**Proceedings of the ASME 2020
International Design Engineering Technical Conferences
and Computers and Information in Engineering Conference
IDETC/CIE2020
August 16-19, 2020, St. Louis, MO, USA**

DETC2020-22563

EVOLUTION OF BRAIN NETWORK CONNECTIVITY IN THE PREFRONTAL CORTEX DURING CONCEPT GENERATION USING BRAINSTORMING FOR A DESIGN TASK

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ABSTRACT

The research results presented in this paper explore the temporal changes in central regions of the prefrontal cortex (PFC) during design brainstorming. Design mobilizes a range of cognitive processes such as problem analysis and framing, concept generation, decision-making, visual reasoning and creative problem solving. Concept generation is supported by an iteration of divergent and convergent thinking. The process of brainstorming focuses primarily on divergent thinking. Measurement techniques from neuroscience were used to quantify neurocognitive activation during concept generation using brainstorming during a design task. Correlations in brain activation were used with graph theory to describe brain network connectivity and present the temporal evolution of network centrality in the PFC during brainstorming. The results reveal shifts of network centrality between the right, medial, and left PFC, suggesting possible shifts in the dominant cognitive functions between divergent and convergent thinking during design brainstorming. The alternations of centrality and connectivity between hemispheres provides a consistent mapping with the theory of dual reasoning process in prior design cognition studies. This empirical study with ten graduate engineering students offers initial results to further explore connections between brain network connectivity and cognitive processes when brainstorming during a design task. It provides new evidence to examine existing theories of design.

Keywords: design cognition, concept generation, brainstorming, neurocognition, brain network connectivity

1. INTRODUCTION

Engineering design is a goal-oriented process that aims to produce solutions for ill-defined problems [1–3]. Engineers use multiple processes to generate designs, such as, problem analysis and framing, concept generation, and decision making. These cognitive processes are nonlinear [4] and generally require making tradeoffs between priorities [5]. Each of these processes relies on a combination of cognitive skills [6], for example, shifting between divergent and convergent thinking [7] and the problem and solution space [8,9]. The generation of initial solutions helps designers reframe and restructure the problem space and begin the design process again [10].

The cognitive processes of design are widely studied using methods based on think-aloud protocol analysis, direct observations, interviews and surveys [11]. More recent methods from neuroscience bring another dimension to the study of design cognition [12,13,15,65]. Neuroscience provides a way to measure designers' brain activation during design ideation [14,66,67] and to explore neurocognition in creativity [68]. Design neurocognition helps demonstrate the high number of neurocognitive processes and the network of connections and communication between disparate regions in the brain [15–17].

The research presented in this paper focuses on measuring patterns of neurocognition during the concept generation phase of design. The purpose is to help explain existing theories of design tasks with new evidence from neurocognition. Cognitive studies suggest that design requires shifting between divergent and convergent thinking [7] and defocused attention (divergent associative thoughts) and focused attention (convergent analytical thoughts) [18]. The broad research question this research attempts to answer is how does neurocognition change and what does this look like over time? The empirical study presented in this paper begins to answer this question using a relatively new and novel technique called functional near infrared spectroscopy (fNIRS). fNIRS provides a measure of brain activation through the analysis of oxygen in the blood (oxy-Hb). The change in oxy-Hb can be used to describe the connections between brain regions and related cognitive processes during the concept generation phase of design. In

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particular, the prefrontal cortex (PFC) and its sub-regions play a critical role in creative and design tasks [19], divergent thinking [20, 21] and problem solving [22]. We present a technique, through graph theory, to describe brain network connections. Brain network connections are a proxy for functional interactions and are used to describe information flow between regions in the brain [24]. We use it to explore brain regions critical to the concept generation phase of design and describe their associated functions [23–25].

The study reported in this paper is based on the analysis of ten graduate engineering students performing a brainstorming design task. The objective of the research presented in this paper is to offer an initial description of the temporal evolution of cognitive network connectivity in the prefrontal cortex (PFC) over time during brainstorming for solutions for a design task. We focus on concept generation because this is a critical step in design and brainstorming is used in many disciplines [26]. Design is a temporal activity that involves multiple cognitive processes, through iteration and concurrency. We study changes in the patterns of network connectivity and hypothesize that the variation of functional interactions in the PFC correspond to varying cognitive processes during brainstorming.

