of design neurocognition provides access to brain behaviour while designing through objective measurements. In this paper, we focus on research literature using the electroencephalographic (EEG) technique for assessing brain activation in design and creativity research. Studies using EEG started by investigating cortical activation in multiple creative tasks (Martindale & Hines, 1975), stage of the creative process and originality (Martindale & Hasenfus 1978). Other studies compared the brain activation of expert and novices (Göker, 1997; Liang, Chang & Liu, 2018). Investigations focused either on design in single domains (Nguyen & Zeng, 2010; Liu, Zeng & Hamza, 2016; Liang et al., 2017; Liu et al., 2018; Vieira et al. 2019a), or compared domains (Vieira et al., 2019b; Vieira et al. 2020a). Design neurocognition studies on the effect of gender are yet not known. In the neuroscience of creative cognition, comprehensive literature reviews have focused on topics relevant to design research, such as mental visual imagery (Pidgeon et al. 2016). We highlight results relevant to the investigation of the effect of gender in design research. Despite the lack of clear differences in creative potential (Baer and Kaufman, 2008; Abraham 2016), women less often than men have outstanding creative achievements. It was found that men overestimate while women underestimate their creative efficacy (Abra & Valentine-French 1991), which was identified in the field of the general intellect as "male hybris-female humility" (Furnham, Fong & Martin 1999). It was further shown that the mechanisms of shaping creative self-efficacy are gender-specific (Karwowski, 2011). Although there is evidence of differences in patterns and areas of strengths between the genders, there is still relative equality in creative ability (Baer and Kaufman, 2008). Women appear more interested in the creative process than in its result or have a lower need of achievement reflecting cultural values and other factors contributing to differences (Ruth & Birren, 1985; Baer and Kaufman, 2008).

Studies using the EEG technique are usually based on the analysis of activation in specific frequency bands (Benedek & Fink, 2020; Stevens & Zabelina, 2019). The oscillatory neuroelectric activity of frequency bands are thought to act as resonant communication networks through large populations of neurons, with functional relations to memory and integrative functions, and complex stimuli eliciting superimposed oscillations of different frequencies (Bazar et al. 1999). Fink and Neubauer (2006) found no behavioral differences for originality between gender, although they significantly differed with respect to task-related synchronization of EEG alpha activity in anterior regions of the cortex. Females in the high ability group demonstrated stronger synchronization with originality than those of average verbal intelligence, whereas the opposite pattern was seen among males. Razumnikova (2004) found that gender differences in beta 2 activity, associated to creativity in both genders, are instantiated in terms of the hemispheric organization of brain activity during creative thinking.

In design research EEG studies associated design activities with beta 2 (Vieira et al. 2020b), gamma 1 and gamma 2 activity (Liu, Zeng & Hamza, 2016). Higher alpha power is associated with open ended tasks and divergent thinking (Liu et al. 2018). Upper alpha power is also associated with visual association in expert designers (Liang et al. 2018). While theta and beta power is associated to convergent thinking in decision-making and constraints tasks (Nguyen & Zeng, 2010), beta power is also associated with visual attention. Higher alpha and beta frequency bands have been found to play a key role from constrained to open design tasks (Vieira et al. 2020b). Design neurocognition studies on the effect of gender on frequency bands are yet not known.

The study reported in this paper is part of an ongoing research investigating design neurocognition, by distinguishing design tasks, and brain behaviour when design is carried out in different domains,

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expertise, and gender. This study is based on the analysis of industrial designers' oscillatory brain activity while performing constrained and open design tasks in an experimental condition previously described (Vieira et al. 2020c). We investigate the following research question:
What are the differences in the brain activations of male and female industrial designers when performing a constrained design task and an open design task?

2 METHODS

The research question is investigated by using the constrained design task as the reference for the open design task. In this study we compared two prototypical stages of each task. We collect brain waves using EEG and 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. 2020a).

2.1 Participants

Participants were industrial designers with the same demographics (language, culture, background) which was gathered beforehand. Results are based on 24 right-handed industrial designers, aged 25-54 (M = 35.5, SD = 9.2), 13 men (age M = 36.8, SD = 7.8) and 11 women (age M = 34.1, SD = 10.7). The participants are all professionals (experience M = 8.2 years, SD = 6.6). An unpaired t-test showed that gender groups did not differ significantly in their experience, $t(22)=2.7$, $p=.11$. This study was approved by the local ethics committee of the University of Porto.

