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Brain Electrical Activation among Experienced Designers Engaging in Tasks that Involve Transforming Imagination

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Abstract

Background and Objective: Experienced designers make connections with knowledge stored in their memory and transform their solutions to respond to design problems. However, little research has explained how they engage in this transformation.

Methods: The current study examined the brain activation, supplemented with narrative information, resulting from pictorial stimulation among experienced designers while they engaged in tasks that involve transforming imagination.

Results: This study recruited 15 healthy and experienced designers to participate in an electroencephalography experiment and a structured in-depth interview.

Conclusions: The results illuminated several key variations in brain activation, including those that existed (i) among various lobes when the designers engaged in both visual stimulation and design improvement tasks involving transforming imagination; (ii) among the three indicators of transforming imagination in both experimental tasks; and (iii) between the two experimental tasks involving transforming imagination.

Key Words: Brain Activation, Electroencephalography, Experienced Designer, Pictorial Stimulation; Transforming Imagination

Introduction

Designers value imaginative capacity and consider it the basis for cultivating creative ideas (Folkmann, 2013). Imaginative capacity typically concerns making associations and analogies between concepts that had not seemed connected previously (Liu & Noppe-Brandon, 2009, p. 182). This type of capacity is known as transforming imagination, and can be understood as the capacity to crystallise mental images through associations across various domains, which depend on the clever application of experiences (Liang & Chia, 2014). Previous studies have concluded that experienced designers make connections with knowledge stored in their long-term memory, and transform their ideas into solutions that are useful and appropriate for design problems (Ericsson, 2006). Recent research has further confirmed that transforming imagination positively predicts design performance (Liang & Lin, 2015; Lin, Hsu, & Liang, 2014).

Experienced designers usually establish rich resources within themselves that can be used to address various design problems. Generally, these resources are visual stimuli of various types (Goldschmidt, 2015) that enhance creative performance (Casakin & Goldschmidt, 2000). Ericsson (2006) indicated that experienced designers associate these visual images with ideas collected from life experiences and transform them into potential resolutions involving people, objects, and contexts, particularly during the early stages of conceptualisation. Although this preliminary design process is critical for problem solving, little research has offered scientific evidence to illuminate how pictorial stimulation influences experienced designers engaged in tasks that involve transforming imagination (Ahmed, Wallace, & Blessing, 2003).

New techniques for detecting brain activity are becoming more widely available, presenting opportunities for exploration through interdisciplinary research that combines insights from cognitive neuroscience and design studies that can be instrumental for testing a variety of hypotheses crucial to design research (Alexiou, Zamenopoulos, Johnson, & Gilbert, 2009). Recent research efforts have shed light on the previously unknown areas of design; for example, numerous studies have investigated design cognition in the brain (Alexiou et al., 2009; Aziz-Zadeh, Liew, & Dandekar, 2013), and scientists are currently exploring which areas of the brain are causally related to creativity in designers (Liang, Lin, Yao, Chang, Liu, & Chen, 2017; Yao, Lin, King, Liu, & Liang, 2017). In particular, scholars have suggested that topics with research potential, such as expertise in designing, visual analogy, visualisation, and embodiment, must be targeted (Seitamaa-Hakkarainen, Huotilainen, Mäkelä, Groth, & Hakkarainen, 2014). The outcomes of these research efforts link cognitive neuroscience to designer imagination, and are expected to offer a concrete foundation for developing educational strategies and for additional applied inquiries.

The current study provides additional contributions towards the understanding of brain activation, supplemented with narrative information, resulting from pictorial stimulation among experienced designers while they engage in the tasks involved in transforming imagination. Electroencephalography (EEG) and an in-depth interview were conducted with each participant to answer the following research questions:

(i) What are the differences in brain activation among various lobes while the designer participants engage in both visual stimulation and design improvement tasks involving transforming imagination?

(ii) What are the differences in brain activation among the three indicators of transforming imagination (i.e., exploration, crystallisation, and transferability) while the participants engage in both experimental tasks?

(iii) What are the differences in brain activation between the two experimental tasks involving transforming imagination?

The outcomes of this study are expected to clarify how these designers apply their experience, and to identify the educational implications of such practices.

Literature Review

Designer Experience and Experienced Designers

Experiences are the transactions that occur between an individual and the world, and which serve as a frame of reference for designers managing design problems (Akin & Akin, 1996). The moves of expert designers build on references gathered through their experiences; drawing inspiration from these experiences, designers look for precedents that share common characteristics with the current situation and introduce new ideas from diverse sources (Lawson & Dorst, 2009). Experienced designers are generally able to cope with uncertainty, patiently awaiting opportunities to synthesise the essential features of various solutions into a new configuration. They are also capable of integrating multiple perspectives into a coherent design. Numerous studies regarding the influence of experience during design problem solving have been conducted over the past thirty years (e.g., Cross, 2001; Lawson & Dorst, 2009).

Experience enables designers to adopt a conjectural approach to their designs, framing design problems in terms of relevant solutions. Ball and Ormerod (1995) indicated that experienced designers usually adopt a flexible mixture of problem-solving modes for realistic control. Furthermore, Cross (2001) stated that designers are solution focused, which he argued is a feature of design cognition that enables designers to move quickly between problem scoping and solution proposal according to their experience in certain problem domains. This generative approach is particularly appropriate given the ill-defined nature of most design problems. Cross thus emphasised that speculating about possible solutions and incrementally improving upon those ideas can be the most effective approach in complex situations, because setting and changing goals are inherent elements of design activity.