2. BACKGROUND

Design is often described as involving two modes of reasoning: convergent and divergent thinking [7], or fast and slow thinking systems [6,27]. Divergent thinking corresponds to Goel's lateral transformations concept, associated with problem structuring through the generation and evaluation of multiple ideas and preliminary design [28]. Since design problems are ill-defined, designing implies a co-evolution of the problem and solution space [8,9]. Evaluating initial concepts serves to analyze, widen and structure the problem space, as cognitive way-finding [28,29]. Convergent thinking, on the other hand, aims at synthesizing information gained from the design problem space and detailing a proposal [30]. Empirical evidence from design cognition studies point to shifts between divergent and convergent thinking [7,31]. Similar evidence is found from neurocognitive studies, where a shift between defocused attention (divergent associative thoughts) and focused attention (convergent analytical thoughts) iterate during a design task [18]. The shift and iteration mode of reasoning during design highlight the temporal characteristic of concept generation.

Concept generation is an important part of the design process. Promoting concept generation supports creativity and innovation as the formalization of design alternatives serves to avoid design fixation on an initial proposal [32]. To that end, multiple techniques can encourage the generation of new concepts [33–35]. Techniques for concept generation rely on diverse cognitive strategies [36] that affect designers' cognitive processes while designing [37,38] and this is reflected in their neurocognition [39].

2.1 Measuring idea generation with neurocognition

Prior literature implies that while carrying out activities similar to designing, multiple regions of the brain are activated [16]. Research in design cognition exploits neuroimaging techniques such as functional magnetic resonance imaging (fMRI) [66,67], electroencephalography (EEG) [40] or functional near infrared spectroscopy (fNIRS) [14,15,17]. For example, differences between problem-solving and open-ended design tasks appear in cortical activation [40] and EEG patterns of activation can relate to a sequence of design moves or action for a specific task [41]. The use of concept generation techniques with different degrees of structuredness, has been shown to affect brain activation and brain network in the prefrontal cortex [17,39]. Using methods from neuroscience to study design cognition, we can deepen our understanding of neurocognitive processes associated with design and refine our theories on design thinking [13,42].

2.2 Associating cognitive functions to areas in the prefrontal cortex (PFC)

Several brain regions are central to the design process [43]; in particular, the prefrontal cortex (PFC) region. The PFC is associated with several cognitive processes such as planning and executing [44], sustaining focused attention, information selection and performing executive functions [45]. Sub-regions of the PFC are associated with diverse cognitive functions that are necessary while designing and performing creative tasks, listed in Table 1.

The right PFC tends to be associated with divergent thinking, whereas the left PFC is more active during rule-based design, goal-directed planning [46], and making analytic judgements [18]. Strong synchronization in the right PFC is associated with higher originality in solution generation [47]. For creative tasks like concept generation, sub-regions of the prefrontal cortex play an active role [29,48,49].

The right and left dorsolateral prefrontal cortex (DLPFC) are bilaterally active while performing creative tasks [46]. High activation in the right DLPFC tends to correlate with performance in creative problem solving as well as visuo-spatial thinking [21]. The left DLPFC is also involved in creative tasks and shows more activation in goal-directed planning of novel solutions [46]. The medial prefrontal cortex (mPFC) is associated with adaptive decision making and memory retrieval that connects to learning situated associations (link between context, locations, events and adaptive responses) [50], and the ability to simulate future imaginative events [51]. The right ventrolateral PFC (VLPFC) plays a role in evaluating problems rather than solving them [52] and supports the generation of alternative hypothesis to explore the problem space [53].