2.2 Experimental tasks

We have adopted and replicated the constrained task based on problem-solving described in Alexiou et al. (2009). This task is considered a problem-solving task as the problem itself is well-defined, and the set of solutions is unique. We designed a block experiment which consisted of a sequence of tasks previously reported (Vieira et al. 2020a). We added an open design task that included free hand sketching, Table 1 and Figure 1. This task is an ill-defined and fully unconstrained task unrelated to formal problem-solving.

Table 1. Description of the constrained and open design tasks.

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

Figure 1. Depiction of the constrained Task 1 and the open design Task 4.

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2.3 Setup and procedure

A physical 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 (authors. 2020a). Electromagnetic interference of the room was checked for frequencies below 60 Hz. One researcher was present in each experiment session to instruct the participant and to check for recording issues. The researcher followed a script to conduct the experiment so that each participant gets the same information and stimuli. The participants were asked to start by reading the text which took an average of 10s of reading period. In the design sketching task, each participant was given two sheets of paper (A3 size) and three instruments, a pencil, graphite and a pen.

2.4 Equipment and data collection

The EEG activity was recorded using a portable 14-channel system Emotiv Epoc+. Electrodes are arranged according to the 10-10 I.S, Figure 2. 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. The subjects performed the tasks on a physical magnetic board, with two video cameras for capturing the participant face and activity and an audio recorder.

The experiments took place between March and July of 2017, and June and September of 2018 in a room with the necessary conditions for the experiment, such as natural lighting from above sufficient for performing experiments between 9:00 and 15:00. Time was given to the participants, in particular in the design sketching task so they could find a satisfactory solution.

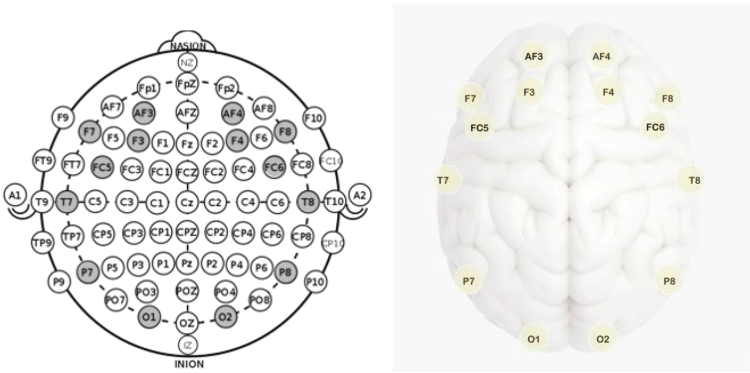

Figure 2. Electrodes placement according to the 10-10 I.S. in the brain cortex.

2.5 Data processing methods

The fourteen electrodes were disposed according to the 10-10 I.S, 256 Hz sampling rate. The signal was band pass-filtered with a 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) 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 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 the adoption of 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 based on gender 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 gender and stage 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

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amplitude of the frequency power per channel and per participant. After a z-score was computed 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 and each frequency band (Vieira et al. 2020c). We present frequency bands Pow values on aggregates of the 24 participants' individual results, by gender and per stage of each task.

2.6 Statistical approach

We focus on the frequency bands activation per channel, stage, and participant as the study aim is to know whether there are gender differences in brain activation during problem-solving and design sketching. Analyses were performed for the dependent variable of Pow for each frequency band. The threshold for significance in the analyses is $p \leq .05$. To compare the two stages total power we performed standard statistical analyses based on the design of the experiment: a mixed repeated-measures design with stage (problem-solving, design sketching), hemisphere (left, right) and electrode (O1/2, P7/8, T7/8, FC5/6, F7/8, F3/4, AF3/4) as within-subject factors and gender as between subjects factor.