The coevolution of problems and solutions for expert designers is a situated process; thus, they invent design requirements situated in their design environment, which enables them to rapidly explore problems and solutions (Cross, 2004). Behaviourally, most expert designers become readily adherent to a limited number of possible solutions, which emerge through the gradual expansion and transformation of a few core ideas and are eventually proven to be the most appropriate strategy (Ericsson, 2006). However, Cross (2001) warned that some designers may be too ready to reuse features of existing designs, rather than to explore the problem and generate new design features; in short, experience should be used to effectively manage problems. Generally, experienced designers refer to past designs often, but also keep their options open. They are aware of the reasons, limitations, trade-offs, and relevant problems behind a particular design decision, and they often question the data at hand and whether a particular approach is worthwhile (Ahmed, Wallace, & Blessing, 2000).

Transforming Imagination and Visual Stimulation

Designers typically use their imaginations to engage target markets and address a range of unstable technologies, standards, and politics that comprise the design process (Knutsen, 2014). Thus, imagination can assist in shifting a designer's focus from current problems to potential solutions through creative thinking (Gkouskos, Normark, & Lundgren, 2014). Designers must also transform user experience into design considerations and cooperate with marketers in creating authentic value propositions to be competitive in the marketplace (Sääksjärvi & Hellén, 2013). This implies that designers commence their creative process with contextual features, and then transform their ideas by determining the association between these features and their experiences until an integrated whole is developed (Nam & Kim, 2011); this practice is also known as transforming imagination.

Transforming imagination is the capacity to explore unknown concepts, crystallise abstract ideas, and recreate mental images according to various domains and situations (i.e., the ability to imagine the future by applying experiences) (Hsu, Peng, Wang, & Liang, 2014). Transforming imagination plays a central role in creative cognition and the development of expertise by applying knowledge to clarify fuzziness. Three indicators are embedded in this capacity, namely exploration, crystallisation, and transferability (Hsu et al., 2014). Exploration refers to the ability of an individual to explore the unknown; crystallisation is the ability of an individual to express abstract ideas using concrete examples; and transferability refers to the ability of an individual to perform tasks by transforming what they know across multiple fields of knowledge (Liang & Chia, 2014). Fallman (2008) indicated that design involves a period of exploration in which ideas are tested and 'what if?' is asked. With growing experience, visualisation (a concept similar to crystallisation) replaces abstract functional models (Ericsson, 2006). Even for experts, who are likely to address nonroutine problems, the explicit search for source analogues and experience transfer are feasible strategies for generating effective design solutions (Ball, Ormerod, & Morley, 2004).

To search for source analogues, particularly in the early stages of the design process, visual analogies are a helpful cognitive strategy for enhancing problem-solving (Casakin & Goldschmidt, 1999). The sensitive designer possesses a 'prepared eye', which is able to take advantage of the stimuli it encounters in any environment (Goldschmidt, 2015); however, such an evocation-enhancing design process depends on both the inspiration sources and the designer's level of expertise (Bonnardel & Marmèche, 2004). Casakin (2005) demonstrated that visual displays particularly benefit expert designers, but not novice designers, working on well-defined problems. Prior research has also indicated that abstract objects are beneficial for generating original ideas and overcoming design fixation (Cila, Hekkert, & Visch, 2014); notably, Goldschmidt and Smolkov (2006) suggested that the influence of visual stimuli largely depends on the type of design problem.

Brain Activation

The cognitive activity of experienced designers can be understood as a pattern of structured organisation and systematic expansion with numerous concurrent actions, rather than an exhaustive search strategy (Kavakli & Gero, 2002). As designer expertise develops, knowledge becomes increasingly structured and integrated with experience, and can be retrieved from memory in larger chunks (Casakin & Goldschmidt, 1999; Popovic, 2004). The strategic knowledge possessed by experts enables them to use fewer processes and to form more groups of processes compared with novices. Furthermore, experts process that knowledge in more efficient ways and demonstrate a superior intuitive performance over novice designers (Ball et al., 2004; Popovic, 2004). Experienced designers are usually capable of applying highly schematised knowledge structures and extensive domain-based experiences, according to the automatic recognition of familiar types of problems and solutions (Ball et al., 2004). Thus, the structure and activity of neural network patterns in designers' memory activation in response to stimuli, and their sensitivity, expertise, and flexibility to focus and defocus attention are combined to generate creative design ideas (Goldschmidt, 2015).