3. METHODOLOGY

3.1 Measuring brain activation: EEG, fNIRS and fMRI

There are several methods to measure brain activation during design tasks [12,13]. Using EEG, intense neural communication is detected via the identification of electrical currents that represent the brain activity (neural connections). fMRI and fNIRS measure brain activity by detecting blood

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oxygenation level-dependent (BOLD) changes connected to neuronal activity. The assumption is that blood flow increases when an area of the brain is activated. Each technique offers varying temporal and spatial resolution. fMRI has the highest spatial resolution and captures blood flow in subcortical regions of the brain but has a low temporal resolution. However, fMRI is limited by its high usage cost and unrealistic experiment environment (i.e., lying down in a scanner) for design studies. EEG has a high temporal resolution but a low spatial resolution. fNIRS provides a better spatial resolution than EEG and higher temporal resolution than fMRI. In this study, fNIRS was used for the experiment because of its mobility and temporal and spatial resolution.

TABLE 1: NON-EXHAUSTIVE FUNCTIONS ASSOCIATED TO THE PREFRONTAL CORTEX IN DESIGN AND CREATIVE THINKING

Part of the brain	*Associated function*	*References*
Prefrontal cortex (PFC)	• Attention • Working memory • Executive functions • Planning and executing	Dietrich, 2004 [44]; Lara & Wallis, 2015 [45]
Right prefrontal cortex	• Divergent thinking • Originality in solution generation • Sustained attention	Aziz-Zadeh et al., 2013 [46]; Wu et al., 2015 [63]; Fink et al., 2009 [47]; Goel & Grafman, 2000 [64]
Left prefrontal cortex	• Rule based design • Goal directed planning • Analytical judgment	Aziz-Zadeh et al., 2013 [46]; Gabora, 2010 [18]
Medial prefrontal cortex (mPFC)	• Retrieve memory • Adaptive decision making • Learn situated associations	Euston et al., 2012 [50]
Right dorsolateral prefrontal cortex (DLPFC)	• Creative problem solving • Visuo-spatial divergent thinking	Kleibeuker et al., 2013 [21]
Left dorsolateral prefrontal cortex (DLPFC)	• Goal directed planning of novel solutions	Aziz-Zadeh et al., 2013 [46]
Right ventrolateral prefrontal cortex (VLPFC)	• Evaluating problems • Generate hypothesis to explore problem space	Aziz-Zadeh et al., 2009 [52]; Goel & Vartanian, 2005 [53]

3.2 Experiment

Ten graduate engineering students (all right-handed, 22-26 years old) were recruited to participate in the study. All participants have taken courses in engineering design and are familiar with brainstorming. The engineering design problem was to design a device to assist the elderly with raising and lowering windows. Participants were instructed to draw on paper to illustrate their design solutions and no time limit was set. A change in participants' oxygenated hemoglobin (oxy-Hb) in their PFC was recorded by an fNIRS machine as participants generate ideas to solve their design task.

The sensor placement on the fNIRS cap is shown in Figure 1. The sensors were located using the 10/20 international systems and formed a total of 22 channels. A channel is the combination of a light source and an adjacent light receiver. Multiple sub-regions of the prefrontal cortex (PFC) are covered, including the dorsolateral prefrontal cortex (DLPFC: channels 1, 2, 3, 9, 10 in the right hemisphere, and channels 5, 6, 7, 13, and 14 in the left hemisphere), ventrolateral prefrontal cortex (VLPFC: channels 16 and 17 in the right hemisphere, and channels 21 and 22 in the left hemisphere), orbitofrontal cortex (OFC: channel 18 in the right hemisphere, and channel 20 in the left hemisphere), and medial prefrontal cortex (mPFC: channels 4, 11, 12 and 19).

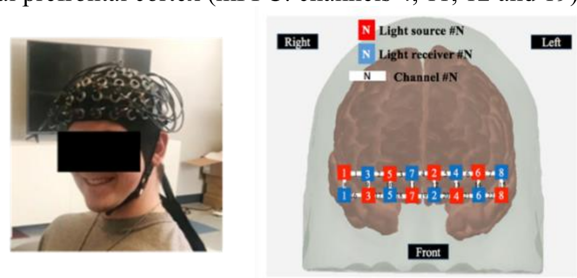

FIGURE 1: A PARTICICPANT WITH THE FNIRS CAP AND SENSORS CONFIGURATION

3.3 Data analysis: brain networks

Graph theory offers a way to understand the structure and function of complex systems, including brain networks [23]. Graph-based representations of brain networks are constructed from a neural correlation matrix. These networks reveal topological relationships between brain regions. The correlation matrix gives data for functional connectivity, which implies that