3 ANALYSIS OF RESULTS

From the analysis of the 24 participants, we found significant main effects and significant interaction effects between multiple factors, Table 2. No significant main effect was found for the between-subjects factor gender (theta, p=.19; alpha 1, p=.91; alpha 2, p=.69; beta 1, p=.87; beta 2, p=.90; beta 3, p=.89). A significant interaction effect between the factors electrode and gender was found for beta 1. Results from the analysis revealed significant main effect of: stage for the beta bands, of hemisphere for the six bands; electrode for alpha and beta bands. Significant interaction effect was found between the factors: stage and hemisphere for alpha and beta bands; stage and electrode for the beta bands; hemisphere and electrode for alpha and beta bands. Of particular interest is the significant main effect of hemisphere. Cohen's *d* was calculated to measure the effect size for each electrode Pow, and each frequency band between the genders for each stage, Tables 2 and 3. Total power (Pow), for each frequency band across the 14 channels per stage and gender are depicted, Figures 3 and 4. Through the analysis of the stages between gender, we connect the results to the literature on cognitive functions.

Table 2. Significant main effects from the ANOVA (2x2x7)

Frequency band	Theta	Alpha 1	Alpha 2	Beta 1	Beta 2	Beta 3
Electrode and gender	-	-	-	.02*	-	-
Stage	-	-	-	<.01*	<.001*	<.001*
Hemisphere	<.001*	<.001*	<.001*	<.001*	<.001*	<.001*
Electrode	-	<.001*	<.001*	<.001*	<.001*	<.001*
Stage and hemisphere	-	.03*	<.01*	<.01*	<.01*	<.01*
Stage and electrode	-	-	-	.03*	<.01*	.03*
Hemisphere and electrode	-	<.001*	<.01*	<.01*	<.01*	<.01*

* $p \leq .05$

3.1 Analysis of gender differences in problem-solving

Total transformed power (Pow) for problem-solving across the 14 channels, frequency bands and gender, are depicted in Figure 3. We look at the cognitive demand and how it translates in brain activation. The plot shows the two hemispheres by distributing the electrodes (10-10 IS) symmetrically around a vertical axis. Total power (Pow) per electrode (average of the entire stage) can be considered by comparing with the vertical scale and across the two tasks.

Cohen's *d* was calculated to measure the effect size of gender differences in frequency power for each electrode, Table 3. The positive effect sizes reflect higher power in females. The solid circles indicate channels of moderate (>.50) and large (>.80) effect size, Figure 3.

Female industrial designers reveal higher effect size in channels of the posterior cortices. In the right hemisphere, the following channels revealed large to moderate effect size: channel O2 associated with the cognitive functions of BA 18 such as visuo-spatial information processing (Wabersky et al. 2008) for alpha 2; channel T8, associated with the cognitive functions of Brodmann area 21, such as observation of motion (Rizzolatti et al. 1996) for beta 1; channels T8 and P8, associated with the

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cognitive functions of BA 37, such as monitoring shape (Le, Pardo & Hu 1998) and drawing (Harrington et al. 2007), for beta 2; and large effect size of the channel P8, for beta 3. In the left hemisphere, one channel revealed moderate effect size, O1, associated with the cognitive functions of BA 18 of visual mental imagery (Platel et al. 1997), for beta 1. Female industrial designers reveal higher posterior alpha 2, and beta bands, mainly in the right hemisphere. Male industrial designers reveal higher prefrontal alpha 2, and beta bands, in the right hemisphere.

Male industrial designers reveal higher effect size in channels of the anterior cortices. In the right hemisphere, the following channels revealed large to moderate effect size: channel AF4, associated with the cognitive functions of BA 09, of coordinating visual spatial memory (Slotnick & Moo 2006) and planning (Fincham et al. 2002), and channel F4, associated with the cognitive functions of BA 08, of executive control (Kübler, Dixon & Garavan 2006) and planning (Crozier et al. 1999), for alpha 2; channel AF4, for beta 1; and channels AF4 and FC6, associated with the cognitive functions of BA 44, of namely goal-intensive processing (Fincham et al. 2002) and search for originality (Nagornova 2007), for beta 2. In the left hemisphere, the channels that revealed moderate effect size are: F3, associated with the cognitive functions of BA 08, of inductive reasoning (Goel et al. 1997), for alpha1; and the channel FC5, associated with the cognitive functions of Broca area, of complex verbal functions and reasoning processes (Goel et al. 1997; 1998) and metaphor processing (Rapp et al. 2004), for alpha 2.