Transforming imagination is closely associated with cognitive activities, such as mental simulations and future imagination. Studies have identified that the medial temporal lobe stores memories and associations from experiences, and that the medial prefrontal lobe facilitates the flexible use of these memories (Buckner, Andrews-Hanna, & Schacter, 2008; Gerlach, Spreng, Gilmore, & Schacter, 2011). These two lobes converge on major integration nodes, including the posterior cingulate cortex (PCC); moreover, cognitive activities occur in the core regions of the default mode network (DMN), dorsolateral prefrontal cortex, and distributed regions, including the medial prefrontal cortex and the medial temporal and parietal regions (Gerlach et al., 2011; Szpunar, St. Jacques, Robbins, Wig, & Schacter, 2014). Beaty et al. (2014) concluded that the high cooperation among the brain regions is associated with cognitive control and imaginative processes. Göker (1997) examined designers' skills in computer simulations, and found that experts used more of the visuospatial brain regions, whereas novices used more of their brain regions associated with verbal–abstract reasoning. This implied that experts rely more on their experiences and visual information than on reasoning to develop a design concept in an abstract manner. Göker further indicated that activity in the right parietal region of the brain increases with experience. Contemporary studies have determined that the frontal and prefrontal regions, particularly the right hemisphere, play a critical role during design conceptualisation (Alexiou et al., 2009). However, Aziz-Zadeh et al. (2013) indicated that even for a task specialised in the right hemisphere, robust parallel activity in the left hemisphere supports creative processing. In addition, other previous studies have indicated that activity levels are lower in experts than in novices because experts process information more efficiently (Kavakli & Gero, 2002; Popovic, 2004).

Method

This study was approved by the Research Ethics Office of the National Taiwan University (NTU-REC No: 201505HS090). A 32-channel EEG experiment with structured interviews was designed to analyse the brain activation among experienced designers while they engaged in the tasks involving transforming imagination. In total, fifteen healthy designers who met the inclusion criteria were invited to join the experiment. Both brainwave and narrative data were collected from the participants, and the differences among the three imaginative-capacity indicators and two distinct tasks caused by several types of visual stimuli were examined. The visual stimuli comprised art from three renowned artists.

Designer Participants

The present study recruited 15 (six female) healthy experienced designers, who all met the following inclusion criteria: (i) 15 or more years of experience working in the design industry, product design in particular; (ii) prominence in the design industry, gained through word of mouth; (iii) experience leading design teams, or being renowned as a freelancer; (iv) participation in international product design competitions where they have received awards; and (v) availability between March and May 2016, and willingness to participate in the experiment. The age of the participants ranged from 39 to 54 years, and they had an average of 19.2 years of working experience in the design industry. The participants were coded from D1 to D15.

Selection of Visual Stimuli and Experimental EEG Device

The visual stimuli used in this study were several pieces of art from three renowned artists, Jean-François Millet, Pablo Picasso, and Joan Miró, who enjoy worldwide recognition within the three major art movements (realism, abstractionism, and surrealism, respectively). In addition to the marked influence of these diverse visual stimuli on designers, the majority of the works by these artists have become public domain in most of the world because they were largely published prior to 1930; thus, the use of this art was limited to research purposes and involved no commercial practices.

First, ten representative pieces by each artist were nominated individually by the researchers, and the selections were then compared with each other to ensure that the same work did not appear twice.

After several runs of nomination and comparison, 15 pieces by each artist were compiled. The art was subsequently compared according to the characteristics of perceptual fluency, including perceptual priming, clarification, repetition, composition, and figure–ground contrast (Reber, Schwarz, & Winkielman, 2004). A final list of six pieces by each artist, which were considered to possess a similar level of perceptual fluency, was developed. One piece by each artist was then randomly selected and assembled as a group, forming six groups; these six groups were randomly presented to the participants during the experiment.

The EEG headset used in this experiment was a 32-channel inflatable and wearable wireless system (Brain Rhythm Inc., Taiwan) consisting of two dry, foam-based EEG sensors that are used only for the forehead Fp1 and Fp2 sites in the international 10–20 system. It also featured spring-loaded dry electrodes and a soft cap, rendering it convenient, precise, and easily donned. The dry sensors were resilient and could be used repetitively on hairy sites without conductive gel. This wearable system has 16-bit quantisation and a sampling rate of 250 Hz. A single reference electrode was placed on the mastoid behind the ear and the electrode impedance was kept as low as possible (≤ 5 KΩ). In addition, the EEG data could be wirelessly received by portable devices, such as laptops, smartphones, or tablets, through the Bluetooth protocol without external devices or cables. Data collected from the experiments were finally exported in ASCII (.txt) format.

Experimental Procedures

After the participants arrived at the lab, a letter of informed consent was read by the chief researcher and written permission from each participant was obtained prior to participation. Simultaneously, a research assistant helped the participants attach an EEG headset and test whether the signal of each EEG channel was received correctly. During the experiment, the participants were first asked to describe a design project that was ongoing or had been completed within the previous 6 months. The structured in-depth interview acquired the necessary information regarding the design problem, purpose, and imagined outcomes of each participant. The interviews, which lasted for approximately 2 minutes, were audio-recorded and subsequently transcribed after receiving additional permission from the participants. After this initial session, the researchers randomly selected and showed one group of art, and asked the participants to complete specific tasks by answering questions corresponding to the indicators involved in transforming imagination (exploration, crystallisation, and transferability in sequence).

