Concept generation techniques change patterns of brain activation during engineering design

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Abstract

Concept generation techniques like brainstorming, morphological analysis, and TRIZ are distinct in their influence on design behavior and outcomes. However, whether these techniques change the underlying neurocognition that generates new solutions is not well understood. To explore the connection between concept generation and neurocognition, thirty engineering students developed three design solutions using these techniques. Change in students' brain activation was measured using functional near-infrared spectroscopy. The results reveal that brainstorming and morphological analysis demand more cognitive activation across the PFC compared to TRIZ. The highest cognitive activation when brainstorming and using morphological analysis is in the right dorsolateral (DLPFC) and ventrolateral PFC. These regions are associated with divergent thinking and ill-defined problem-solving. TRIZ produces more cognitive activation in the left DLPFC. This region is associated with convergent thinking and making judgments. Morphological analysis and TRIZ expand the brain regions that are most central. Central regions when using TRIZ include the left, right, and middle PFC. Central regions when brainstorming are isolated to the right DLPFC. Morphological analysis and TRIZ also enable greater coordination between brain regions. These findings offer new evidence that structured techniques like TRIZ reduce cognitive load, change patterns of activation, and increase coordination in the brain.

Introduction

Engineering design is an iterative process of problem exploration, concept generation, and evaluation (Cross, 1989). This process of design is not linear (Lawson 2006). It is an activity that evolves through time (Dorst and Cross 2001). Arguably the most critical time is during concept generation (French 1999). The quality and quantity of concepts generated in this intermediate phase ultimately determine the outcome (Helm et al. 2016; Bryant 2005; Shah et al. 2003).

There are numerous techniques to enhance the concept generation process (Helm et al. 2016; Jablokow et al. 2015; Bohm et al. 2005). Concept generation techniques rely on diverse procedures, classified into broad categories based on their intuitiveness (intuition and logical steps) (Shah et al. 2003) their structure (unstructured or partially structured) (Gero et al. 2012) and the amount of motivation required from the designer (intrinsic motivation or goal-directed motivation) (Shealy and Gero 2019; Taura and Nagai 2013). Three well-known techniques that vary in these categories are brainstorming (Osborn 1953), morphological analysis (Allen 1962), and TRIZ (Altshuller 1984).

Brainstorming is characterized as intuitive, unstructured, and inner sense-driven (Shealy and Gero 2019). It requires the designer to be intrinsically motivated (Shai et al., 2009). A general guideline for brainstorming is to generate as many ideas as possible and suspend evaluation until the next design phase (Daly et al. 2012). Contrary to brainstorming, TRIZ is a logical, structured, and problem-driven (Gero et al. 2013; Shah et al. 2000; