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NEURO-COGNITIVE DIFFERENCES BETWEEN BRAINSTORMING, MORPHOLOGICAL ANALYSIS, AND TRIZ

Tripp Shealy
Virginia Tech
Blacksburg, VA, USA

Mo Hu
Virginia Tech
Blacksburg, VA, USA

John Gero
University of North Carolina, Charlotte
Charlotte, NC, USA

ABSTRACT

This paper presents the results of an experimental study comparing cortical activation in the brain when generating solutions using brainstorming, morphological analysis, and TRIZ. Twelve engineering students were given the same three design tasks, respectively, using the three solution generation techniques. Students generated solutions while change in oxygenated blood along the prefrontal cortex (PFC) was measured using functional near-infrared spectroscopy. The results show that generating solutions using brainstorming, morphological analysis, and TRIZ leads to differences in cortical activation, specifically along the region of the brain associated with spatial working memory, cognitive flexibility, and abstract reasoning, called the left dorsolateral prefrontal cortex (left DLPFC). Brainstorming evokes a high average blood oxygenation level dependent (BOLD) response in the left DLPFC early during the solution generation process but this high response is not sustained. In comparison, morphological analysis and TRIZ evoke multiple high average BOLD responses across the solution generation process. Not only was the high average BOLD response sustained but the density of network coordination among brain regions across the PFC was greater for morphological analysis and TRIZ. Higher density is a proxy for higher cognitive effort. The brain regions most central to coordination also varied. During brainstorming the right hemisphere, in a region associated with memory encoding (right PFC), was most activated. During morphological analysis, the left hemisphere, the left DLPFC was most activated. During TRIZ, both the middle and left hemisphere included regions of high activation. These results indicate neuro-cognitive differences of activation patterns, cognitive effort over time, and brain regions central for coordination when using these three concept generation techniques. Future research can begin to explore neuro-cognitive differences as a result of these techniques over multiple uses and the effects of design education.

INTRODUCTION

Numerous techniques developed over the last half century help facilitate concept generation (Helm et al. 2016; Jablokow et al. 2015; Bohm et al. 2005). These techniques can be broadly classified as either structured or unstructured (Gero et al. 2013; Moon Sungwoo et al. 2012; Shah et al. 2000). Structured techniques provide a formal procedure to meet functional requirements. For example, TRIZ is a structured technique that offers a systematic approach based on logic and a knowledge base (Vidal et al. 2015; Blackburn et al. 2012; Altshuller 2002). Unstructured means no predefined direction is given (Gero et al. 2013). Unstructured techniques remove boundaries that may otherwise limit the number and novelty of concepts. For example, brainstorming is a commonly used unstructured technique (Gero et al. 2012). Only after brainstorming ends is judgement applied to filter concepts within given parameters (Osborn 1953).

Unstructured and structured techniques fundamentally elicit different cognitive functions (Gero et al. 2013). The more structured the technique, the more focused designers are about reasoning through problems (Gero et al. 2013; Tang et al. 2012). This reasoning correlates to more novel design outcomes (Jaarsveld and Lachmann 2017; Sun and Yao 2011). A possible explanation for why structured techniques lead to more focus and more novel solutions is structured techniques provide a framework for designers to think through the problem and then solutions (Gero et al. 2014). For instance, TRIZ requires designers to break the problem into smaller components. In contrast, the lack of direction in brainstorming means designers may overlook the problem and jump directly to generate as many solutions as possible.

Whether structured or unstructured, creative processes like concept generation involve shifting between different kinds of thinking (Gero 2015; Gero et al. 2012). For example, developing new ideas requires recall, working memory, and abstract reasoning. This type of thinking engages multiple regions of the brain (Alexiou et al. 2011; Boccia et al. 2015; Heinonen et al. 2016). For instance, the left anterior insula (this is the region in the brain associated with completing visual tasks) increases more in activation during concept generation compared to just object identification (Heinonen et al. 2016). Increase in oxygenated blood in the brain, which is a proxy for neuro-cognitive function (Ferrari and Quaresima 2012; Fishburn et al. 2014), in the anterior cingulate cortex (this is the region in the brain associated with attention) positively correlates with the quantity and order of concepts generated during design (Heinonen et al. 2016). Using sketches that elicit long term memory during concept generation also leads to a significant increase in activation in the prefrontal cortex (PFC: this is the region of the brain broadly associated with broad executive functions) (Kato et al. 2018).