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two locations in the brain have coherent and synchronized dynamics. Functionally, an activity in one part of the brain can have a causal effect on the dynamics of other areas of the brain [23]. The co-activation of brain areas suggests that the role of a region in the brain related to a particular behavior should be considered in the context of its interaction with other regions [54]. Functional networks are considered to provide physiological markers for information processing and mental representation [55]. In this study, we looked at topological centrality in brain networks as it expresses the capacity of a node to influence or be influenced by other nodes [23]. Network centrality based on node degree describes the nodes with the most edges in the network. Central nodes facilitate functional interaction and act as a control for information flow as it interacts with many brain regions [24].

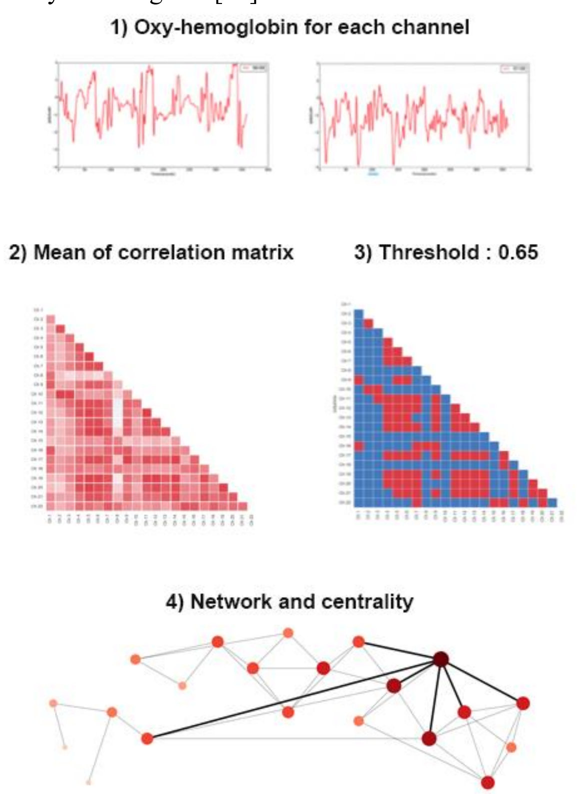

FIGURE 2: NETWORK GENERATION FROM CORRELATION MATRIX OF OXY-HEMOGLOBIN VALUES FROM EACH CHANNEL

Prior to carrying out a network analysis, the fNIRS raw data was processed using a bandpass filter (frequency ranging between 0.01 to 0.1 Hz, third-order Butterworth filter) to remove high-frequency instrumental and low-frequency psychological noise [56]. In order to remove motion artifacts, an ICA (independent component analysis) with a coefficient of spatial uniformity (CSU) of 0.5 was applied. Pearson's correlation matrices were developed using the change of oxy-Hb in all channels during the brainstorming for each participant and then averaged cross the ten subjects. Networks were generated using the python NetworkX package [69]. A global threshold was applied to convert values from the correlation matrix into a binary matrix with connected nodes and edges. Correlations higher than the threshold indicate a functional connectivity between brain regions that demonstrate similar activation patterns [23,57]. A threshold of 0.65 was chosen based on pilot analysis and prior studies [58–60,25]. The graph is generated from correlated nodes that meet the 0.65 threshold. Node degree centrality is then measured from the generated graph. Node centrality is the nodes with highest number of edges. The central nodes are more likely to act as a control for information flow between brain regions [24]. Figure 2 illustrates the process of network development.

To better understand the evolution of neurophysiological activation in participants' PFC, we looked at network centrality over time and divided each session into deciles to normalize the sessions. The design session for each design task for each participant was divided into 10 equal and non-overlapping segments. The segmenting into deciles was based on prior design cognition research [39,61,62]. We also tried three and 20 segments and found relatively similar patterns of connectivity that are presented below. Oxygenated blood for each decile were averaged together for all participants to create an average oxy-Hb for each of the ten deciles. We generated the correlation matrix and utilized the threshold to produce the binary connections illustrated in Figure 2 for each decile. For each decile, nodes with centrality were identified and reported in the results. As described in Section 2.2, each node measures the activation of a specific sub-region in the PFC.

