Characterization of concept generation for engineering design through temporal brain network analysis

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*This research explores the effect of the structuredness of design concept generation techniques on temporal network neurocognition. Engineering graduate students (*n = 30*) completed three concept generation tasks using techniques with different levels of structuredness: brainstorming, morphological analysis, and TRIZ. Students' brain activation in their prefrontal cortex (PFC) was measured using functional near-infrared spectroscopy (fNIRS). The temporal dynamic of central regions in brain networks were compared between tasks. Central regions facilitate functional interaction and imply information flow through the brain. A consistent central region appears in the medial PFC. Consistent network connections occurred across both hemispheres suggesting a concurrent dual processing of divergent and convergent thinking. This study offers novel insights into the underlying neurophysiological mechanism when using these concept generation techniques.*
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Concept generation is a critical step in the design process (Yang, 2009). The cognitive activities involved in concept generation mobilize a large range of cognitive functions (Heilman et al., 2003). For example, divergent and convergent thinking, and the co-evolution of the problem and solution spaces (Dorst & Cross, 2001; Maher & Poon, 1996). The temporality of designing is an essential aspect of design cognition and relates to the situatedness of design (Schön, 1983) both at a contextual level (design artifact) and personal level (designer). The process of design follows phases of analysis, synthesis, and evaluation (Asimov, 1962; Lawson, 2006) organized in time in a non-linear, non-monotonic form (Goel, 1995; Schön, 1992; Visser, 2006).

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Many techniques are available to designers during the critical phase of concept generation, such as brainstorming, morphological analysis and TRIZ (Smith, 1998). These techniques vary in intuitiveness, motivation (e.g., inner sense driven like brainstorming or problem driven like TRIZ) and structuredness in their implementation (Gero et al., 2013). Using different techniques to generate concepts leads to varying cognitive responses (Chulvi et al., 2012; Gero et al., 2013; Tang et al., 2011). For example, structured techniques like morphological analysis and TRIZ encourage designers to first think through the problem before considering potential solutions (Gero et al., 2013). This forced process can lead to varying patterns of neurocognitive activation in response to the order of tasks and steps (Alexiou et al., 2011; Hu & Shealy, 2019; Shealy et al., 2018). Structured techniques like TRIZ, that follow a well-defined set of steps can alter the temporal organization of design cognition (Altshuller, 1997).

The purpose of the research presented in this paper is two-fold: 1) to understand the temporality of the underlying channels of communication in the brain that support concept generation and 2) how the different structuredness of techniques for concept generation leads to varying forms of coordination between brain regions. Capturing and describing the temporal coordination of distinct brain regions can provide a more complete understanding of the drivers of design outcomes when using these techniques. Previous research in design cognition has defined the foundations of design thinking processes through indirect measurements like protocol analysis (Ericsson & Simon, 1984; Gero & Mc Neill, 1998; Van Someren et al., 1994). More recently, the emergent use of neurophysiological techniques to study design cognition (Alexiou et al., 2011, *e*2009; Borgianni & Maccioni, 2020; Fu et al., 2019; Goucher-Lambert & McComb, 2019; Goucher-Lambert et al., 2019; Hay et al., 2019; Vieira et al., 2020) and evaluation of design artifact (Goucher-Lambert et al., 2017; Sylcott et al., 2013) offers a unique approach to better understand the relation between designers' minds and brains (Gero & Milovanovic, 2020). The exploration of mapping between cognitive design processes and neurological measurements can help determine whether the process of design is a set of unique mental activities or a unique combination of generic mental activities. The research presented in this paper is a step in that direction.

This paper describes an exploratory experiment to characterize the design cognition of concept generation using three ideation techniques. Changes in brain connectivity, a marker of information flow, were measured over time while generating design ideas using brainstorming, morphological analysis, and TRIZ. There are many techniques for brainstorming (Osborn, 1993). In the experiment presented here, brainstorming meant the fluid generation of ideas and did not include a formal step of problem structuring. The process of morphological analysis and TRIZ integrate steps to structure the problem before ideating.

Functional near-infrared spectroscopy (fNIRS) was used to measure changes in patterns of brain activation. fNIRS captures cerebral hemodynamic responses by measuring the variation of oxygen in the blood, where an increase in oxygenated hemoglobin (HbO) is considered as a proxy for brain activation. The methods and analysis techniques contribute to a relatively new approach in design cognition research by measuring changes in brain activity during design (Gero & Milovanovic, 2020). The experiment allowed designers to mimic a natural ideation phase of design by specifying a task and providing them time to generate concepts at their own pace.

The framework used for data analysis stems from network neuroscience and aims to explore the temporal changes in brain functional connectivity depending on the particular concept generation technique. Network neuroscience provides tools to analyze patterns of brain structure and function (Bassett & Sporns, 2017; Fornito et al., 2016). Specifically, the ability to compare participants' brain functional connectivity using node centrality and its evolution over time. An exploratory study investigating neuro-network patterns of activation during brainstorming provided initial evidence of concurrent dual processing between convergent and divergent thinking during brainstorming using similar network centrality methods (Milovanovic et al., 2020). The analysis presented in this paper extends the prior work by comparing differences in neuro-network patterns of activation when using three concept generation techniques. Compared to prior studies (Alexiou et al., 2011; Goucher-Lambert et al., 2019; Hay et al., 2019; Vieira et al., 2020), this study focuses on the temporal dimension of design ideation and how differences in design states (level of structuredness) in the ideation process are characterized using network analysis, a proxy for how information flows in the brain.

The next section provides an overview of the cognitive functions associated with concept generation and introduces brain network analysis as an approach to measure changes in coordination between brain sub-regions during concept generation. The methods section describes how changes in brain networks were measured. The results and discussion sections offer new empirical evidence of the underlying patterns of neurocognitive mechanisms while using brainstorming, morphological analysis, and TRIZ. A mapping between cognitive processes and brain functional connectivity is presented in the result and discussion sections. The results and discussion also provide a synthesized analysis of the temporal aspects of neurocognitive activity during concept generation.

1 Background

1.1 Brainstorming, morphological analysis and TRIZ in design cognition

Concept generation is a necessary part of the design process as it sustains designers' reflective thinking while developing ideas (Schön, 1983). Promoting idea generation supports creativity and innovation in design proposals and aims to limit early design fixation (Gero, 2011; Purcell et al., 1993). Many tools can encourage concept generation (Goldenberg et al., 1999; Jonson, 2005; Knoll & Horton, 2010) and rely on different strategies (Smith, 1998). Three of these techniques are brainstorming, morphological analysis and TRIZ.

Brainstorming involves suspending judgment and criticism during the fluid ideation of concepts (Osborn, 1993). The purpose of brainstorming is to increase the flow of ideas (Osborn, 1993). In this study, brainstorming was defined as the spontaneous generation of ideas. Morphological analysis relies on a two-step process starting with an analytic strategy to decompose the problem followed by a systematic association of partial solutions to sub-problems to stimulate unconscious thoughts (Allen, 1962). TRIZ provides even more structure to the concept generation process, with a set of procedures to generate inventive solutions by defining the problem and looking at existing solution principles, before developing a solution (Altshuller, 1997).

All three techniques rely on a co-evolution of the problem and solution spaces (Dorst & Cross, 2001; Maher & Poon, 1996), but the use of a specific technique might force the focus on one space over the other in time. By definition, TRIZ elicits a cognitive behavior more focused on the problem compared to brainstorming. More structuredness in the concept generation technique, as in morphological analysis and TRIZ, leads to more reasoning in the problem space than the solution space (Gero et al., 2013). Over time, the first half of a concept generation session using morphological analysis looks similar to a TRIZ session, and its second half looks like a brainstorming session. Design cognition literature states the effect of techniques on design processes (Chulvi et al., 2012; Gero et al., 2013; Tang et al., 2011). Neurocognitive studies also suggest that techniques affect how brain regions are recruited during concept generation (Shealy, Gero, Hu, & Milovanovic, 2020; Shealy & Gero, 2019).