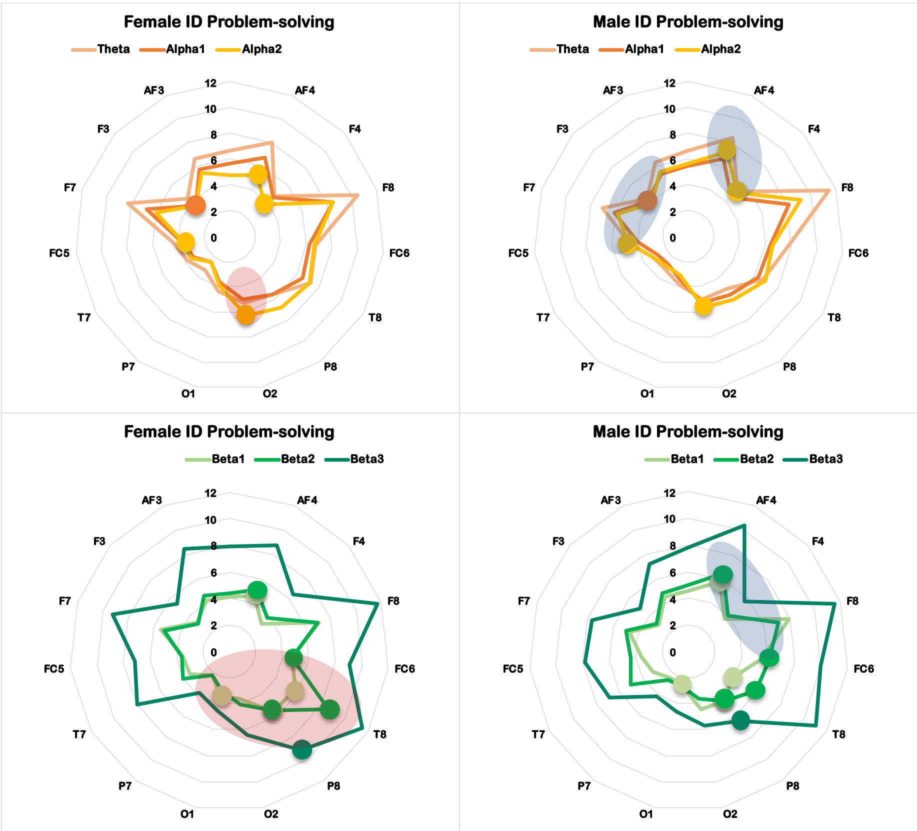

Figure 3. Transformed power (Pow) per channel for theta, alpha and beta frequency bands of the female and male industrial designers for the problem-solving stage. The solid circles indicate channels of moderate (>.50) and large (>.80) effect size. Shaded areas refer to higher frequency power in that group.

Table 3. Cohen's d for gender differences in the channels and bands of problem-solving.

Band	AF3	F3	F7	FC5	T7	P7	O1	O2	P8	T8	FC6	F8	F4	AF4
Theta														
Alpha 1		.52												
Alpha 2				-.52				.54					-.75	-.84
Beta 1							.63		.50	.74				-.63
Beta 2									.52	.56	-.58			-.60
Beta 3									1.00					

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3.2 Analysis of gender differences in design sketching

Total transformed power (Pow), for the design sketching stage across the 14 channels, frequency bands and gender, are depicted, Figure 4. We look at the cognitive demand in the sketching stage per gender and how it translates in brain activation. Cohen's *d* was calculated to measure the effect size for each electrode transformed power (Pow), between the genders for the sketching stage, Table 4. The solid circles indicate channels of moderate (>.50) and large (>.80) effect size, Figure 4.
Female industrial designers reveal increased prefrontal theta, and higher beta, in the left hemisphere, and increased beta 1 in the temporal cortex of the right hemisphere. Male industrial designers reveal increased prefrontal upper alpha and beta 1, and both alpha bands and beta 1 in the dorsolateral prefrontal cortex, of the right hemisphere.