The order in which information is presented and when and how parameters are given can also affect what regions of the brain are accessed and in what order. For example, including parameters about sustainability (e.g. solutions found in nature, energy efficient, or regenerative) during brainstorming significantly shifts cortical activation in the brain from the left to right hemisphere (Shealy et al. 2017). Similarly, using a concept generation technique called concept mapping reduces the neural network coordination among regions in the brain (Hu and Shealy 2018). Just as adding a sustainability parameter shifts cortical activation and concept mapping localizes activation, structured techniques like TRIZ may elicit distinctive patterns of cortical activation because of the strict requirements to first think through the problem before considering potential solutions.

Measuring change of cortical activation during design can help explain how different concept generation techniques inform behavior. The broad hypothesis is that design techniques provoke distinct cortical patterns of activation. Observing change in cortical activation can provide supporting evidence for why and how design techniques like brainstorming and TRIZ differ. The following section outlines instruments for measuring change in cortical activation associated with cognitive function necessary in design (i.e. executive functions like planning, abstract reasoning, cognitive flexibility, recall, and working memory).

Neuro-imaging techniques to measure design cognition

There are several methods to measure neuro-cognition during design. Electroencephalogram (EEG) is frequently used because of its high temporal resolution (i.e. ability to detect quick changes), ease of use, and relatively low initial purchase price (Hu and Shealy 2018). EEG, however, has poor spatial resolution (i.e. ability to detect where the change in neuro-cognition occurs) because the ionic current being measured can interfere with other signals, which makes it difficult to pinpoint specific brain regions. In contrast to EEG, fMRI has a high spatial resolution. It measures activity through changes in blood flow. Increase in oxygenated blood (also called oxygenated hemoglobin) in the brain is associated with an increase in cognitive activity (Gramann et al. 2014). Blood flow change over time is slower than ionic current in neurons so the temporal resolution of fMRI is not as quick as EEG (i.e. order of seconds compared to milliseconds) (Eysenck & Keane, 2015). Another constraint of fMRI is that data collection process can be awkward for participants because they must remain still and lay down while partially enclosed inside the MRI scanner. The cost to operate is also high. A fMRI requires a trained technician upwards of $500 per hour.

The spatial resolution limitations of EEG and unrealistic environment during testing of fMRI make both options less than ideal for studying neuro-cognition during design. Another instrument, called function near infrared spectroscopy (fNIRS) is unique compared to EEG and fMRI because participants can operate a computer or perform a task in an upright sitting position, similar to EEG, and has a high spatial resolution, similar to fMRI. It is worn as a cap, similar to EEG, and light is emitted at a specific wavelength (between 700-900 nm) into the scalp. The light scatters, and some is absorbed, before reflecting back to the sensor. The deoxy-hemoglobin (HbR) and oxy-hemoglobin (HbO) absorb more light than water and tissue in the brain. The ratio of HbR and HbO is calculated using a Modified Beer-Lambert Law. Shown in Figure 1, is the blood oxygenation level dependent (BOLD) response. The HbR and HbO are inversely related. While both are measured, typically only one is reported (Shealy and Hu 2017).

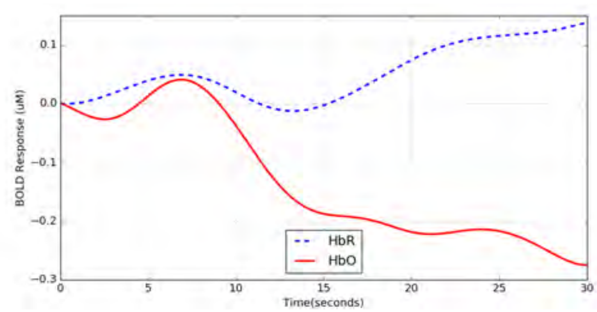


Figure 1: HbO and HbR are inversely related

A drawback of fNIRS is the inability to provide information about sub-cortical brain regions. However, areas relevant for design neuro-cognition, such as the PFC, associated with executive function (e.g., planning, problem solving, decision making, and design), are sufficiently accessible with fNIRS (Fuster 1988). Table 1 outlines the advantages and disadvantages of EEG, fMRI, and fNIRS. The high spatial resolution compared to EEG, mobility in data collection compared to fMRI, and relatively ease of use is why fNIRS is the preferred neuroimaging instrument in this context (Shealy and Hu 2017).