To understand the exploration indicator (i.e., the ability to inquire about the unknown), each participant was asked to select an item from the three pieces of art to answer the following questions: ‘From this picture group, please select an item that arouses your curiosity’; ‘What do you want to explore further (e.g., the originality of the idea, the techniques used)?’; and ‘How would this additional exploration improve your originally imagined outcome?’ The first question was related to the task of visual stimulation, whereas the second was for the task of design improvement. When responding to each question, the participants first remained silent and EEG data were recorded for 20 seconds; the participants then verbalised their answers for 100 seconds. Therefore, each run of this session lasted for 2 minutes. The purpose of the 100-second narration subsession was to acquire the qualitative data and to provide intertrial intervals to avoid recording overlapping brain responses. To ensure the quality of this experiment, the researchers then repeated the same procedure for the exploration indicator with a different piece of art as the visual stimulus.

To understand the crystallisation indicator (i.e., the ability to visualise abstract concepts by using concrete examples), each participant was again asked to select one piece of art from the group of three and answer the following questions: ‘What concepts do you want to express in this project?’; ‘From this picture group, please select an item representative of the concepts you want to express’; and ‘How does this artwork help you to crystallise your concepts? How does it improve your originally imagined outcome?’ Similar to the exploration indicator session, two runs of the experiment were conducted to examine crystallisation.

Finally, to understand the transferability indicator (i.e., the ability to perform tasks by applying information acquired across multiple fields of knowledge), each participant was asked to select another piece of art from the group of three and answer the following questions: ‘What experiences gained from this project do you think can be transferred to the follow-up project?’; ‘Which item in this group would benefit from this transfer?’; and ‘How would this item benefit the experience transfer? How does it improve your originally designed outcome?’ Again, two runs of the experiment were conducted.

Through this series of six 2-minute sessions, each group of artwork was presented, and an understanding of the three indicators of transforming imagination was acquired. In total, the experiment lasted for approximately 30 minutes, including the periods of project description and EEG headset testing. The process was identical for all participants to ensure the validity of the inquiry. Finally, both the brainwave results and interview answers were analysed.

Data Analyses

Gamma (γ) waves are patterns of neural oscillation in the human brain with a frequency between 25 and 100 Hz, although 40 Hz is typical. These waves are associated with bursts of insight and high-level information processing in the brain, which foster intuition and creativity (Reedijk, Bolders, & Hommel, 2013). Scholars have indicated that γ waves in the visual cortex are associated with critical functions, including perceptual grouping and selection, attentional stimulus selection, and efficient stimulus representation (Brunet et al., 2015); the activation of γ waves thus served as a target for observing the transforming imagination of experienced designers in the current study.

All EEG data were inspected to remove nonfunctional EEG channels. A low-pass filter with a cutoff frequency of 50 Hz and a high-pass filter with a cutoff frequency of 0.5 Hz were subsequently applied to remove the line noises and drifting artefacts, respectively (Wang, June, & Lin, 2015), and the average correlation coefficient of the filtered signals was computed for each of the channels. The filtered EEG signals were decomposed into independent brain sources through an independent component analysis (ICA) using EEGLAB. Once a component is identified as artefactual (including eye blinks, eye movements, muscle activity, and bad channels), it is isolated and removed from the data by reversing the ICA linear unmixing process (Jung et al., 2001). Notably, nonartefactual component scalp maps often strongly resemble the projection of a single dipole, enabling the location and orientation of the best-fitting equivalent dipole (or other source model) to be easily determined (Onton, Westerfield, Townsend, & Makeig, 2006; Wang et al., 2015).

Finally, the interview transcripts were prepared for a two-coder analysis strategy, and were coded independently to avoid influencing the analyses. A theory-driven strategy was used as the initial coding frame, which enabled new codes or themes to emerge through data analysis (Braun & Clarke, 2006). Triangulation was also applied to ensure the quality of this study, and the following tests were conducted to ensure reliability and validity: (i) a topic guide was used to ensure that a similar range of topics was expressed by each participant; (ii) interview transcripts were sent to the participants for revision and confirmation; and (iii) the researchers compared the content of the transcripts with the extant literature to determine whether any topics required further discussion.

The interrater reliability of each indicator was calculated by two raters (the authors). The Cohen kappa statistical test was used to measure intercoder reliability, revealing statistically significant consistency in the scores assigned by the two experts in design creativity, and indicator classification was used to assess the reliability of the agreement between the two raters. The Cohen kappa of this score was 0.84 (> 0.70), indicating a significant correlation ($p < .01$) between the qualitative data assessed by the raters (Banerjee, Capozzoli, McSweeney, & Sinha, 1999).

Results

Differences in Brain Activation Involving Transforming Imagination and Its Indicators

During the visual stimulation experiment, γ waves from the T8 (M = 2.90 μV, SD = 0.23 μV), FC3 (M = 2.58 μV, SD = 0.29 μV), and F8 (M = 2.46 μV, SD = 0.21 μV) locations were the most activated [F(31, 448) = 1.6298, $p < .05$], indicating that the frontal and right temporal regions of each participant were used the most during the visual stimulation of transforming imagination (Figure 1a).