4. RESULTS AND DISCUSSION

On average, students took 7.53 minutes (Standard Deviation = 3.25 minutes) to complete the design task. During that time, half of the students proposed one design concept whereas the rest came up with three to four distinct design concepts. Students that developed a unique concept usually also explored sub-concepts.

4.1 Node centrality and cognitive functions

Node centrality varies from decile to decile, Figure 3. Overall, we found an alternation of brain regions with central nodes, either in the right PFC (deciles 4, 5, 6, 8 and 9), the medial PFC (deciles 2, 4, 9, 10), or the left PFC (deciles 1, 3, 7 and 10). In several deciles, we found multiple central nodes that correspond to different sub-regions of the brain. For instance, in decile 9, the central nodes are channels 9 and 18, located in the right DLPFC and channel 19 the medial PFC.

In Table 1 (see Section 2.3), we described a non-exhaustive list of cognitive functions associated with the sub-regions within the PFC. Since design is a temporal activity with iterations of dual type of thinking (e.g., divergent and convergent thinking, fast and slow thinking, or intuitive and analytical thinking), the dynamic shift of central nodes, their connected nodes in the network, and associated cognitive functions were identified for further discussion. Table 2 describes the brain regions with central nodes for each decile as well as the regions that the central nodes connect to. For each region, associated cognitive

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functions are detailed to better grasp potential relationships between the neurocognitive centrality patterns and cognitive functions related to the inherent dual reasoning process of design.