1.2 Brain regions of interest to study concept generation in neurocognition

The experiment presented in this paper focuses on analyzing the prefrontal cortex (PFC) since it plays an important role in ideation and creativity for design tasks (Aziz-Zadeh et al., 2013; Fink et al., 2009; Goel, 2014; Goel & Grafman, 2000). Goel et al. (1997) found that patients with lesions in the

PFC when engaged in real life open-ended planning, struggled to structure the design problem, compared to patients without such lesions. This finding supports the importance of the PFC for ill-structured planning and problem solving. According to Miller and Cohen (2001), the PFC is critical for internal representation of goals and the means to achieve them. The PFC controls executive functions in the brain, such as planning, decision-making, attention, and working memory (Glimcher & Fehr, 2013). A prior study found concept generation produces bilateral coordination between the left and right hemispheres in the PFC (Shealy & Gero, 2019).

Sub-regions in the PFC are interconnected, especially the ventrolateral PFC (VLPFC) and dorsolateral areas (DLPFC) (Miller & Cohen, 2001). The PFC anatomical sub-regions are shown in Figure 1. Sub-regions within the PFC are especially necessary for concept generation and critical for the dual reasoning process required for design (Goldschmidt, 2016). Creative tasks strongly involve the right DLPFC and association tasks actively recruit the medial PFC (Bhattacharya & Petsche, 2002). Goel and Grafman (2000) investigated concept generation abilities of a designer with lesions in the right hemisphere and a designer without brain damage. They found the right DLPFC is critical for ill-structured representation and computations. This finding is supported by Gilbert et al. (2010) analysis of neural activation comparing structured and ill-structured design problems.

Generally, the left PFC controls judgments (Luft et al., 2017) and the right PFC is activated for empathy (Henson et al., 1999) and divergent thinking (Zmigrod et al., 2015). Another sub-region of interest is the right ventrolateral PFC as it supports the generation of alternative hypotheses to explore the problem space (Goel & Vartanian, 2005). Even though PFC sub-regions tend to be associated with specific functions, according to Miller and Cohen (2001) sub-regions in the PFC can respond to a variety of information types. Concept generation relies on dual cognitive processes, such as convergent and divergent thinking. While convergent and divergent thinking tend to be associated with particular regions in the PFC, some studies suggest a bilateral activation while performing such tasks (Aziz-Zadeh et al., 2013). Table 1 summarizes, non-exhaustively, the cognitive functions associated with the PFC and its sub-regions when generating concepts.

1.3 Brain networks to explore brain region co-activation while designing

Functional connectivity networks provide an approach to analyze possible parallel activity in the brain. Brain networks help construct a better understanding of the underlying mechanisms in the brain that support cognitive processing during concept generation. Functional connectivity is defined by measuring co-occurrence of brain signals from different brain regions

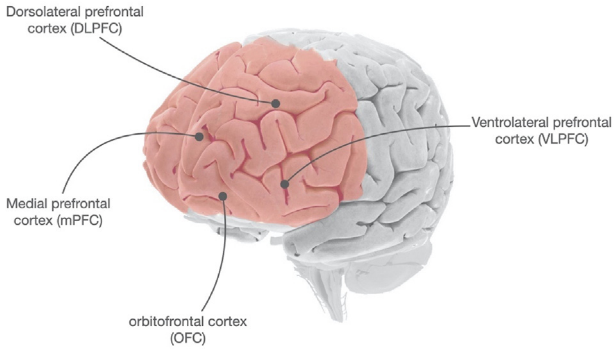

Figure 1 Position of the PFC and its sub-regions in the brain (Base of brain image copyright © Society for Neuroscience (2017))

Table 1 Cognitive functions associated to the PFC and its sub-regions in concept generation and creative tasks

Part of the brain	*Associated functions*
Prefrontal cortex (PFC)	• Planning and executing (Dietrich, 2004) • Sustaining focused attention, information selection and perform executive functions (Lara & Wallis, 2015)
Right prefrontal cortex (PFC)	• Divergent thinking (Aziz-Zadeh et al., 2013; Goel & Grafman, 2000; Wu et al., 2015) • Strong synchronization in the right PFC is associated with higher originality in solution generation (Fink et al., 2009)
Right dorsolateral prefrontal cortex (DLPFC)	• Bilaterally active with left DLPFC while performing creative tasks (Aziz-Zadeh et al., 2013) • Performance on creative problem solving and visuo-spatial divergent thinking (Kleibeuker et al., 2013) • Plays a critical role for ill structured representation and computations (Goel & Grafman, 2000) • Higher activation for design tasks (ill structured) than for problem-solving tasks (structured) (Gilbert et al., 2010)
Right ventrolateral prefrontal cortex (VLPFC)	• Evaluating problems rather than solving it (Aziz-Zadeh et al., 2009) • Support the generation of alternative hypothesis to explore the problem space (Goel & Vartanian, 2005)
Left prefrontal cortex (PFC)	• Rule-based design and goal-directed planning (Aziz-Zadeh et al., 2013) • Making analytical judgment (Gabora, 2010) • Control judgment (Luft et al., 2017)
Left dorsolateral prefrontal cortex (DLPFC)	• Bilaterally active with right DLPFC while performing creative tasks (Aziz-Zadeh et al., 2013) • Goal directed planning of novel solutions (Aziz-Zadeh et al., 2013)
Medial prefrontal cortex (mPFC)	• Ability to simulate future imaginative events (Meyer et al., 2019)

(Fornito et al., 2016). It implies that two regions in the brain have coherent and synchronized dynamics. Pearson's correlation reveals similarity of behaviors between two regions (measured through the channels in fNIRS). A strong correlation, however, between two regions may not guarantee functional connectivity (Mohanty et al., 2020). From correlation matrices, functional connectivity networks are built. Their topological analysis enables a quantitative description of functional coordination and highlights potential connections between brain regions (Bassett & Sporns, 2017).

Whole brain networks can be classified through modules (Meunier et al., 2009). A module contains an ensemble of dense short-range connections and can connect to other modules in the brain through longer-range connections (Fornito et al., 2016). High order cognitive tasks, like concept generation, likely engage multiple modules simultaneously (Meunier et al., 2009). Through the analysis of networks, the role of regions in the brain while generating concepts can be identified and mapped onto design cognitive processes.

Brain networks metrics serve to explore functional connectivity and information processing in the brain, through characteristics such as node centrality (i.e., nodes with the most edges in the network) (Borgatti, 2005; Fornito et al., 2016, pp. 137–161). This universal concept in social network analysis is widely used in neurocognitive studies (Fornito et al., 2016; Zuo et al., 2012). For example, brainstorming, morphological analysis, and TRIZ produce distinctly different patterns of network connections (Hu et al., 2018). Different patterns of network connections reflect different ways of processing information in the brain. Brainstorming produces the least dense network and offers the fewest solutions compared to morphological analysis and TRIZ (Shealy et al., 2018).

Central regions in the brain facilitate functional interaction and act as a control for information flow as it interacts with many other brain regions (Borgatti, 2005; Rubinov & Sporns, 2010). The interactions between dynamics of brain regions might be influenced by the technique being used during concept generation. What remains unclear is what sub-regions in the PFC are most central to these network connections. Brain networks have been used to explore underlying neural correlates of creativity (Beaty et al., 2015, 2018) for the generation of alternate uses to common objects (Guilford, 1967) but little is known about brain functional connectivity during concept generation. Prior studies in design neurocognition focused primarily on brain activation (Alexiou et al., 2009, 2011; Hay et al., 2019; Vieira et al., 2020) more than functional connectivity. The expectation in the study presented in this paper was to observe a change in brain network connection over time because different cognitive processes are engaged at different times (McIntosh, 2000). The order that sub-regions are recruited for task completion fundamentally shifts how information is processed, interpreted, and organized in the brain (Mheich et al., 2019).

2 Research questions

The design research community has begun to explore design neurocognition (Borgianni & Maccioni, 2020). Prior research highlights differences between problem solving and ideation (Alexiou et al., 2009; Hay et al., 2019; Vieira et al., 2020) and temporal changes in design neurocognition (Goucher-Lambert & McComb, 2019; Nguyen et al., 2019) but research comparing the effect of problem structuring on design neurocognition is underexplored. The exploratory study presented in this article provides new insight about how information flows through brain functional connectivity and the effect of design techniques on the temporal dynamic of brain functional connectivity. The research questions addressed are what sub-regions in the PFC are most central during concept generation and how does node centrality in the PFC change over time when generating concepts using techniques with varying levels of design problem structuring?