Table 1: Comparison of Neuro-imaging technologies

Criteria	EEG	fMRI	fNIRS
Spatial resolution	Poor	High	High
Temporal resolution	High	Poor	Moderate
Mobility	Participants sit upright	Participants must lay down	Participants sit up right
Data processing	Moderate	Intensive	Moderate
Cost to operate	$0 (after purchase)	~$500 per hour	$0 (after purchase)
Ease of use	Time intensive placing electrodes	Requires technician	Less time intensive and invasive than EEG

In combination with observational data and self-reporting information, fNIRS provides another level of data to triangulate findings. The next section offers more background about the specific brain regions of interest and analysis techniques for this type of neuro-cognitive data. The methods section offers an overview of the types of experimental procedures and outlines the specific method for the study presented in this paper.

BACKGROUND

fNIRS is used to study risky decision making in economics and problem solving in mathematics (Holper et al. 2014; Ayaz et al. 2012; Cazzell et al. 2012). In engineering, fNIRS is used in human factors (McKendrick et al., 2017) and transportation research (Tsunashima & Yanagisawa, 2009). In each of these previous studies, pre-identifying regions of interest in the brain is necessary because baseline brain activity even at rest is still very active and thus it is necessary to demonstrate both that a stimulus causes additional activation in a region of interest and that it does not cause additional activation in a nonrelated region. Studies in design cognition are limited. However, tasks about creativity (Pisapia et al. 2016), divergent thinking (Gibson et al. 2009), and problem solving (Ayaz et al. 2012; Ruocco et al. 2014) point to several specific regions in the PFC. In particular, the DLPFC is frequently associated with creativity (Boccia et al. 2015; Liu et al. 2012; Pisapia et al. 2016), improvisations (McPherson et al. 2016), cognitive flexibility, working memory (Curtis and D'Esposito 2003) and abstract reasoning (Huettel and McCarthy 2004; Zhang et al. 2003; Pochon et al. 2002).

Regions within the PFC are often categorized by Brodmann Areas (BA). These are regions described by specific lobes of the cerebral cortex (Brodmann, 2007). The DLPFC is composed of BA 9 and 46. Other BAs in the PFC include 8, 10, 11, 12, 45, and 47. BA 8 is activated when subjects are required to predict future events with internal or external uncertainties (Volz et al. 2004). Figure 2 shows the placement of fNRIS sensors and detectors covering several BAs in the PFC, including BA 8, 9, and 46. This placement of sensors and detectors is the layout for the study presented in results section of this paper.

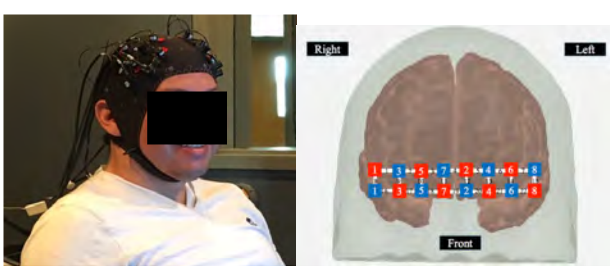


Figure 2: Example fNIRS placement along the frontal cortex

Network analysis

With good spatial resolution, network analysis can be applied in fNIRS studies to describe functional connections within the brain (Martijn and Hilleke 2010; Demuru et al. 2013; Niu et al. 2013). The channels located at specific brain regions can be regarded as nodes, as shown in Figure 3. These nodes are the lines between the light emitters and sensors in Figure 2. The functional connectivity between nodes can be estimated using a Pearson's correlation, where a threshold is applied (e.g. a correlation above 0.7) indicates a relationship between synchronized cognitive activation of different brain regions.