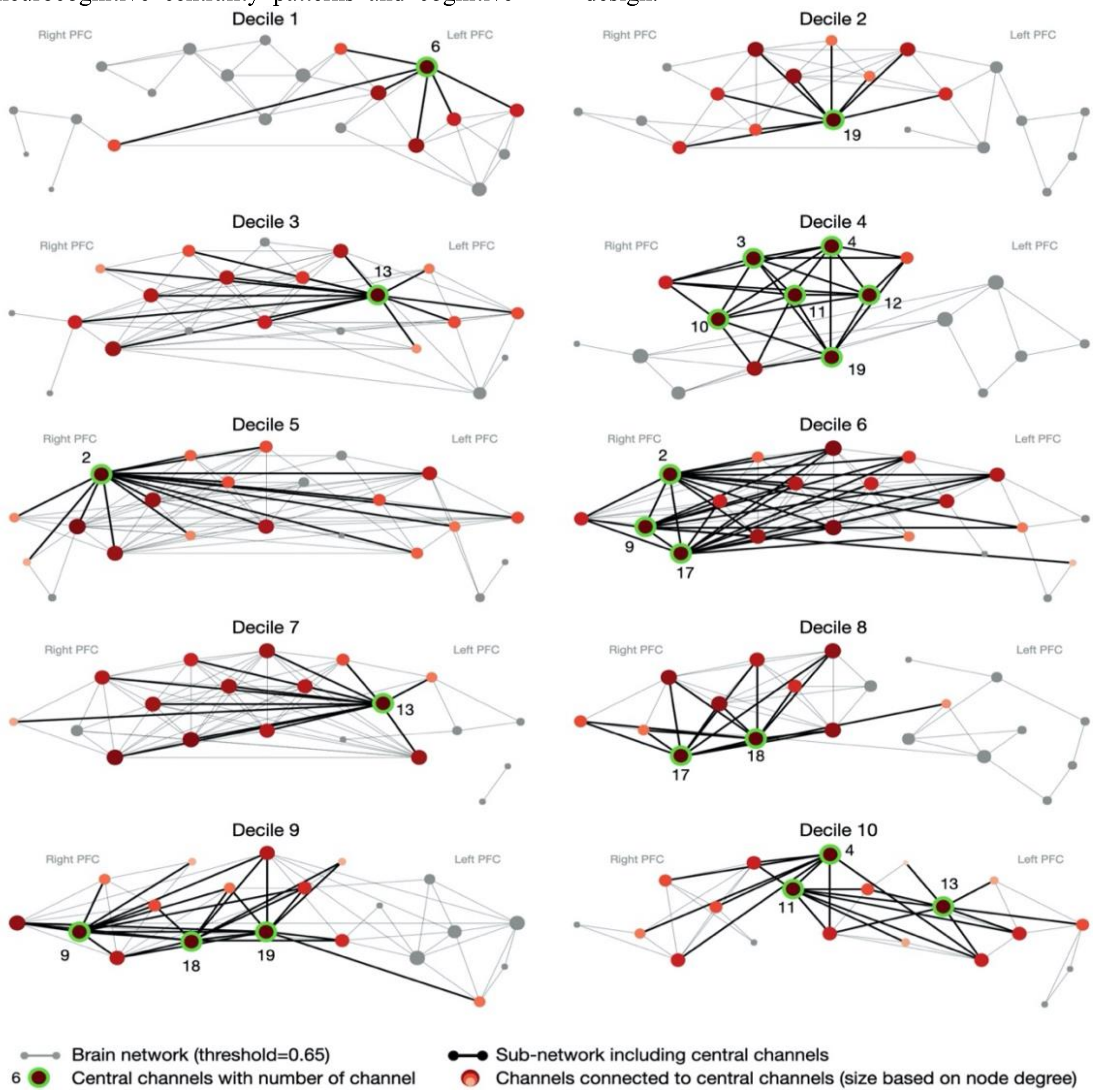

FIGURE 3: GRAPH OF PREFRONTAL CORTEX FUNCTIONAL NETWORK (THRESHOLD = 0.65) FOR EACH DECILE. Deciles represent chunks of the brainstorming session in a chronological order to provide a temporal evolution of the average functional network of participants' prefrontal cortex. Nodes that are part of the network are represented on the graph based on the node degree, represented in light grey. Central nodes, represented in dark red and green, are nodes with the highest node degree. Nodes highlighted in a color range (red / orange) are nodes directly connected to central nodes. Sub-networks including central nodes and their connected nodes are represented in darker edges.

In our data set, for the first decile, the central node is situated in the left DLPFC. This region is known to aid in goal-directed planning. In the second decile, central nodes shift to the medial PFC. This region is generally associated with memory retrieval. The two following deciles also display shifts of central nodes from channel 13 for decile 3 (left DLPFC), to channels 4, 11, 12 and 19 (medial PFC) and channel 3 (right DLPFC) for decile 4. During deciles 5 and 6 that are the middle of the brainstorming activity, central nodes are in the right DLPFC. The right DLPFC is associated with divergent thinking and creative problem solving. Decile 7 central nodes appear in the left DLPFC. For deciles 8, one of the central nodes is in the right VLPFC. The right VLPFC is often observed in the evaluation and exploration of problems. During the last two deciles, at the end of the brainstorming task, central nodes shift back to the medial PFC and the DLPFC (right then left). This may illustrate an alternation from creative problem solving to goal directed planning, combined with memory retrieval and adaptive decision-making. A synthesis of cognitive functions associated with central nodes is provided in Table 2.

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TABLE 2: SYNTHESIS OF FUNCTIONS ASSOCIATED TO CENTRAL CHANNELS AND FUNCTIONS OF CORRELATED CHANNELS FOR EACH DECILE