Specifically, the γ waves from the T8 (M = 2.39 μV, SD = 0.31 μV), FT8 (M = 1.85 μV, SD = 0.19 μV), and T7 (M = 1.77 μV, SD = 0.18 μV) locations, representing the bilateral temporal and right frontotemporal regions, were the most activated [F(31, 448) = 1.9343, $p < .05$] during questions about exploration. Conversely, the γ waves from the CP4 (M = 2.11 μV, SD = 0.20 μV) location, representing the right parietal region, were the most activated [F(31, 448) = 1.2162, $p < .05$] during questions about crystallisation. Finally, the γ waves from the T8 (M = 2.65 μV, SD = 0.19 μV), CP4 (M = 1.63 μV, SD = 0.12 μV), and T7 (M = 1.62 μV, SD = 0.11 μV) locations, representing the bilateral temporal and right parietal regions, were the most activated [F(31, 448) = 1.2222, $p < .05$] during discussions about transferability (Figures 2a, 3a, & 4a).

During the design improvement experiment, γ waves from the T8 (M = 3.45 μV, SD = 0.28 μV), FC3 (M = 2.18 μV, SD = 0.19 μV), Oz (M = 1.92 μV, SD = 0.15 μV), and CP4 (M = 1.69 μV, SD = 0.11 μV) locations were the most activated [F(31, 448) = 2.5362, $p < .05$], indicating that the frontal, parietal, temporal, and occipital regions of each participant were used the most at this stage (Figure 1b).

Specifically, the γ waves from the T8 (M = 3.59 μV, SD = 0.26 μV), Cz (M = 2.58 μV, SD = 0.38 μV), Oz (M = 2.30 μV, SD = 0.29 μV), and T7 (M = 1.95 μV, SD = 0.15 μV) locations, representing the parietal, temporal, and occipital regions, were the most activated [F(31, 448) = 1.6298, $p < .05$] during questions about exploration. Conversely, the γ waves from the T8 (M = 2.88 μV, SD = 0.25 μV), CP4 (M = 1.93 μV, SD = 0.21 μV), and FT8 (M = 1.93 μV, SD = 0.22 μV) locations, representing the right frontotemporal, right temporal, and right parietal regions, were the most activated [F(31, 448) = 1.6466, $p < .05$] during questions about crystallisation. Finally, the γ waves from the T8 (M = 2.87 μV, SD = 0.45 μV) and CP4 (M = 1.81 μV, SD = 0.22 μV) locations, representing the right temporal and parietal regions, were the most activated [F(31, 448) = 2.3973, $p < .05$] during discussions about transferability (Figures 2b, 3b, & 4b).

Visual stimulation (a)

Design improvement (b)

Figure1: Activation of γ waves associated with transforming imagination.

Visual stimulation (a Design improvement (b)

Figure 2: Activation of γ waves associated with the exploration indicator.

Visual stimulation (a Design improvement (b)

Figure 3: Activation of γ waves associated with the crystallisation indicator.

Visual stimulation (a Design improvement (b)

Figure 4: Activation of γ waves associated with the transferability indicator.

Differences in Brain Activation During the Experimental Tasks

The γ-wave activation from the FCz location significantly differed $[t(14) = 2.2275, p < .05]$ between the visual stimulation and design improvement tasks during questions about transforming imagination, indicating that the brain activation resulting from the two experimental tasks primarily diverged in the central frontal region.

Specifically, the γ-wave activation from the FCz location significantly differed $[t(14) = 2.1403, p < .05]$ between the visual stimulation and design improvement tasks during discussions of exploration, indicating that the brain activation resulting from the experimental tasks was primarily different in the central frontal region. Similarly, the γ-wave activation from the F8, FT8, TP7, CP4, and P3 locations significantly differed $[t(14) = 2.4655, p < .05; t(14) = 3.0326, p < .05; t(14) = 2.5186, p < .05; t(14) = 2.3508, p < .05; t(14) = 2.4527, p < .05]$ between the visual stimulation and design improvement tasks during discussions of crystallisation, indicating that the brain activation resulting from the experimental tasks was primarily different in the right frontal and parietal regions. Conversely, no significant difference in γ-wave activation between visual stimulation and design improvement tasks during discussions of transferability was observed, indicating that brain activation was similar in the two experimental tasks.

Narrative Information from Structured Interviews

An analysis of the structured interviews was conducted for supplementary information, rather than scientific comparison, in the current study. For exploration, most of the participants (12/15) were attracted to either surrealist or abstract artworks, indicating that unusual or surprising visual stimuli provoked further inquiry. In addition, sophistication may have been a key factor promoting deeper analysis. During the visual stimulation task, the participants stated, 'The luminous effect attracts me, making me think of the Na'vi in the movie Avatar' (D2); 'What is the foggy white spot for? Is there anyone behind it?' (D5); 'This picture seems loud, full of children's language. I'd like to know what they are doing together' (D11); and 'The usage of colours is interesting—particularly the combination of white, silver, and gold' (D13). Similarly, during the design improvement task, the participants noted the following: 'It looks like aliens, making me rethink the relationship between different objects in my design' (D5); 'The presentation of dynamic lines is inspiring. I wish I tried it on my project' (D9);

‘The objects are sophisticated but also cute… I’d like to try it in my design’ (D11); and ‘This work makes me rethink the ideation process of my design. How can this new initiation bridge the gap between the brand and the target market?’ (D12).