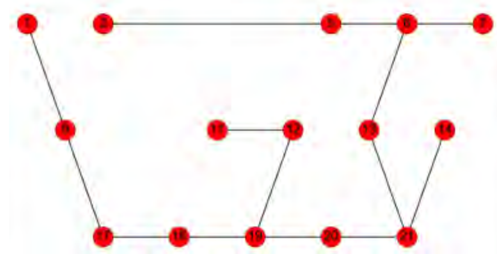


Figure 3: A drawing of graph containing nodes and edges using a correlation above 0.7

Brain network features were analyzed using network density and centrality. Network density is the proportion of number of actual connections (edges) to the number of possible connections in a network. Density was used because it provides a measure of cognitive resource requirements of the network (Bullmore and Sporns 2009), thus, providing a proxy for cognitive effort required to complete the task. A low network density means low cognitive effort. The connections between nodes changes over time so a density graph can illustrate these changes and was used to report increase or decrease in cognitive effort over time during the solution generation process for design tasks. Centrality was also used to measure differences in network connectivity. Centrality describes the nodes with the most edges in the network. Centrality helps describe how the network coordination changes and the region most critical for task completion. For example, in Figure 3 there are three nodes each with three edges.

RESEARCH QUESTIONS AND HYPOTHESES

The broad objective of the research presented in this paper was to measure neuro-physiological change in the PFC during the solution generation process of engineering design. More specifically, to measure difference in patterns of activation within the most central regions within the PFC, and the cognitive effort required over time while designing using three different concept generation technique.

Three design techniques, varying in structuredness were used to aid designers during the solution generation process: brainstorming, morphological analysis, and TRIZ. Brainstorming provides no predefined direction (unstructured). Morphological analysis requires designers to decompose the problem into sub-functional components before offering solutions (semi-structured). TRIZ requires designers to think through both the problem and solution using a predefined knowledge base (structured). Morphological analysis is a hybrid between brainstorming and TRZ because it does not specifically prescribe a solution generation procedure for the decomposed problems; most designers tended to revert to their default unstructured concept generation approach (Gero et al. 2013). As a result, the latter part of a design session using morphological analysis resembles many characteristics of intuitive designing process using the unstructured brainstorming technique.

The specific research questions are:

(1) What are the differences in cortical activation patterns in the prefrontal cortex (PFC) when using brainstorming, morphological analysis, and TRIZ?
(2) What regions within the PFC are most central during concept generation when using brainstorming, morphological analysis, and TRIZ?
(3) How does the density of connections across regions in the PFC change over time when using brainstorming, morphological analysis, and TRIZ?

The hypothesis is that brainstorming, morphological analysis, and TRIZ lead to significant differences in activation patterns along the PFC among engineering design students. The lack of structure in brainstorming means designers are not forced to use varying ways of thinking. Requiring designers to break down the problem into smaller pieces (morphological analysis) or reviewing engineering design principles (TRIZ), likely requires a balance between cognitively searching for possible design approaches and assessing how these ideas align with constraints. So, the second hypothesis is that the more structured techniques of morphological analysis and TRIZ elicit varying connections of regions in the brain compared to brainstorming.

During brainstorming, designers can engage less because the process involves fewer benchmarks for the designer to meet. The third hypothesis is that higher cognitive effort is required with more structured design techniques. Higher effort is measured by an increase in network density, meaning a higher number of connected regions based on the total possible number of connections.

METHODS

Twelve graduate engineering students participated in the study. Before each experiment began, the three concept generation techniques were introduced to each participant. After the introduction, participants were instructed to finish three design tasks at their own pace and were assigned brainstorming to be used with the first design task, morphological analysis to be used with the second design task, and TRIZ to be used with the third design task. The first design task required participants to assist the elderly with raising and lowering windows. The second design task was to design an alarm clock for the hearing impaired and the third task asked participants to design a kitchen measuring tool for the blind. Participants were able to use figures or words to describe their design for each task on paper. Between tasks, participants had 30 seconds to relax. This was also meant to bring cognitive function back to the general baseline level before the task. The process of including a baseline cognitive measurement and rest period between each design is based on prior defined methods in neuroscience (Tak and Ye 2014). Participants were outfitted with functional near infrared spectroscopy (fNIRS) to measure cognitive activation during each task. During each task, fNIRS captured and recorded participants' neurophysiological change in oxygenated hemoglobin in the PFC. The sensor placement on the fNIRS cap and the channels (formed by the combination of a source and a detector) covered multiple Brodmann areas (BA) in the PFC and DLPFC, including BA 8, 9, and 46.