Deciles (time)	Subregions of PFC with central channels (Channel and node degree centrality value)	Functions subregions of PFC with central channels	Subregions of PCF coactivated	Functions of subregions of PCF coactivated with central channels
1	Left DLPFC (channel 6: 0.368)	Goal directed planning of novel solutions (left DLPFC)	left and right VLPFC	Evaluating problems, generate hypothesis to explore problem space (right VLPFC)
2	mPFC (channel 19: 0.474)	Retrieve memory, adaptive decision making, learn situated associations (mPFC)	left and right DLPFC left VLPFC	Goal directed planning of novel solutions (left DLPFC) Evaluating problems, generate hypothesis to explore problem space (right VLPFC)
3	Left DLPFC (channel 13: 0.650)	Goal directed planning of novel solutions (left DLPFC)	right DLPFC mPFC left and right VLPFC	Creative problem solving, visuo-spatial divergent thinking (right DLPFC) Retrieve memory, adaptive decision making, learn situated associations (mPFC) Evaluating problems, generate hypothesis to explore problem space (right VLPFC)
4	mPFC (channels 4, 11, 12, 19: 0.438) Right DLPFC (channels 3, 10: 0.438)	Retrieve memory, adaptive decision making, learn situated associations (mPFC) Creative problem solving, visuo-spatial divergent thinking (right DLPFC)	left DLPFC	Goal directed planning of novel solutions (left DLPFC)
5	Right DLPFC (channel 2: 0.762)	Creative problem solving, visuo-spatial divergent thinking (right DLPFC)	left DLPFC left and right VLPFC mPFC	Goal directed planning of novel solutions (left DLPFC) Evaluating problems, generate hypothesis to explore problem space (right VLPFC) Retrieve memory, adaptive decision making, learn situated associations (mPFC)
6	right DLPFC (channels 2, 9: 0.737) right VLPFC (channel 17: 0.737)	Creative problem solving, visuo-spatial divergent thinking (right DLPFC) Evaluating problems, generate hypothesis to explore problem space (right VLPFC)	mPFC left DLPFC	Retrieve memory, adaptive decision making, learn situated associations (mPFC) Goal directed planning of novel solutions (left DLPFC)
7	Left DLPFC (channel 13: 0.684)	Goal directed planning of novel solutions (left DLPFC)	right DLPFC mPFC left and right VLPFC	Creative problem solving, visuo-spatial divergent thinking (right DLPFC) Retrieve memory, adaptive decision making, learn situated associations (mPFC) Evaluating problems, generate hypothesis to explore problem space (right VLPFC)
8	right VLPFC (channel 17: 0.684)	Evaluating problems, generate hypothesis to explore problem space (right VLPFC)	Right and left DLPFC mPFC	Creative problem solving, visuo-spatial divergent thinking (right DLPFC) Goal directed planning of novel solutions (left DLPFC) Retrieve memory, adaptive decision making, learn situated associations (mPFC)
9	Right DLPFC (channel 9: 0.526) mPFC (channel 19: 0.526)	Creative problem solving, visuo-spatial divergent thinking (right DLPFC) Retrieve memory, adaptive decision making, learn situated associations (mPFC)	right and left VLPFC left DLPFC	Evaluating problems, generate hypothesis to explore problem space (right VLPFC) Goal directed planning of novel solutions (left DLPFC)
10	mPFC (channels 4, 11: 0.421 left DLPFC (channel 13: 0. 421)	Retrieve memory, adaptive decision making, learn situated associations (mPFC) Goal directed planning of novel solutions (left DLPFC)	right DLPFC left and right VLPFC	Creative problem solving, visuo-spatial divergent thinking (right DLPFC) Evaluating problems, generate hypothesis to explore problem space (right VLPFC)

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Central nodes connect to a high number of other nodes from the network. Connections between central nodes and correlated nodes suggest a causal relationship between them [23]. Noticeably, for every decile in this data set, if the central nodes are situated in the right PFC, they connect to the left PFC and inversely. Moreover, when the central nodes are situated in the mPFC, they connect to nodes in both hemispheres.

4.2 Concurrent dual processing in design ideation

The temporal brain network connectivity analysis in this study highlights a possible mapping between cognitive processes and neurocognitive activation. The findings are limited by the sample size and need to be taken with caution. Nonetheless, results from the network provide elements to open discussion about dual processing during design ideation.

The brainstorming session lasted on average 7.53 minutes, which implies that a decile in our analysis represents 45 seconds. During the first three deciles, participants' network centrality shifts from the left PFC to the right PFC. This may relate to a shift between a goal-directed analytical cognitive process to a more intuitive visuospatial divergent reasoning. In the second and fourth decile, the medial PFC is the region with the most central network. Based on neurocognitive literature (Table 2), this may suggest that participants retrieve memories to engage in an adaptive decision-making process. This first half of the brainstorming session aligns with cognitive concepts of the idea generation process where the designers formulate intuitive ideas partially based on experience to explore the design problem space [10].