For crystallisation, almost all of the participants (14/15) effectively used concrete examples to express abstract concepts. The stimuli selected by the participants largely depended on the participants’ design problems and purposes. During the visual stimulation task, they observed, ‘The people in this artwork have distinctive characters, easily identified in our daily life. This presentation ensures the message is easily grasped’ (D1); ‘Nature is the core concept in this design. This realist work matches the concept’ (D4); ‘I tend to use bright tones because the style is relatable to my target audience’ (D6); and ‘The levels and details of this work make the concept concrete’ (D8). Similarly, during the design improvement task, the participants noted the following: ‘It is easy to sense the atmosphere from this artwork even without any annotation. I think that I should add more elements like this to my project’ (D3); ‘People and landscapes are central in this design. This picture reminds me to consider user needs’ (D10); ‘The variation in light and shadow, the story presented, and the depth of artistic expression are pretty self-promoted, which inspires me’ (D14); and ‘The colours are dynamic but also harmonious, reminding me that the core of this mobile system is diversity and convenience’ (D15).

For transferability, most participants (13/15) selected surrealist or abstract works as tools for transferring existing experiences or design ideas, which implies that the designers may need to transform their experiences into nonrealistic concepts for further application. During the visual stimulation task, they stated, ‘The simple geometrics, bright colours, and varied patterns in this artwork help me to extend ideas’ (D3); ‘The strong but also elegant presentation of lines inspires me for my own ongoing proposal’ (D7); ‘The design concept of this work is simple and clear, and is therefore easy to apply’ (D10); and ‘The simplified colour blocks can be applied in the future’ (D15). Similarly, during the design improvement task, the participants noted the following: ‘The picture is full of kids’ signs. To embody the features of childhood can be the main approach to recreating the current design’ (D1); ‘I will try the sophisticated combination of diverse elements presented in this work to rebuild my design’ (D4); ‘This unified colour tone with various levels of detail could be applied to my follow-up project’ (D9); and ‘I may break apart patterns that I have built, and rebuild them based on new goals’ (D14).

Discussion

Brain Activation Regarding the Exploration Indicator

Within transforming imagination, exploration refers to the ability of an individual to explore the unknown. Although prior research has demonstrated that exploratory behaviour is closely associated with particular characteristics, such as curiosity and passion (e.g., Colello, 2007), the present study further suggests that sophisticated, unusual, or surprising visual presentations can trigger design exploration. In addition, design exploration relies heavily on synthetic processes in which designers often seek to provoke, criticise, and experiment to reveal alternatives that transcend current paradigms, to negotiate and exchange the space between the known and unknown, and to be proactive and societal in expression (Fallman, 2008; Folkmann, 2013). Our results support this view, and provide further insights into how visual stimuli can inspire design exploration.

Design exploration involves numerous activities for seeking alternatives and insights. Our results indicated that the right anterior temporal lobe (ATL) was particularly activated during the visual stimulation task, acting as a domain-general semantic hub that was critical for generating insights and stimulating the participants to ‘think outside the box’ (Kaufman, 2012). In addition, the bilateral temporal regions were also frequently activated. One notable part of the temporal lobe, the hippocampus, plays a key role in human memory and is associated with the interpretation of visual stimuli and the establishment of object recognition (Smith & Kosslyn, 2007). Because design exploration often involves mentally negotiating and exchanging the space between the known and unknown, interaction between the right ATL and bilateral temporal regions is necessary.

The design improvement task for the exploration indicator required that the participants respond to visual stimuli, recall a current or recent project, identify absences, and propose strategies for enrichment. It is reasonable to predict that the DMN plays a central role in this task, because the network is active when people engage in internally focused tasks, including autobiographical memory retrieval, conceptualising others’ perspectives, episodic future thinking, mental simulation, and mind wandering according to personal experiences (Beaty et al., 2014; Buckner et al., 2008). Probing the functional anatomy of this network in detail reveals that it is best understood as multiple interacting subsystems throughout the distributed brain regions, including the parietal and temporal lobes. In addition to the ATL–temporal network, our findings suggest the crucial role of designers’ DMNs in their exploratory behaviour.

Brain Activation Regarding the Crystallisation Indicator

Crystallisation in this study refers to the ability of an individual to express abstract ideas by using concrete examples. Human imagination can bridge the gap between images and ideas (Perdue, 2003), which implies that rational thought occurs in the form of images that are stored and combined in a person’s imagination. With this ability, designers effectively use concrete examples to express abstract concepts and interpret perceptions, as indicated by the narrative analysis of the structured interviews herein. As Vygotsky (1930/2004) asserted, all objects that are common in life appear as the crystallisation of an imagined concept. Our findings expound the influences of design problems and purposes on how designers illustrate their ideas, and suggest that using life examples may help designers crystallise their ideas for their team members and clients.

Crystallisation enables designers to effectively elucidate abstract ideas by using examples from common life. Our results reveal that the right parietal region was particularly activated during the visual stimulation task for this indicator. Notably, this brain region is activated when people are planning their own behaviours or imaging the behaviours of others (Decety & Sommerville, 2006) and is closely associated with the information process of concrete spatial representations (Goel & Dolan, 2001), establishing the theoretical foundation for further inquiry of the crystallisation indicator. In addition, Sandkühler and Bhattacharya (2008) indicated that notable γ waves are detected at the parietal lobe when research participants generate insightful problem solving, offering further support for the enlightenment of designer behaviour through crystallisation.