3 Methods

Multiple instruments are available to measure changes in brain activation, including electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and functional near-infrared spectroscopy (fNIRS). EEG has excellent temporal resolution but relatively low spatial resolution. This limits the ability to locate brain regions, although recent, high-end models have increased the spatial resolution through the use of 256 channels. The spatial resolution of fMRI is much higher than EEG and fNIRS. However, data collection with fMRI is constrained because the scanner encloses participants inside a large tube. The relatively low spatial resolution of EEG and the unrealistic setting of fMRI makes fNIRS an appropriate instrument for design research (Shealy & Hu, 2017). fNIRS allows subjects to sit in a naturalistic setting and provides relatively good spatial (with a brain penetration of around 3 cm depth) and temporal resolution. It emits near-infrared light into the human cortex, and sensors detect reflected light that is not absorbed. The change in light absorption indicates a change in oxygenated (HbO) and deoxygenated hemoglobin. fNIRS is regularly used as an instrument to measure neurocognition (Ferrari & Quaresima, 2012). Its resistance to head and body movement makes it a relevant tool to measure more naturalistic tasks such as the process of design (Balardin et al., 2017).

3.1 Experiment design

3.1.1 Design tasks

Thirty graduate engineering students (all right-handed, 22−26 years old) were recruited to participate in the study. All participants had taken courses in engineering design and were familiar with brainstorming. They were given instructions on morphological analysis and TRIZ. Participants received three design tasks: designing a device to assist the elderly with raising and lowering windows, designing an alarm clock for the hearing impaired, or designing a kitchen measuring tool for the blind (see Appendix for design briefs). Participants were instructed to use one of three techniques to develop a conceptual solution for each of the problems. In our study, we used Altshuller's 40 design principles and a digital table of contradiction as TRIZ tools. The order of techniques and problems were assigned randomly. Each student generated concept solutions for all three problems using one of the three techniques. No time limit was given to participants. Students were encouraged to draw their designs on paper or write their ideas (Figure 2). Students took an average of 7.53 min (SD = 3.25 min) for brainstorming, 11.02 min (SD = 4.70 min) for morphological analysis, and 13.34 min (SD = 5.03 min) for TRIZ. Most participants generated multiple design solutions or sub-solutions when using each of the techniques.

Compared to brainstorming, morphological analysis and TRIZ are structured in phases. The first phase consists of refining the design problems, that is followed by the generation of solutions. In this experiment, these phases were monitored but the analysis presented here focused only on the solution generation phase for all three techniques. This enabled comparison of concept generation for all three levels of design problem structuredness. Open-ended problems, like the design tasks given to participants, are considered ill-structured problems. For brainstorming, concept generation was parallel to problem structuring. No instructions were provided about how to structure the problem. As part of the morphological analysis technique, participants were given instructions to fragment the problem in sub-problems before generating solutions, and therefore, the problem was semi-structured when participants started proposing conceptual solutions. As part of the TRIZ technique, participants were asked to first identify the problem and formulate it, before generating conceptual solutions to answer the problem. Analysis and comparisons were made for the phases of the concept generation technique, not problem framing or decomposition. Example results for the task of designing a device to assist the elderly with raising and lowering windows are presented in Figure 2.

3.1.2 Data collection

The fNIRS cap from the LIGHTNIRS fNIRS system (Shimadzu Co., Kyoto, Japan) was used with a sampling frequency of 4.44 Hz to record the change in participants' HbO in their PFC. The sensor placement on the fNIRS cap is shown in Figure 3(a). The sensors were placed using the 10/20 international system and formed a total of 22 channels. A channel is the combination of a light source and an adjacent light receiver. Participants were instructed to reduce their head motion during the task, although they had the freedom to use a pen and paper. Multiple sub-regions of the prefrontal cortex (PFC) were covered, including the dorsolateral prefrontal cortex (DLPFC: channels

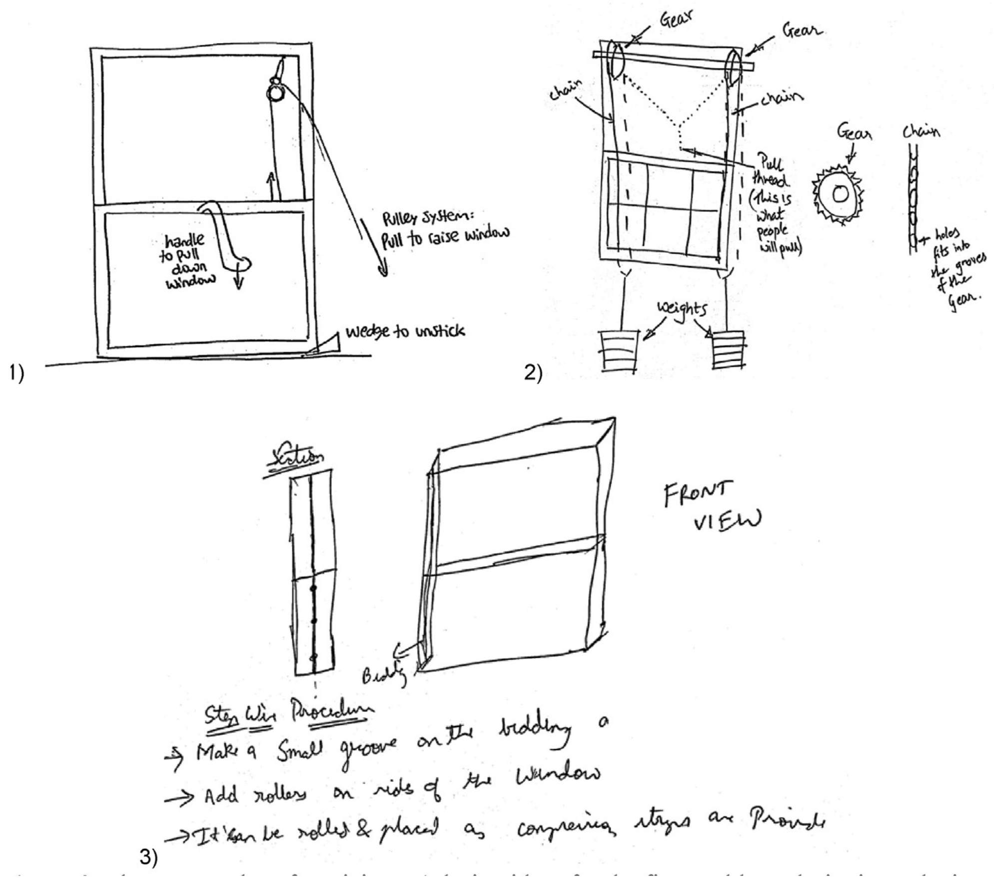

Figure 2 Three examples of participants' design ideas for the first problem: designing a device to assist the elderly with raising and lowering windows

1, 2, 3, 9 and 10 in the right hemisphere, and channels 5, 6, 7, 13, and 14 in the left hemisphere), ventrolateral prefrontal cortex (VLPFC: channels 8, 16 and 17 in the right hemisphere, and channels 15, 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) as represented in Figure 3(b). This same source dataset analyzed in previous studies (Hu et al., 2018; Milovanovic et al., 2020; Shealy et al, 2018, 2020a; Shealy & Gero, 2019) was used in this network study.