Data analysis

A fractioning technique was used to divide every design session into non-overlapping ventiles (20 equal segments) (Gero, 2010). Only oxygenated hemoglobin (HbO) in fNIRS data was analyzed and reported across these ventiles. Two participants' data were removed from analysis due to bad data signal. fNIRS raw data was filtered using a bandpass filter between frequency of 0.1 and 0.01 to remove instrumental and psychological noise (Huppert et al. 2009).

To investigate the differences in cortical activation patterns in the PFC during brainstorming, morphological analysis, and TRIZ, the average change in BOLD response was calculated for each ventile for each participant. Participant ventiles were then averaged together to produce an average oxy-hemoglobin (HbO) level response for each ventile during brainstorming, morphological analysis, and TRIZ. An analysis of variance (ANOVA) was used to measure statistical difference in the pattern of HbO across the whole PFC and across the left and right DLPFC. The significance level was defined as 0.05.

To measure regions central for coordination among brain regions. Correlation matrices were developed using the change of oxygenated hemoglobin in all channels during each design task. Only high correlations (greater than 0.7) were considered as connective functions. When the correlation coefficient was greater than the threshold (0.7), data was set as a 1, below the threshold was set as a 0. A threshold coefficient of 0.7 was used because of its use in previous fNIRS studies (Hu and Shealy 2018; Worsley et al. 2005). From the binary matrix, links were drawn between channels where data was 1 to get the topology of brain network, shown in Figure 4. There were 22 nodes representing 22 channels and links between nodes representing connectivity between brain regions. Network density and centrality were than calculated to provide descriptive measures of the network.

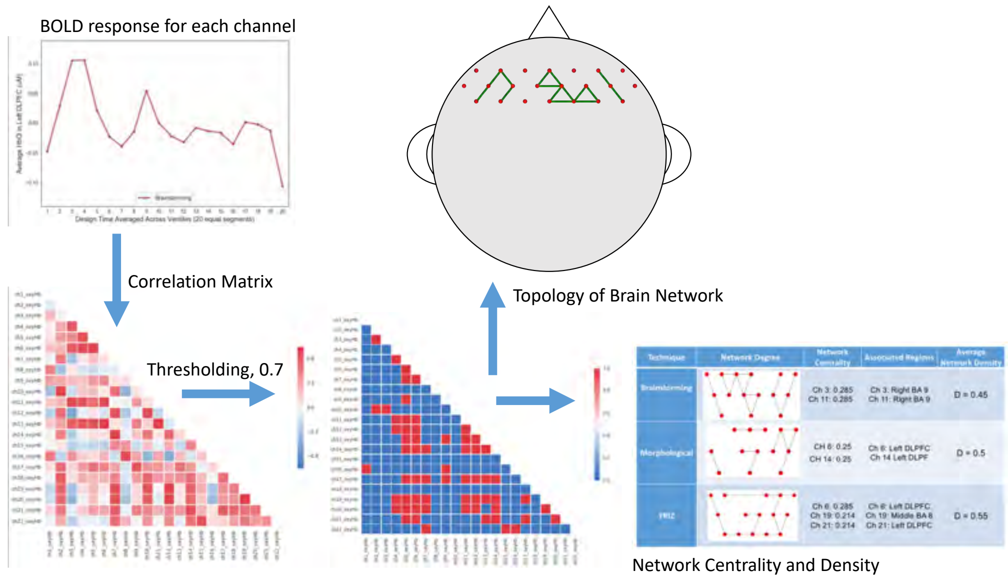


Figure 4: Brain networks and metrics

RESULTS AND DISCUSSION

Patterns of cortical activation in the left DLPFC are significantly different (F=4.58, p=0.014) when using brainstorming, morphological analysis, and TRIZ. Further analysis finds differences occur between brainstorming and morphological analysis (T=-3.1, p=0.004) and brainstorming and TRIZ (T =-2.11, p=0.04). Figure 5, illustrates these differences. The x-axis are the ventiles, which represent 20 equally sized segmented sections of the design session. The y-axis is the average change in oxygenated blood (HbO). Brainstorming led to high HbO early during the solution generation process but this high response was not sustained or repeated. In contrast, both morphological analysis and TRIZ led to multiple high levels of HbO in the left DLPFC. TRIZ shows high cortical activation distinctively in the first half (ventiles 1-9) and second half (ventiles 11-20) of the solution generation process. This aligns with prior cognitive research that finds TRIZ increases focus during the design process (Gero et al. 2013). Similarities between the three techniques also exist. An increase in activation occurs between the first and second ventile and decrease occurs from the 19th and 20th ventile in all three techniques.