During deciles 5 and 6, which are half way through the brainstorming session, participants' network centrality is situated in the right DLPFC. This region is generally associated with divergent creative problem solving. This might be a marker of the formalization of a concept based on the previous problem exploration and reframing. In the following two deciles, network centrality shifts to the left DLPFC (possibly an indicator of goal-directed functions) and the right VLPFC (possible indicator of evaluation and problem hypothesis). These time segments can relate to the evaluation of the proposed concept, based on the context of the solution itself (network centrality in left DLPFC, associated with evaluation and problem hypothesis) and the participants own experience (network centrality in the right VLPFC, which is associated with memory retrieval).

In the last part of the session, network centrality stays high in the mPFC and shifts from the right DLPFC (associated with divergent creative problem solving) partially to the left DLPFC (associated with goal-directed planning).

These findings align with previous findings in neurocognitive studies that report shifts between divergent and convergent thinking for a design task [18] and the importance of interactions between both hemispheres of the PFC while designing. These findings build on Goel and colleagues prior research in design cognition [28] and design neurocognition [29,53,64], which provides an articulation between two complementary ideation processes, divergent (lateral transformation in Goel's words) and convergent thinking (vertical transformations in Goel's words), that respectively tend to correlate with a higher activation in the right part of the PFC and in the left part of the PFC. In this study, we explore the co-activation between nodes that presents a new account for functional connectivity [23] and shifts in central nodes that are a proxy for coordination and information processing [24, 70] between brain regions. Our results support Goel's prior results.

In our dataset, we notice that for more than half of the deciles, central nodes are from the right DLPFC, potentially representative of divergent thinking, and are connected to nodes situated in the left DLPFC, which supports goal-directed convergent thinking. In a recent article, Goldschmidt presented empirical evidences supporting concurrent divergent and convergent thinking based on a temporal cognitive study of a design task [7]. The neurocognitive results presented in this paper also parallel Goldschmidt's results [7] as we observed a systematic co-activation of PFC nodes (central nodes and co-activated nodes) in both hemispheres of the PFC in 9 out of 10 deciles.

5. CONCLUSION

The purpose of the research presented in this paper was to understand the evolution of neurocognitive activation during design brainstorming and particularly to identify possible neurocognitive markers (co-activation) of concurrent dual cognitive thinking process (divergent and convergent) in design ideation. We explored the network centrality in the prefrontal cortex over time using deciles. The results describe how brain network centrality shifts between the right, medial, and left PFC. These shifts in activation suggest possible shifts in the dominant cognitive functions between divergent and convergent thinking during design. The alternations of centrality and connectivity between the left and right hemispheres provide a consistent mapping with the theory of dual reasoning process in prior design cognition studies [7]. Our neurocognitive results provide new and supporting evidence for an existing theory of design [7]. This empirical study offers new and novel results exploring connections between brain network connectivity and cognitive processes related to design. Future research can begin to explore how varying techniques for ideation change neurocognitive function and how this correlates with design outcomes.

Better understanding changes in the brain during design concept generation can provide new evidence about the benefits of using one method over another. This type of data can help motivate the development of new techniques and offers a more in-depth explanation about how these techniques inform creative thought and behavior. Future research can also begin to explore the correlation between the neurocognitive response, design behavior measured with think-aloud protocol analysis, and creative design outcomes during concept generation. By combining theory about design behavior and measurements from neurocognition, this type of study, and future studies can contribute to design research providing a framework and methods to enhance concept generation.

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APPENDIX A

Design task :Window Opening Device

Your design team has been approached by Warm Heart Estates, a local nursing home, to design a new product to assist its elderly residents. The nursing home administrators have noticed that changes in humidity during the summer months cause the windows of the 65-year old building to "stick," thus requiring significant amounts of force to raise and lower the window panes. The force required to adjust the windows is often much too large for the nursing home tenants, making it very difficult for them to regulate their room temperature. Your team has been tasked with designing a device that will assist the elderly tenants with raising and lowering the building's windows. Since each window is not guaranteed to be located near an electrical socket, this device should not rely on electric power. The building's windows are double-hung. The double-hung window consists of an upper and lower sash that slide vertically in separate grooves in the side jambs. This type of window provides a maximum face opening for ventilation of one-half the total window area. Each sash is provided with springs, balances, or compression weatherstripping to hold it in place in any location.

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