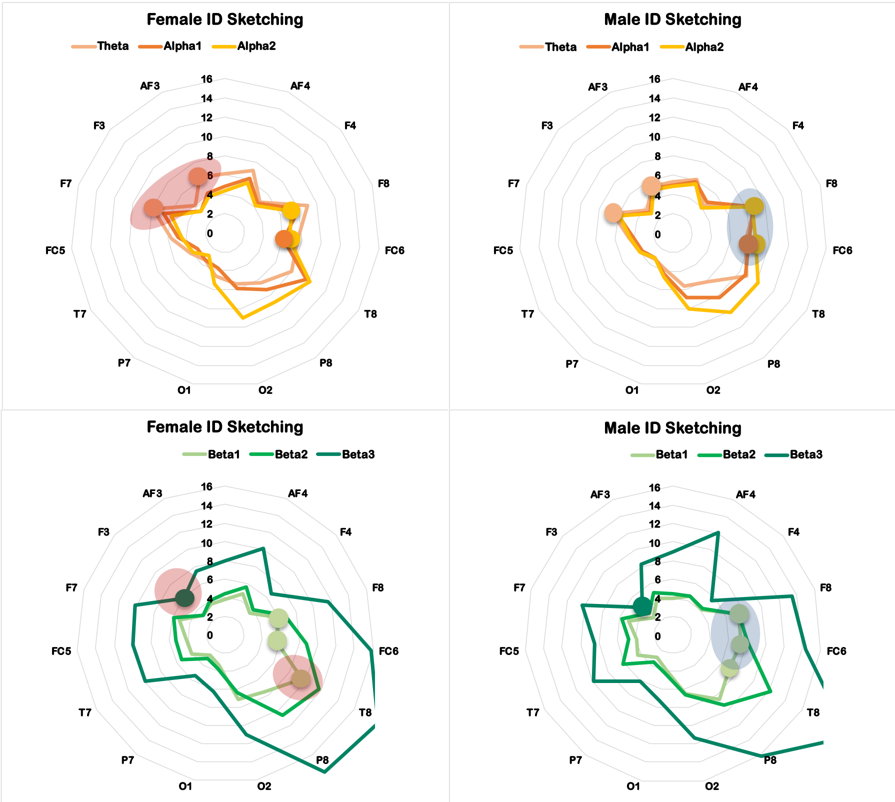

Figure 4. Transformed power (Pow) per channel for theta, alpha and beta frequency bands of the female and male industrial designers for the sketching stage. The solid circles indicate channels of moderate (>.50) and large (>.80) effect size. Shaded areas refer to higher frequency power in that group.

Female industrial designers reveal higher effect size in channels of both hemispheres. In the right hemisphere, one channel revealed moderate effect size, channel T8, associated with the cognitive functions of observation of motion (Rizzolatti et al. 1996), for beta 1. In the left hemisphere, female industrial designers revealed moderate effect size in the channels: AF3, associated with the cognitive functions of BA 09, of deductive reasoning (Goel et al. 1997) and metaphoric comprehension (Shibata et al. 2007), and F7, associated with the cognitive functions of BA 47, of deductive reasoning and semantic processing (Goel et al. 1997), for theta; and large effect size for F3, associated with the cognitive functions of BA 08, of inductive reasoning (Goel et al. 1997), for beta 3. Female industrial designers reveal channels with effect size in the left prefrontal cortex and right temporal cortex. Male industrial designers reveal moderate effect size in channels of the right dorsolateral prefrontal cortex, namely: channel F8, associated with the cognitive functions of BA 45, of response inhibition (Marsh et al. 2006), for alpha 2 and beta 1; and FC6, associated with the cognitive functions of BA 44, of goal-intensive processing (Fincham et al. 2002) and search for originality (Nagornova 2007), for alpha 1, alpha 2 and beta 1.