Differences across the whole PFC and right DLPFC were also explored. While the differences appear similar graphically, the patterns of activation did not meet the significance level of 0.05 in the right PFC (F=2.47, p=0.09). The whole PFC did meet significance levels (F =3.38, p=0.04) but upon further analysis, the difference only appears between morphological analysis and TRIZ (T=-2.83, p=0.007).

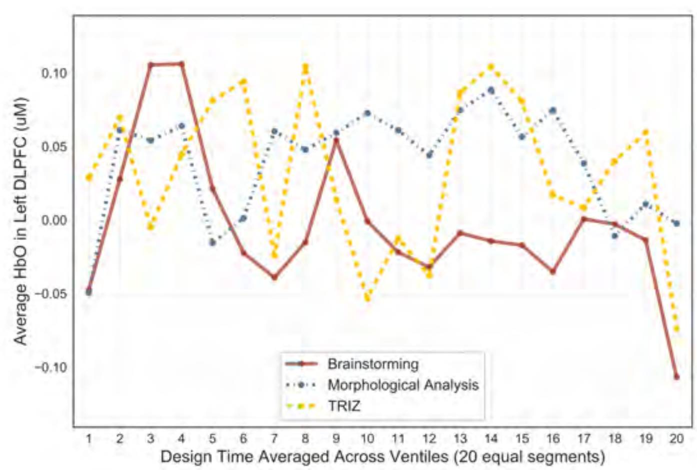


Figure 5: Change of oxygenated hemoglobin (HbO) in the Left DLPFC during each of the three design tasks

To explore regions within the PFC that are most central during concept generation, a Pearson correlation was calculated for each of the 22 channels comparing the average change in HbO. Figure 6 illustrates the correlation matrices for the three design techniques. A correlation threshold of 0.7 was applied so that channel pairs above this level appear as 1 (red) and below 0.7 appear as 0 (blue).

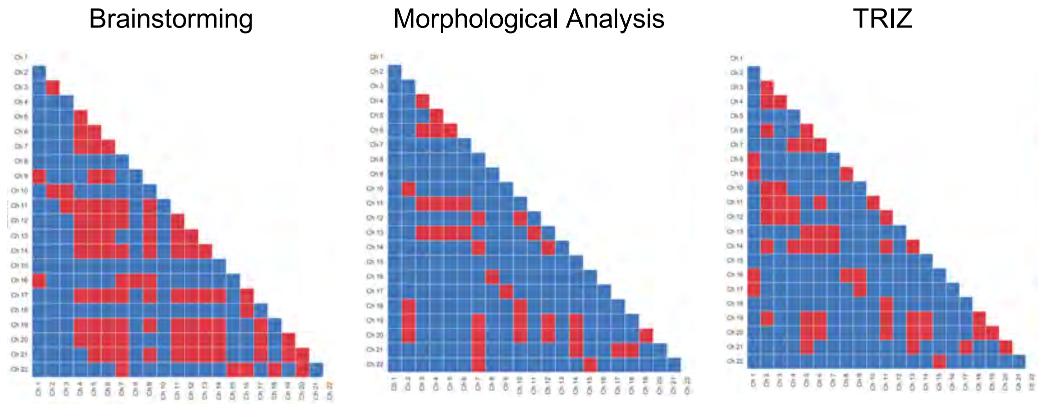
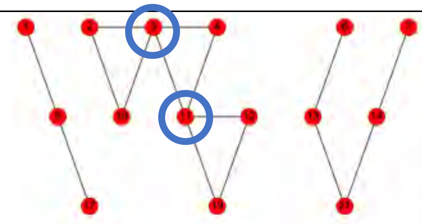
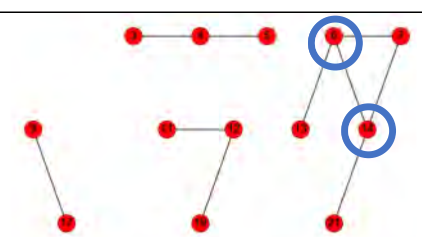
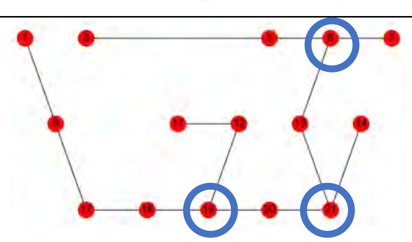