3.2 Data analysis

3.2.1 fNIRS data pre-processing

Many techniques are available to pre-process fNIRS raw data but no specific standards are defined (Kamran et al., 2016). In the following section, the steps taken were based on previous fNIRS studies to process the data (Hu & Shealy,

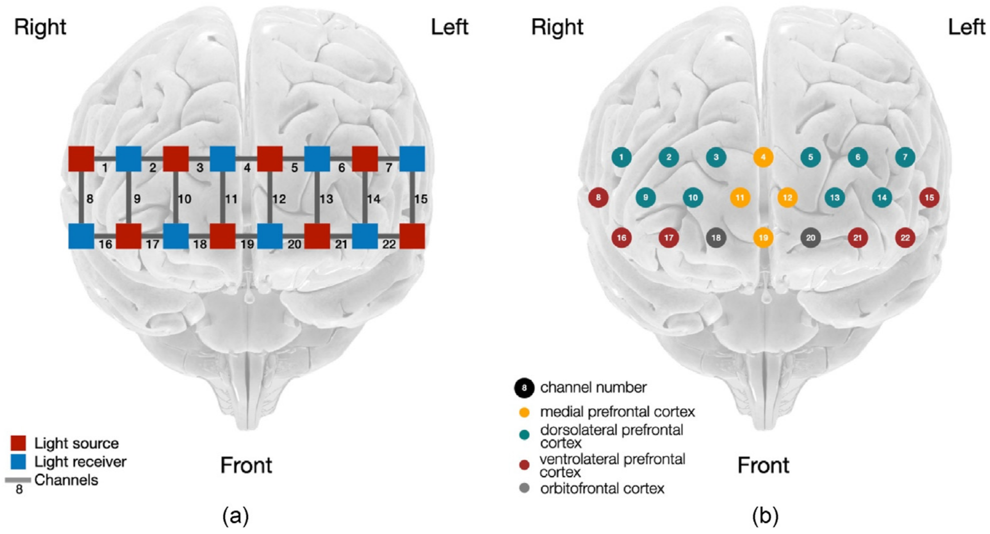

Figure 3 (a) Sensor configuration and (b) sub-regions of the PFC monitored with channel placement (Base of brain image copyright © Society for Neuroscience (2017))

2019; Naseer & Hong, 2015; Sato et al., 2011). The data for three subjects were removed from the analysis due to bad signals. The remaining fNIRS raw data were processed using a bandpass filter (frequency ranging between 0.01 and 0.1 Hz, third-order Butterworth filter) to remove high-frequency instrumental and low-frequency psychological noise (Santosa et al., 2017). To remove motion artifacts, ICA (independent component analysis) with a coefficient of spatial uniformity (CSU) of 0.5 was applied. The filtering process was done with Shimadzu fNIRS software. The analysis was based on filtered HbO, which aligns with previous studies (Baker et al., 2018; Brockington et al., 2018).

3.2.2 *Brain networks metrics*

Functional connectivity is defined as a statistical dependence between the time series of measured neurophysiological signals (Fornito et al., 2016). Brain networks are representations of functional connectivity and stand as useful tools to study complementary characteristics of brain activation during a task (Bassett & Sporns, 2017; Fornito et al., 2016; McIntosh, 2000). Two regions can be functionally connected if they have coherent and synchronized dynamics. In this study, a Pearson correlation matrix between variations in HbO processed signal channels provided an indicator of activation similarity between two channels. This technique for network metrics is illustrated in Figure 4(a) and (b). It follows the method from prior studies (see Allen et al., 2014; Fornito et al., 2016; Kitzbichler et al., 2011; Zhang & Zhu, 2020). Using a threshold on the correlation matrix, a network of the most correlated nodes was generated, i.e., nodes that undergo a similar trend of

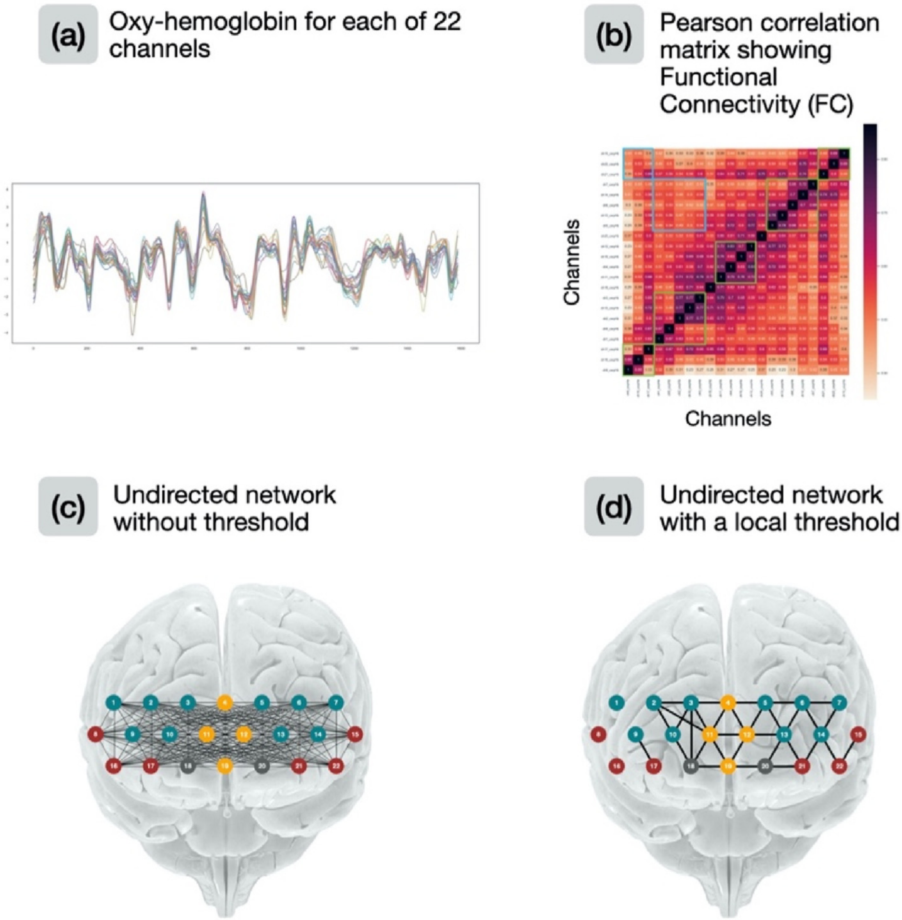

Figure 4 Network generation from the correlation matrix of HbO values from each channel (Base of brain image copyright © Society for Neuroscience (2017))

activation across time (Figure 4(d)). Thresholding is a critical step in network analysis as it highly influences the network's topology. There is no consensus on the particular value for the threshold to be used (Fornito et al., 2016, pp. 383–419). Using a local threshold across participants allowed for a unique network for each subject representing their brain network backbone (Serrano et al., 2009) and conserve the same number of connections so that network densities remain constant.

Neural networks are described as small-world networks, between regular lattice graphs and random ones, meaning that brain networks normally have a dense local connectivity with fewer long-range connections (Achard & Bullmore, 2007; Fornito et al., 2016). According to Achard and Bullmore (2007) selecting a local threshold to obtain a network representing the top

5−34 % of the network provides networks with small-world characteristics, and are representative of functional connectivity networks. In Achard and Bullmore's (2007) study, within that range of threshold, networks representing the top 21 % of the edges had the best network cost efficiency. Different local thresholds were used so that networks represented either 15 %, 20 % or 25 % of the highest node correlations. This is similar to previous studies (Achard & Bullmore, 2007; Jiang et al., 2019; Mizuno et al., 2019). This part of the analysis was conducted using Python libraries (Numpy, Pandas, and Networkx).

3.2.3 Temporal functional connectivity analysis

Studying network connectivity over time is a key aspect because functional connectivity is temporal (Zhang & Zhu, 2020). The analysis used a non-overlapping window approach to equally divide the design process into ten segments. This segmentation normalizes the concept generation sessions over time, given that each concept generation phase had a slightly different time length because participants were not given a time constraint. The segmentation of the design process into ten equal segments, or deciles, is common in design cognition studies (Kan & Gero, 2017). The use of deciles provided a method to characterize the temporal aspect of concept generation neurocognition for each technique over time. The approach for creating deciles followed similar design cognition studies (Gero et al., 2013; Kan & Gero, 2017; Milovanovic & Gero, 2018, pp. 2099−2110). For each technique, a Pearson's correlation matrix was generated for each participant for each of their deciles, then each decile was averaged across participants. Each decile's averaged correlation matrix serves as input to generate the network. See Figure 5 for analysis steps.

For each technique and each decile, the PFC network was generated for all three thresholds (15 %, 20 %, and 25 %). Network characteristics provide a lens to analyze functional connectivity through measures like centrality. Topological centrality in brain networks expresses the capacity of a node to influence or be influenced by other connected nodes (Fornito et al., 2016). Network centrality based on node degree describes the nodes with the most edges in the network. Central nodes, or nodes with the highest number of connections in the network, facilitate functional interaction and act as a control for information flow as it interacts with many brain regions (Borgatti, 2005). Central nodes account for fNIRS channels that co-activate in a similar pattern with a high number of other channels. It implies that their variations in HbO are alike and account for a form of coordination between brain regions. From each network, node centrality is measured for each node based on the number of connections they have with the other nodes in the network. To identify consistent central nodes, node centrality values (ranging from 0 to 1) for each of the brain network (top 15 %, 20 % and 25 %) were averaged.

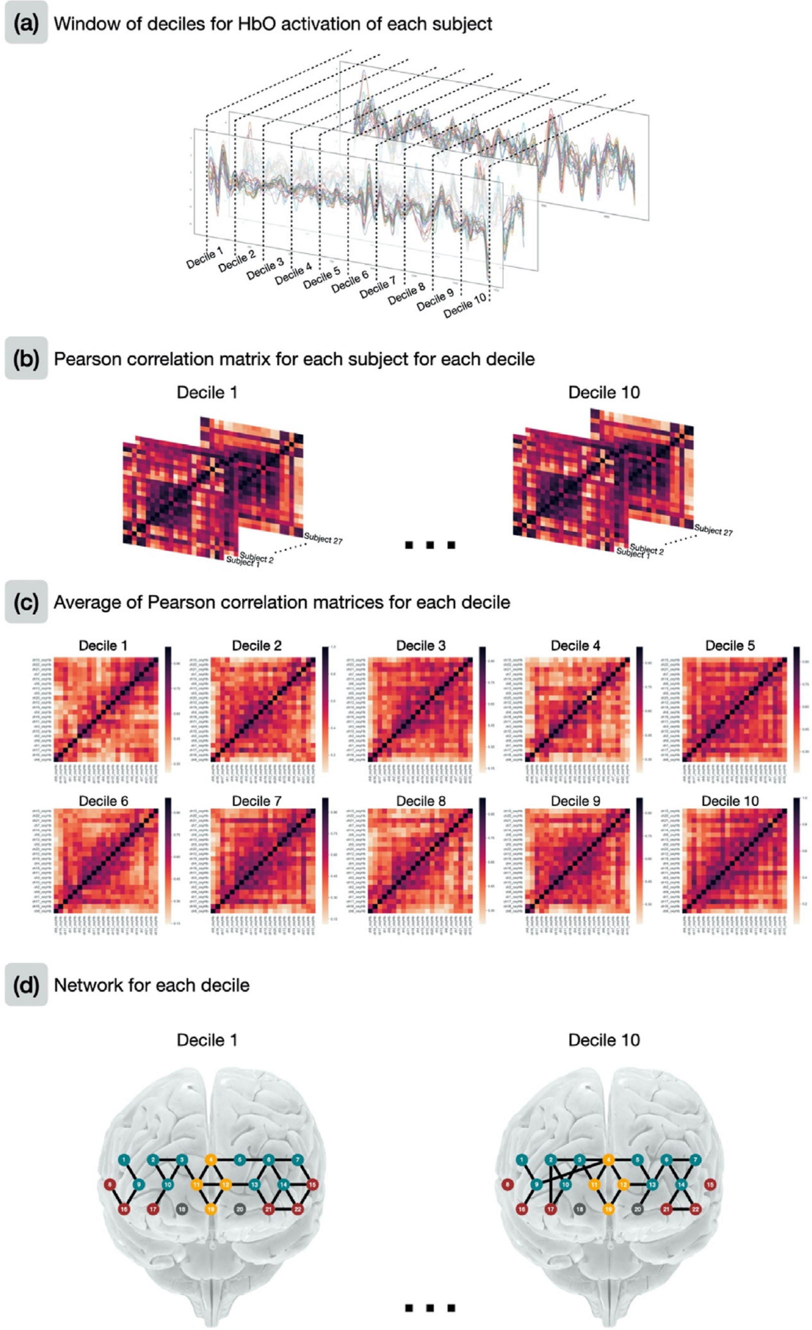

Figure 5 Example of group analysis steps for the analysis of the dynamic functional connectivity: (a) segmentation of participant brain activation in ten deciles, (b) generation of a correlation matrix for each decile of each participant, (c) average of correlation matrices for each decile, (d) generation of PFC network for each decile. (Base of brain image copyright © Society for Neuroscience (2017))

4 Results: temporal analysis of brain networks while generating concepts

Following the analysis steps described in section 4.2.2 and in Figure 5, node centrality shifts over time were analyzed for each decile for each task. As introduced in section 2.3, node centrality relates to functional interaction and central nodes act as a control for information flow (Borgatti, 2005; Rubinov & Sporns, 2010).

4.1 Observations of bilateral activation across deciles for all tasks

A common finding across all concept generation techniques is a bilateral coactivation. For example, in Figure 6 (a) representing decile 5 of the morphological analysis task, the central node appears in the right part of the DLPFC, a region associated with higher performance on creative problem solving and visuo-spatial divergent thinking (Kleibeuker et al., 2013). The activation of this central node is correlated with 10 other nodes. Four are situated in the same part of the PFC that represents short-range connections. Four other co-activated nodes are situated in the left part of the PFC (DLPFC or VLPFC). These long-range connections in the network suggest a bilateral activation between left and right DLPFC, observed while performing creative tasks (Aziz-Zadeh et al., 2013). Here, the left part of the DLPFC (central node) acts as a control for information flow (Borgatti, 2005; Rubinov & Sporns, 2010). This pattern of connection between the central node and coactivated node also appeared in TRIZ.

A symmetric network pattern occurred frequently across deciles for each task. The central node appears in the left part of the PFC, with short range connections to adjacent nodes and long-range connections to the right PFC as in Figure 6(b) representing decile 5 in the brainstorming task. A similar pattern appears in other deciles of the concept generation session (see deciles 1 and 5 in the brainstorming task; deciles 1, 2 and 7 in the morphological analysis task; deciles 1, 2, 5 and 10 in the TRIZ task). When central nodes are situated in one side of the PFC, they are always connected to nodes in the medial PFC and the other side of the PFC.

Central nodes appearing in the medial PFC always connect to nodes in the left and right sub-regions of the PFC, implying a co-activation between those nodes (see an example of such pattern in Figure 6 (c) representing decile 8 in the TRIZ task). The medial PFC (central node), relating to adaptative decision-making, memory retrieval (Euston et al., 2012) and the ability to simulate future imagined events (Meyer et al., 2019), becomes the control for information flow (Borgatti, 2005; Rubinov & Sporns, 2010). This third common pattern emerges across all tasks (all deciles expect 1, 5 and 8 in the brainstorming task; deciles 3, 4, 8, 9 and 10 in the morphological analysis task; deciles 4, 8 and 9 in the TRIZ task).

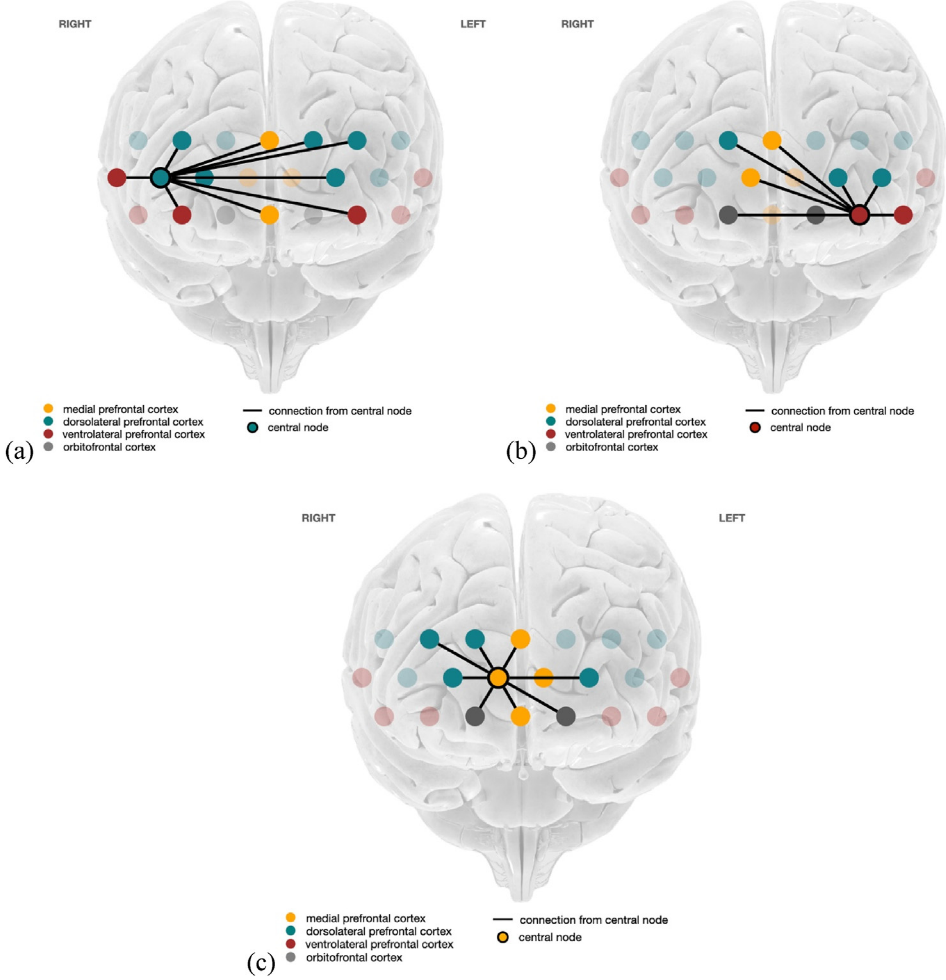

Figure 6 Exemplary patterns of central node connections to other sub-regions of the PFC for networks representing the top 20 % of the correlation between nodes: (a) the central node is situated in the right part of PFC and connects to the left side of the PFC, example of decile 5 in the brainstorming session (b) the central node is situated in the left part of PFC and connects to the right side of the PFC, example of decile 5 in the morphological analysis session (c) the central node is situated in the medial part of PFC and connects to the left and right side of the PFC, example of decile 8 in the TRIZ session. (Base of brain image copyright © Society for Neuroscience (2017))

4.2 Unstructured concept generation: brainstorming temporal analysis

For the brainstorming task, the central node appears repeatedly in the mPFC for 7 deciles (see, Figure 7). For the first 5 deciles, the central node moves from the left orbitofrontal cortex (OFC) to the medial part of the PFC and then to the left VLPFC for the 5th decile. The left part of the PFC tends to be associated with rule-based design (Aziz-Zadeh et al., 2013) whereas the mPFC is associated with adaptive decision making and memory retrieval (Euston et al., 2012). In the

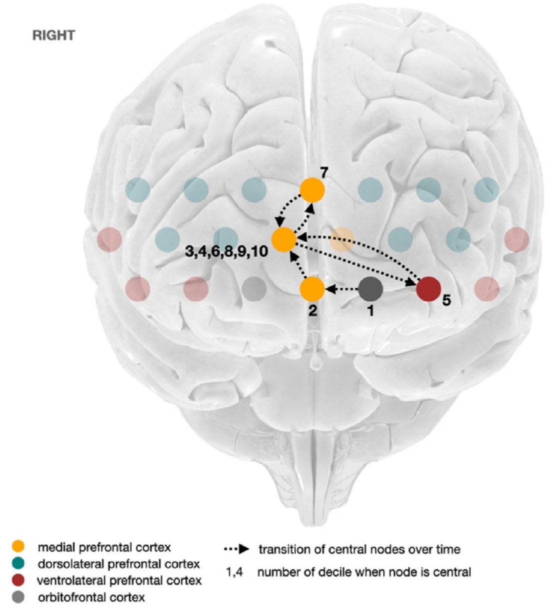

Figure 7 Transition paths of central nodes for brainstorming across time (Base of brain image copyright © Society for Neuroscience (2017))

second half of the session, the central node appears in the mPFC, a region generally associated with creative problem solving and visuo-spatial divergent thinking (Kleibeuker et al., 2013).

4.3 Semi-structured concept generation: morphological analysis temporal analysis

For morphological analysis, similar to brainstorming, the central node often appears in the mPFC (deciles 2, 8, 9 and 10), associated with adaptive decision making, memory retrieval (Euston et al., 2012) and the simulation of future events (Meyer et al., 2019) (Figure 8). Central nodes also appear in the left DLPFC (deciles 3), a region generally related to rule-based design (Aziz-Zadeh et al., 2013) or the left OFC (deciles 1 and 7), generally associated with dynamic reward in decision-making (Shimokawa et al., 2009). In the middle of the concept generation phase, nodes situated in the right PFC are central (deciles 4, 5 and 6), regions generally associated with creative problem solving and visuo-spatial divergent thinking (Kleibeuker et al., 2013) and the generation of alternative hypothesis to explore the problem space (Goel & Vartanian, 2005) (Figure 8).

4.4 Structured concept generation: TRIZ temporal analysis

For TRIZ, the central node appears less frequently in the mPFC than for brainstorming. In the first 5 deciles, the central node shifts between the

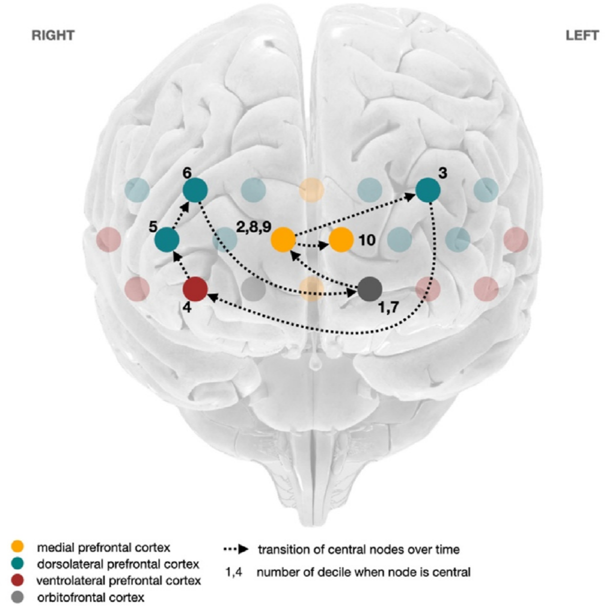

Figure 8 Transition paths of central nodes across time for morphological analysis (Base of brain image copyright © Society for Neuroscience (2017))

mPFC (deciles 1,3 and 4) to the left DLPFC (deciles 2 and 5). In decile 3, two central nodes are situated in the mPFC and the right DLPFC (Figure 9). Each region associates with different cognitive functions in design and creativity. For the two following deciles (6 and 7), the central node remains in the OFC, a region recruited in risky decision-making (Shimokawa et al., 2009). In the last deciles, the central node is situated within the left DLPFC (Figure 9), a brain region generally associated to rule-based design, goal directed planning (Aziz-Zadeh et al., 2013) and analytical judgement (Gabora, 2010; Luft et al., 2017) and in the right OFC.