Furthermore, during the design improvement experiment of the crystallisation indicator, γ waves were observed in the right frontotemporal, right temporal, and right parietal regions. Previous studies have demonstrated that the frontal lobe plays a crucial role in understanding abstract concepts, and the activation of the right frontotemporal lobe is conducive to the formation of new ideas (Gerlach et al., 2011; Kaufman, 2012). In addition, the bilateral temporal regions are involved in transforming sensory input into derived meanings for the appropriate retention of visual memories (Smith & Kosslyn, 2007). The temporoparietal cortex has a critical role in abstract concept representation, and is part of a larger network of functionally cooperative regions required for abstract word processing (Skipper-Kallal, Mirman, & Olson, 2015). Our findings support the vital role of the right frontotemporal and temporoparietal lobes for developing designers' crystallisation abilities.

Brain Activation Regarding the Transferability Indicator

Transferability in this study refers to the ability of an individual to perform tasks by transforming what they know across multiple fields of knowledge. Similarly, Vygotsky (1930/2004) indicated that analogies occur not only from thinking about a singular object but also from connecting one object or field to another, as the designers expressed in this study. Ball et al. (2004) suggested that analogical reasoning and the application of highly schematised knowledge structures could be a feasible strategy for facilitating the generation of design solutions. The results of the structured interviews herein additionally verify the influence of nonrealistic visual stimuli on idea applications and experience transfers. Such stimuli may include diverse combinations of colours, lines, patterns, signs, levels of detail, and even the design concept or overall design presentation.

Accordingly, high levels of design transferability optimise designers' idea transformations, and analogical reasoning plays a central role in creative cognition and experience transfer. Our results reveal that, during the visual stimulation task, the most activated brain regions were the bilateral temporal and right parietal lobes, which particularly contribute to analogical reasoning (Sandkühler & Bhattacharya, 2008). Ball et al. (2004) indicated that experienced design behaviour is characterised by the presence of more schema-driven analogising than case-driven analogising, because, for experts, domain-based problems fall more towards the familiar end of the familiar–unfamiliar continuum. Krawczyk (2012) further suggested that posterior areas within the temporal, parietal, and occipital lobes provide evidence of domain dependence in analogical reasoning, whereas the prefrontal areas exhibit domain independence in relational reasoning.

During the design improvement experiment for this indicator, γ waves were observed in the right temporal and parietal regions. In agreement with the preceding discussion, the activation of these regions supports domain-dependent analogical reasoning. According to the automatic recognition of familiar types or categories of problems and solutions, analogical reasoning and the application of schematised knowledge structures can facilitate the generation of feasible design strategies (Ball et al., 2004). Our findings regarding this indicator support the decisive role of the right temporoparietal regions for design transferability.

Brain Activation During Transforming Imagination

Transforming imagination, by definition, is the capacity of imagininga future by applying knowledge to clarify fuzziness. Nam and Kim (2011) indicated that the creative process of designers is initiated through the association between contextual features and their experiences, and is continually transformed until an integrated whole of design ideas is developed. In the current study, although the stimuli selected by the participants was dependent on their design problems and purposes, their transforming imagination was observed to be primarily stimulated by surrealist visual stimuli, featuring elements of surprise, unexpected juxtapositions, and non sequiturs, as described by the Phaidon Editors (2001). The designers tended to use these stimuli as references for transforming ideas and transferring experiences; our findings also suggest that designers may need to transform experiences to nonrealistic concepts before proceeding with further applications.

Designers' sensitivity and flexibility to focus and defocus attention on visual stimuli are combined for creative design, as observed from their neural network activities (Goldschmidt, 2015). Our results indicated that, during the visual stimulation task, the frontal and right temporal regions were the most activated, a finding consistent with previous studies (Buckner et al., 2008; Gerlach et al., 2011). Although these studies identified that the medial temporal lobe creates associations from experiences, and the medial prefrontal lobe facilitates the use of these experiences, the current study demonstrated that notable memory retrieval from the frontal and right temporal lobes is the key to facilitating transforming imagination in experienced designers. Because the right temporal lobe is responsible for nonverbal memory and communication, our results also echo the claim that experts rely more on visual information than on reasoning to develop design concepts in an abstract way (Göker, 1997).

During the design improvement experiment, the results revealed that engagement in transforming imagination was associated with γ-wave activation in the parietal region, and with a widespread pattern over the frontal, temporal, and occipital regions; this is consistent with research by Sandkühler and Bhattacharya (2008), who noted that strong γ waves were detected at the parietooccipital lobes of participants while they generated insights. In addition, our results implied that the PCC plays a critical role as the hub of the DMN in the parietal lobe. The PCC is essential for bridging the left and right temporal lobes, as well as the prefrontal and parietal lobes (Fransson & Marrelec, 2008), processing highly divergent information and enforcing concentration to provide conscious awareness (Leech & Sharp, 2014). All of these functions were helpful for the performance of transforming imagination in our participants, particularly during the design improvement task.

Differences in Brain Activation between Experimental Tasks

Our results indicate that the brain activation resulting from the the visual stimulation and design improvement tasks primarily differed in the central frontal region when the experienced designer engaged in transforming imagination. Specifically, we observed significant differences in brain activation at the central frontal region related to exploration, as well as differences in the right frontal and parietal regions related to crystallisation; there were no particular differences related to transferability.