Figure 6: Differences in correlation among channels along the prefrontal cortex

To further assess differences in network coordination, network degree centrality was calculated using the correlation matrices in Figure 6. Network centrality values were normalized by dividing by the maximum possible degree (n-1 where n is the number of nodes in the network). Table 2 provides the nodes with the highest normalized centrality values for each of the three design techniques. The nodes are also highlighted with a circle surrounding the node in each network degree graph. The two nodes during brainstorming most central to the network are both located in the right DLPFC. This region is generally associated with working memory (Pochon et al., 2002; Zhang et al., 2003), memory encoding and recognition and error processing/detection (Chevrier et al., 2007). Two nodes during morphological analysis most central to the network are both located in the left DLPFC. This region is general associated with working memory, cognitive flexibility, planning, inhibition, and abstract reasoning (Bembich et al., 2014). During TRIZ, the most central regions were middle BA 8 and left DLPFC. The middle BA 8 is general associated with management of uncertainty (Volz et al., 2004, 2005; Rämä et al., 2001), and executive control of behavior and planning (Burton et al., 2001; Kübler et al., 2006; Sarazin et al., 1998).

Table 2: Network density during brainstorming, morphological analysis, and TRIZ

Technique	Network Degree, Threshold 0.7	Network Centrality	Associated Regions
Brainstorming		Ch 3: 0.285 Ch 11: 0.285	Ch 3: Right DLPFC Ch 11: Right DLPFC
Morphological		Ch 6: 0.25 Ch 14: 0.25	Ch 6: Left DLPFC Ch 14: Left DLPF)
TRIZ		Ch 6: 0.285 Ch 19: 0.214 Ch 21: 0.214	Ch 6: Left DLPFC Ch 19: Middle BA 8 Ch 21: Left DLPFC

Network density across the PFC was measured over the ventiles to describe the cognitive effort required when using each of the three concept generation techniques. Network density is the actual number of connections divided by the total number of possible connections. Greater network density suggests more cognitive resources, or effort, was applied during the design task. The network density between brainstorming, morphological analysis, and TRIZ is statistically different (F=3.079, p=0.05). Further analysis finds difference occurs between brainstorming and TRIZ (T=2.50, p=0.017). The TRIZ network is denser than brainstorming. In other words, TRIZ required more cognitive effort among the designers. Morphological analysis was not statistically different to TRIZ or brainstorming (T=-1.33, p=0.19). Figure 7, illustrates the differences in network density. All three techniques lead to an increase in network density throughout the design task.