4.5 Temporal representation of cognitive functions associated to central regions for each technique

Using deciles serves to characterize the temporal aspect of concept generation neurocognition for each technique. In Figure 10, each timeline represents variations of central regions over time for each concept generation technique. Central regions are represented for each decile on the timeline and are associated with cognitive functions related to those regions based on previous work (see Table 1). Central nodes play a role in information flow in the brain (Borgatti, 2005; Rubinov & Sporns, 2010). We observe qualitative differences between techniques. For instance, during brainstorming, the mPFC appears as the main central region. For morphological analysis and TRIZ, the central region tends to shift between hemispheres. This dynamic could be related to the

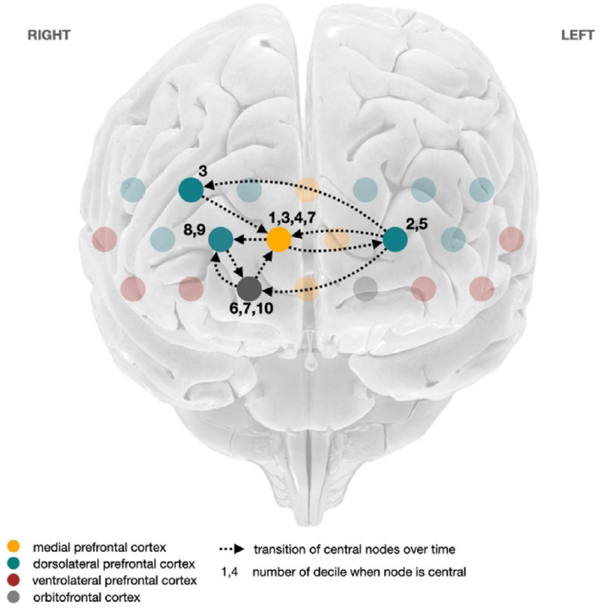

Figure 9 Transition paths of central nodes across time for TRIZ (Base of brain image copyright © Society for Neuroscience (2017))

level of structuredness of the design problem before generating concepts as different cognitive functions are engaged by participants for each case.

5 Discussion

The results identify central nodes in the brain network over time. Highly connected nodes might act as focal points to converge and diverge information in the network (Fornito et al., 2016). The temporal analysis revealed changes in node centrality over time, which suggests changes in cognitive functions during concept generation. The three main findings from the study are:

1) The results provide evidence of concurrent activation in left and right PFC during ideation. This suggests concurrent divergent and convergent design processes during concept generation.
2) The mPFC is recurrently a central node implying that this sub-region is key in information flow during concept generation. This could account for the socio-emotional processes involved in designing.
3) Three similar patterns of networks appear for all three techniques, presented in Figure 6. Each network pattern suggests a different type of information flow which could be characteristic of concept generation. The temporal organization of those patterns over time changes for each technique, which could be related to specificity of cognitive processes engaged to generate ideas from design problems with different levels of structuredness.

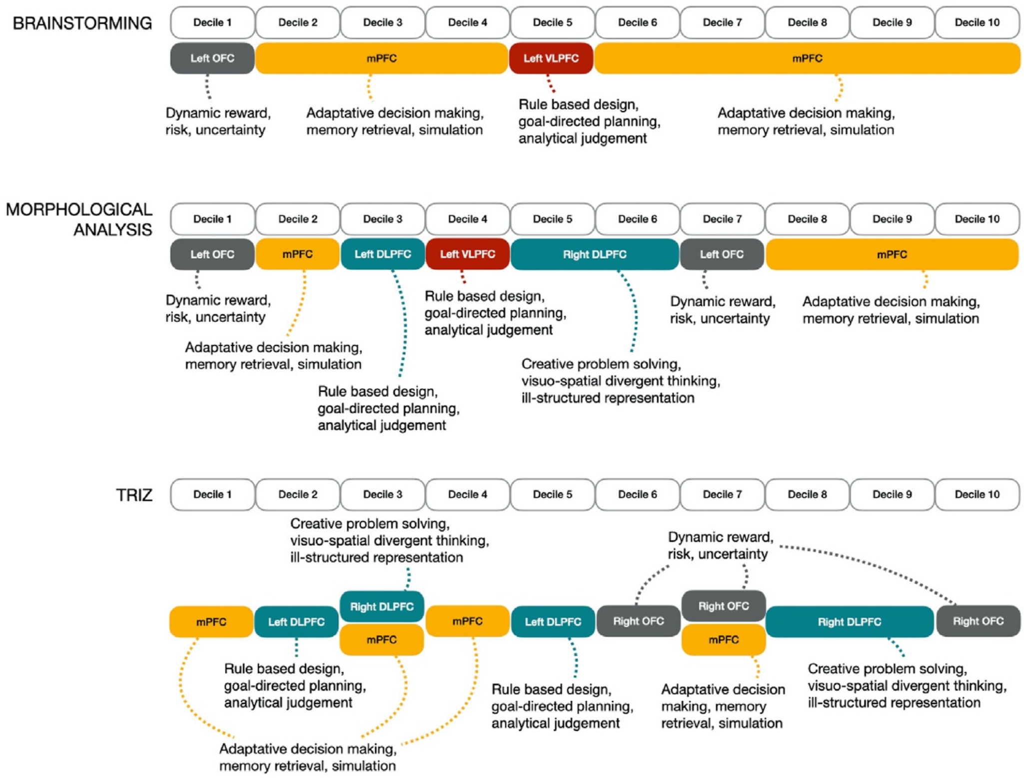

Figure 10 Concept generation timeline showing PFC sub-regions centrality, a proxy for information flow, for brainstorming, morphological analysis and TRIZ. Cognitive processes that recruit each sub-region are associated to it based on previous findings

5.1 Concurrent convergent and divergent thinking when generating concepts

In the design literature, designing is described as an iteration of divergent and convergent thinking (e.g., lateral transformation – divergent thinking – and vertical transformation – convergent thinking (Goel, 1995)) that relates respectively to two neural states, defocused attention and focused attention (Gabora, 2010; Goel, 2014; Goldschmidt, 2016). Across tasks, a recurrence of bilateral connections between the central node and connected nodes is sustained. If the central node appeared on the left or right side of the PFC, it is most likely connected to the other side of the PFC through long range connections. If the central node appeared in the medial PFC, it is commonly connected to both sides of the PFC. Connections in the network symbolize a similar behavior between connected nodes, and suggest information flow between nodes (Borgatti, 2005; Rubinov & Sporns, 2010). At a cognitive level, a possible explanation for these observations is the occurrence of a concurrent divergent (activation in the right part of the PFC) and convergent thinking (activation in the left part of the PFC). Using linkography (Goldschmidt, 1990, 2014), Goldschmidt (2016) provided empirical evidence of concurrent divergent and convergent thinking while designing. The long-range bilateral connections observed in the PFC across time and tasks suggest a concurrent dual processing of divergent and convergent thinking while generating concepts. These findings align with previous work pointing toward a co-activation of multiple networks (executive and default brain network) during creative processes (Beaty et al., 2015; Dietrich, 2004; Ellamil et al., 2012). These results point toward an association of both processes instead of the common discretization of divergent and convergent thinking in the cognitive approach to creativity (Guilford, 1967; Jaarsveld & Lachmann, 2017).

5.2 *Role of the mPFC during concept generation: adaptative decision making*

The mPFC is recurrently central during brainstorming, morphological analysis, and TRIZ. Central nodes appear primarily in the medial part of the PFC during the brainstorming sessions (during 7 deciles, see Figure 10), half of the time in the morphological analysis sessions (see Figure 10) and less in the TRIZ sessions (during 3 deciles, see Figure 10). When the central nodes appear in the mPFC, it connects to regions in both hemispheres of the PFC (see Figure 6, A2 and A3 in Appendix), implying a possible transfer of information between those sub-regions. The mPFC is widely believed to be an essential node for neural networks relevant for socio-emotional processing, such as cognitive empathy and perspective-taking (Seitz et al., 2006). Given that three similar design problems asked participants to design products for disadvantaged groups (i.e., elderly, the hearing impaired, and the blind), this consistently central region might suggest processing of cognitive empathy when generating concepts. Prior neuroscience literature also suggests the mPFC is recruited in memory retrieval and association learning (Euston et al., 2012). Another possible explanation for the recruitment of this region as most central in the mPFC is that students cognitively made associations during concept generation. The dominance of the mPFC centrality over time correlates with the structuredness of the concept generation technique. For the unstructured technique (i.e., brainstorming), the mPFC is dominantly central (8 deciles out of 10) whereas for the structured techniques (i.e., TRIZ) the mPFC remained central for 4 deciles out of 10. During creative tasks, the ability to simulate future imagined events is associated to the mPFC (Meyer et al., 2019), which provides a possible explanation for the difference in the mPFC centrality dominance over time.