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Table 4. Cohen's d for gender differences in the channels and bands of sketching

Band	AF3	F3	F7	FC5	T7	P7	O1	O2	P8	T8	FC6	F8	F4	AF4
Theta	.52		.50											
Alpha 1											.77			
Alpha 2											.64	-.50		
Beta 1										.60	.77	.52		
Beta 2														
Beta 3		.86												

4 DISCUSSION AND CONCLUSION

The results from this study demonstrate that it is possible to address the investigation of gender differences and distinguish these differences in constrained and open design tasks. Results show hemispheric gender differences for the problem-solving stage of the constrained design task, and for the design sketching stage of the open design task performed by these industrial designers. Results provide initial answers to the research question and therefore we can infer the following:

- When problem-solving, male and female designers have different results for alpha power. Male designers show higher alpha in the right and left prefrontal cortices, with large effect size for the channel AF4. Female designers show higher alpha in the right secondary visual cortex. This is not entirely consistent with results from creativity research, where females demonstrated stronger synchronization of alpha power in the anterior cortex than males for originality (Fink and Neubauer 2006). This may be because the task is a problem-solving design task rather than a creativity task.
    - In the right hemisphere, male designers show higher alpha power associated with the cognitive functions of coordinating visual spatial memory (Slotnick & Moo 2006), and planning (Crozier et al. 1999, Fincham et al. 2002), while female designers show higher alpha power associated to visuo-spatial information processing (Wabersky et al. 2008). In the left hemisphere, male designers show higher alpha 1 power associated with inductive reasoning (Goel et al. 1997), and higher alpha 2 power associated with reasoning processes (Goel et al. 1997; 1998).
- Similarly, male and female designers have different results for beta power in problem-solving. Male designers show higher beta bands (1 and 2) in the right prefrontal cortex. Female designers show higher beta bands (1, 2 and 3) in the right occipitotemporal cortex, and secondary visual cortices, with large effect size for the channel P8 in beta 3.
    - In the right hemisphere, male designers show higher beta power associated with the cognitive functions of coordinating visual spatial memory (Slotnick & Moo 2006), planning (Crozier et al. 1999, Fincham et al. 2002), and executive control for beta 1 and 2, and goal-intensive processing (Fincham et al. 2002) and search for originality (Nagornova 2007), for beta 2, while female designers show beta 1, 2 and 3 power associated to observation of motion (Rizzolatti et al. 1996), and monitoring shape (Le, Pardo & Hu 1998) for beta 2 and beta 3. In the left hemisphere, female designers show higher beta 1 associated with visual mental imagery (Platel et al. 1997).
- When design sketching, male designers show results for alpha power in the right prefrontal cortex, while female designers do not, but instead show results for theta power in the left prefrontal cortex.
    - In the right hemisphere, male designers show higher alpha power associated with the cognitive functions of response inhibition (Marsh et al. 2006), and both alpha power associated with goal-intensive processing (Fincham et al. 2002) and search for originality (Nagornova 2007), differently from the results for problem-solving. In the left hemisphere, female designers show higher theta power associated with the cognitive functions of deductive reasoning (Goel et al. 1997), metaphoric comprehension (Shibata et al. 2007), and semantic processing (Goel et al. 1997).
- Male and female designers have different results for beta power in sketching. Male designers show higher beta 1 in the right prefrontal cortex. Female designers show higher beta 1 in the right temporal cortex, and higher beta 3 in the left prefrontal cortex with large effect size for channel F3.
    - In the right hemisphere, male designers show higher beta 1 power associated with the cognitive functions of goal-intensive processing (Fincham et al. 2002), search for originality

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(Nagornova 2007), and response inhibition (Marsh et al. 2006), while female designers' beta 1 power is associated with the cognitive functions of observation of motion (Rizzolatti et al. 1996). In the left hemisphere, female designers show higher beta 3 power associated with the cognitive functions of inductive reasoning (Goel et al. 1997).

The hemispheric differences found in beta power for both stages, and genders, are consistent with Razumnikova (2004) findings that associate creativity to beta power in both genders, differing in terms of hemispheric organization of brain activity during creative thinking. Prioritising different cognitive functions seems to play a role in each gender's approach to constrained and open design tasks. This study has shown that brain activations can be used as a measure to identify frequency bands associated to each gender, while performing problem-solving and design sketching. Results can be useful to understand the practice of design when gender and task differences emerge and can be useful for design professionals, students and design educators, and to the development of methodological approaches in design research and education.

ACKNOWLEDGEMENTS

The research is funded by the Portuguese Foundation for Science and Technology, grant number SFRH/BPD/104281/2014 and has support of the US National Science Foundation, Grant Nos CMMI-1762415 and EEC-1929896. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

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