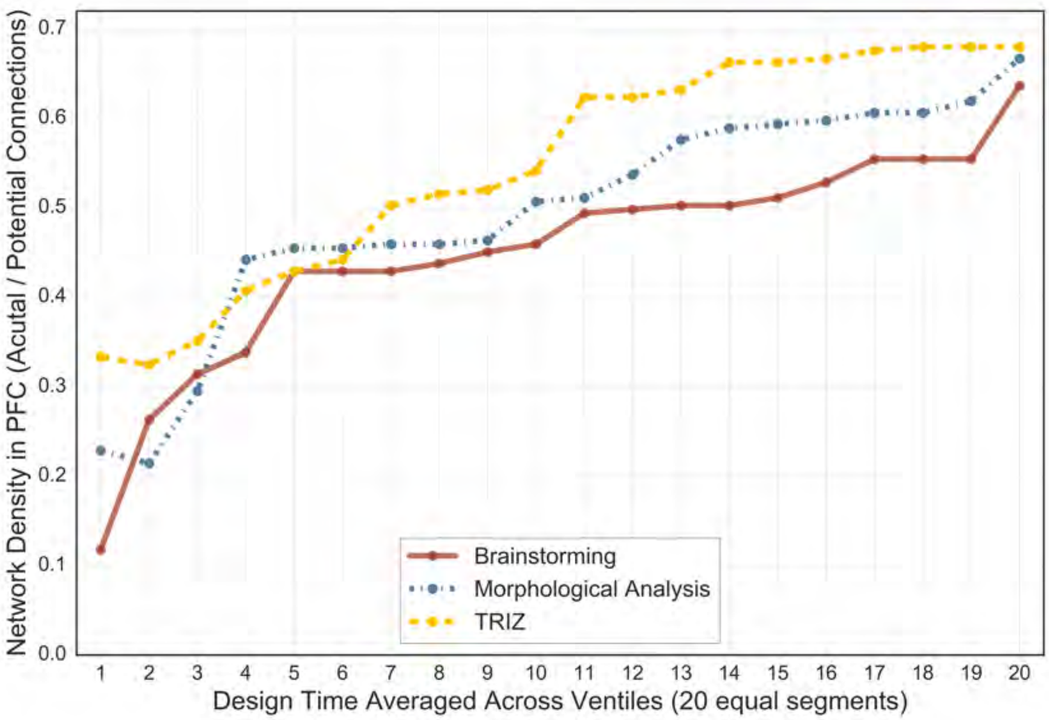


Figure 7: Network Density in the Prefrontal Cortex During Brainstorming, Morphological Analysis, and TRIZ

The neuro-cognitive differences between brainstorming, morphological analysis, and TRIZ suggest these techniques influence patterns of cognitive activation in the brain (Figure 5), influence regions most critical to the design process (Table 2), and influence the effort exerted by the designers (Figure 7). Brainstorming was observed to increase oxygenated blood to the region of the brain associated with creativity and abstract reasoning (left DLPFC) early in the design process but this activation was not sustained. Using techniques like morphological analysis and TRIZ elevated the oxygenated blood to this region of the brain much longer and more frequently during the design process than did brainstorming. The regions, or nodes, most central during the design process varied by technique. Brainstorming elicited greater centrality of regions in the right hemisphere, broadly associated with working memory, memory encoding, and recognition. Morphological analysis provoked greater centrality of regions in the left hemisphere, general associated with abstract reasoning (left DLPFC). Centrality of regions when using TRIZ was similar to morphological analysis with the addition of a node in the middle BA 8, associated with management of uncertainty.

These differences suggest higher reliance on creative thought processes during solutions generation using morphological analysis and TRIZ. During morphological analysis students break down the problem into smaller pieces and then combine them to develop a solution. Whereas, the structured approach, students have to make decisions about which of the 39 principles and 40 TRIZ elements are relevant and which to discard. The higher number of choices when using the principles and TRIZ could lead to greater feeling of uncertainty and this also appears evident in the results. Future analysis on the design outcomes and post-task interviews can provide additional evidence and support for these assumptions and explanations.

The greater network density when using TRIZ implies this technique requires more cognitive coordination among brain regions compared to brainstorming. In all three design processes, the results demonstrate users continue to expend effort during the process, however, TRIZ elicits the most effort. When the increase occurs is also worth noting. The largest increase between ventiles illustrated in Figure 7 occur early for both brainstorming and morphological analysis, whereas, during TRIZ this increase occurs about half way through the design process. The difference in slope steepness also suggests these techniques change cognitive effort and may explain why TRIZ in prior studies was shown to engage more focus and attention for longer time (Gero et al. 2013).

CONCLUSION

The goal of the research presented in this paper was to explore how specific design techniques influence neuro-cognitive response. Brainstorming was observed to produce high cognitive response early during the solution generation process but the high response was not sustained. Techniques like morphological analysis and TRIZ helped enhance cognitive response, leading to much more frequent cognitive effort, especially in the regions of the brain associated with cognitive flexibility, creativity, and working memory. These results provide supporting evidence for the use and purpose of design techniques like morphological analysis and TRIZ during design. This study also contributes to engineering design research by demonstrating a new measurement tool to observe and collect data about design cognition. Through a better understanding of neuro-cognition this type of research can provide supporting evidence for the use of design techniques, the development of new techniques, and a deeper explanation about how these techniques inform creative thought and behavior. Future research can begin to explore the use of brainstorming, morphological analysis, and TRIZ when used more frequently, how cognitive patterns change in response, and form the basis for exploring how engineering design education changes students' neuro-cognition.

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