5.3 *Characterization of concept generation neurocognition depending on ideation techniques*

Observing a similar brain activity (i.e., location of central nodes and type of connections) between techniques is not surprising since the core activity is idea generation. This finding aligns with some previous work pointing out no significant changes in neural activation between a constrained design task and an open-ended design, implying that a similar neural process was engaged for both tasks (Hay et al., 2019), although contrary results have been found in other studies (Vieira et al., 2020).

Across tasks, similarities are found in the position of central nodes and type of networks. The differences observed in the three techniques appear more in the temporal organization of network patterns. This could relate to the level of structuredness of the design problem before generating concepts, soliciting different types of design thinking processes.

5.4 Limitations

Brain network analysis with fNIRS data provides a set of useful tools to explore patterns of neurocognition, but it still lacks a well-defined analytic framework as no specific standards are defined (Fornito et al., 2016; Kamran et al., 2016). The results presented in this paper have several limitations connected to the network analysis methods regarding the similarity measure, thresholding and the dynamic analysis. Networks in this study were built on Pearson's correlation commonly used to build brain networks (Allen et al., 2014; Fornito et al., 2016; Kitzbichler et al., 2011; Zhang & Zhu, 2020). Other correlation methods such as wavelet coherence can also be used to generate brain networks (Achard & Bullmore, 2007; Bullmore & Sporns, 2009) and provide an alternative measure of similarity that is not well captured by Pearson's correlation (Mohanty et al., 2020). In future work, several types of correlation techniques could test for variations in representation of functional connectivity.

A second limitation of the method is the network thresholding technique. Thresholding is an important step in network analysis because it defines the network's topology. There is no consensus on the particular value for the threshold to be used (Fornito et al., 2016). A global threshold, based on a fixed limit value, or a local threshold, based on a varying limit value, are two alternatives to threshold the network. In previous studies, a global threshold was set (Milovanovic et al., 2020; Shealy, Gero, Hu, & Milovanovic, 2020). Here, a local threshold across participants was used because it provides the same density networks for each subject. The threshold technique and value used were chosen based on previous work (Achard & Bullmore, 2007; Jiang et al., 2019; Mizuno et al., 2019).

Most experiments in design neurocognition studies are based on block experimental design (Hu & Shealy, 2019) and well-defined tests such as the AUT (Alternate Uses Task) (Beaty et al., 2015), meaning they capture a series of repeated short tasks lasting between 30 and 90 s. In the experiment presented in this paper, participants experienced a more realistic concept generation task. From a cognitive point of view, lifting the constraints of a block experimental design (Hay et al., 2019) is key to better understanding the underlying cognitive processes of design concept generation. A major limitation appears in the means to analyze the temporal changes in brain network at a group level. To address this issue, methods from cognitive studies based on a segmentation of non-overlapping windows at the individual level were used (Kan & Gero, 2017). The deciles (non-overlapping windows) varied in length depending on the participant. A sliding window approach is common in neuroscience but less common in design studies. Future research could explore using a sliding window technique to study dynamic functional connectivity (Allen et al., 2014; Zhang & Zhu, 2020). The use of sliding windows and a clustering method, as in Allen et al. (2014) or Zhang and Zhu (2020), could help better tackle the challenge of integrating a temporal analysis of brain activation signal at the individual level and at the group level.

This study aimed at exploring dynamic neurocognitive patterns during concept generation. Studies on brain network in creativity or concept generation usually study whole brain networks (Beaty et al., 2015; Ellamil et al., 2012). Our exploratory study only measured brain activity in the PFC, which was selected because of its important role in ideation and creativity for design tasks (Aziz-Zadeh et al., 2013; Fink et al., 2009; Goel & Grafman, 2000).

5.5 Implication of using neuroimaging for research on design thinking

Research in design using methods and tools from cognitive science have helped develop a better understanding of underlying cognitive processes while designing. Decision-making, reasoning, memory retrieval, mental imagery processing, visual perceptions and creative output production describe some of the cognitive processes that occur in design thinking (Hay et al., 2017a, 2017b). Each of those processes have been studied separately in neuroimaging studies. Using neuroimaging tools and findings from prior work in neuroscience provides a new perspective to observe and describe design thinking. In this paper, the characterization of neural networks in the PFC while generating concepts gives new insights into how information flows over time through the region of the brain that deals with executive functions. Sub-regions recruited during concept generation tend to associate with specific cognitive processes like analytical reasoning or visuo-spatial thinking (see Table 1). Observing and characterizing design thinking from a neurocognitive perspective serves to test design thinking models stemming from cognitive studies (Gero & Milovanovic, 2020).

The findings from this paper are one step toward an integrative approach of design thinking models that include cognition and neurocognition. A larger body of work is needed to develop a more comprehensive model. For example, recent research proposed an adaptation of the dual process theory including System One (or thinking fast) and System Two (or thinking slow) (Kahneman, 2011) as a framework for ideation (Gonçalves & Cash, 2021; Kannengiesser & Gero, 2019). Each type of thinking system, thinking intuitively (fast) or rationally (slow), could relate to different neural networks. Integrative models of design thinking will help provide a better understanding of design thinking and can lead to the development of new design tools to improve idea generation behaviors, such as timing the display of inspirational stimuli (Goucher-Lambert et al., 2019) with neuro-feedback (Agnoli et al., 2018; Shealy, Gero, Milovanovic, & Hu, 2020).

6 *Conclusion*

The study presented in the paper explores how different levels of concept generation technique structuredness when using different techniques (i.e., brainstorming, morphological analysis, and TRIZ) change node centrality and patterns of functional connections in the prefrontal cortex (PFC) across time. The results find a consistent centrality in the medial PFC when using all three techniques and begin to indicate a possible tendency of cognitive empathy and memory association during concept generation. Central node shifts are frequent during concept generation, moving between the left, medial and right part of the PFC. These changes are likely to impact how information is transmitted within regions of the PFC and other parts of the brain. This could be related to the forced dual processing between divergent and convergent thinking that concept generation requires (Goldschmidt, 2016). The sequential variation in centrality of sub-regions between techniques could reflect a sequential variation of cognitive processes related to the level of structuredness of the design problem.

Design neurocognition is a promising research field for exploring design cognition with methods and tools anchored in neuroscience. Cognition research aims to find processes used by designers to generate ideas and address design problems. Methods from neuroscience applied to the research presented in this paper serve to reveal neurophysiological patterns in the brain when generating concepts. A challenge arises in developing methods and experiments to analyze correlations between cognitive processes and neurophysiological signals captured while designing. The work presented in this paper builds on multiple research fields (design, cognition and neuroscience) to investigate connections between cognitive processes and neurophysiological signals while designing. Identifying dynamic patterns of brain networks provides a first layer of information about how the brain acts while designing, but remains limited to mapping generic cognitive processes onto it. More work in design neurocognition is needed to explore mapping between findings about the temporal aspect of designing from cognitive studies and temporal variation of neurophysiological patterns.

Identifying associations between cognitive processes and neural activation while designing is a first step to a design thinking framework based on a holistic approach, including both designers' minds and brains (Gero & Milovanovic, 2020). Our future work will move in that direction and focus on developing methods and experiments to analyze micro-scale correlations between brain activations and cognitive processes, for instance by studying design cognition via the analysis of verbal utterance (protocol analysis) while monitoring brain activation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A1 - Design briefs

Design brief #1 - Double-Hung (Sash) Window Opener

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 (as seen in the figure above). 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.

Design brief #2 - Alarm Clock for the Hearing Impaired

Hearing loss is one of the most chronic health conditions among Americans next to arthritis and high blood pressure. One in ten Americans (or 31.5 million) experiences some degree of hearing loss. As such, there is a tremendous need to design products to assist those with this condition.

Your team has been hired to design an alarm for the hearing impaired.

Design brief #3 - Measuring Tools for the Blind

According to a 2008 CDC study, more than 3.4 million Americans are either legally blind or visually impaired. Of those, approximately 1.3 million Americans are legally blind. As such, there is a tremendous need to design products to assist those with this condition.

Your employer has been contracted to design and develop a line of kitchen products for blind customers. As part of this larger project, your team has been hired to design measuring tools to aid the blind in the kitchen (i.e., assist in the measurement of liquid and dry substances).

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