The central frontal region is where the anterior cingulate cortex (ACC) is located. The cingulate cortex is associated with motivation, executive functions, and goal-directed behaviour (Holroyd & Yeung, 2012), whereas the ACC controls mechanisms that detect and resolve conflicts by monitoring differential familiarity (Bunge, Burrows, & Wagner, 2004), contributing in identifying design faults and resolving them by adjusting differential design quality. It is thus predictable that the ACC is activated more during the design improvement task than in the visual stimulation task; however, this phenomenon was not observed in either the crystallisation or transferability indicators, possibly because the activation signals for the various brain regions cancelled each other out. This warrants further investigation for theoretical integration.

The interaction of the frontal and parietal regions forms the frontoparietal network (FPN). The FPN is composed of brain regions that, according to task requirements, rapidly alter their functional connectivity with other neural networks that are more task specific. The FPN contains flexible hubs, whose connectivity patterns are systematic and structured, reflecting compositional coding that enables an immediate transfer of knowledge to facilitate learning novel tasks (Cole et al., 2013; Zanto & Gazzaley, 2013). Therefore, the right FPN, which is commonly activated for response inhibition, may promote a more general cognitive control process involved in allocating top-down attentional resources during a variety of cognitive tasks (Fassbender et al., 2016). Although the aforementioned research outcomes only partially support the results, our findings regarding design crystallisation are valuable and warrant future inquiry.

Conclusions, Implications, and Research Limitations

Neuroscience studies provide more robust evidence for establishing theoretical foundations of design cognition compared with other methodological approaches. This study provides insights into the complexities of the designer transforming imagination, from which several notable conclusions can be drawn. First, the frontal and right temporal lobes played a critical role in facilitating experienced designers' transforming imagination during the visual stimulation task, whereas the parietooccipital lobes, specifically the PCC, were particularly activated during the design improvement task. Second, the interaction between the right ATL and the bilateral temporal regions was necessary for design exploration during the visual stimulation task, whereas the DMN was mostly activated during the design improvement task. Third, the parietal lobe was involved in design idea crystallisation during the visual stimulation task, whereas the right frontotemporal and temporoparietal lobes were especially activated during the design improvement task. Fourth, the bilateral temporal and right parietal lobes were principal contributors to design transferability during the visual stimulation task, whereas the right temporoparietal regions were mostly activated during the design improvement task. Finally, significant differences in brain activation were observed at the ACC when the experienced designer engaged in transforming imagination, and exploration in particular. The right FPN was the primary location from which to observe the variations of brain activation regarding the crystallisation indicator.

The aforementioned results offer a scientific foundation for future applied research and educational strategies for design education. For example, individual brain regions are known to be developed at various stages during human development. Knowledge and experience in a specific field are preconditions for the development of expertise, a result of accumulating numerous conclusions regarding the activation of diverse brain regions. Critically evaluating the association of design imagination with the activation of different brain regions may help in making more informed decisions about talent development in schools and in industries. In addition, project-based learning with authentic barriers could be a feasible strategy commonly used by design educators to help students develop their transforming imagination. Effective project-based learning centres focus on realistic problems that incorporate intended learning objectives and align with student skills and interests. With the results of this study, evaluation mechanisms can be designed to monitor the learning process and assess learning outcomes through the activation of specific brain regions according to time-course analysis.

Although this study offers unique contributions to the field, several limitations should be noted. First, the present study was limited in the number and expertise of the participants. Fifteen designer participants may be considered a small number for an experimental study, although they are representative. In addition, the selection of participants who were specialised in product design may have restricted the generalisability of our findings; thus, increasing the number of participants and including other design fields (i.e., visual, spatial, and interaction design) should be considered for further inquiry in this research area.

Second, the experimental stimuli used in this study were limited to three artists' paintings; consequently, diverse forms of stimulation were underexplored. For future research, the stimuli should be expanded to include other media, such as videos, three-dimensional objects, spatial displays, and other types of perceptual stimuli (e.g., melody, sound, text, short poems, touch). Although we aimed to control the perceptual fluency of the stimuli across items, the same measures were not applied to the selection of artists, which should be considered in future research. Continual trials and fine-tuning the experimental stimuli and tasks will enhance research validity.

Third, EEG was used to measure the voltage fluctuations resulting from ionic currents within the neurons of the brain. However, although EEG has a highly temporal resolution and is relatively tolerant of participant movement, its low spatial resolution on the scalp makes it difficult to trace activity to its exact origin in the brain. In addition, the difference in luminance and contrast could produce a systematic bias in the gamma band which is known to be sensitive to early perceptual processes. Furthermore, the wireless EEG headset used in this study was merely a prototype with considerable room for improvement in both hardware and software.

Alexiou and colleagues (2009) indicated that there may be many objections from the design community to the notion that neuroscience research can offer crucial insights to design. To confront the aforementioned limitations is not only to face these objections but also to begin inquiry into this novel area. Although the limitations of this study must be considered, the results reported here provide intriguing insights into the complexities of designer imagination. There is no reason to think that designer imaginations can be easily explained: the current study is only one sketch of the terrain; other sketches are certainly required.

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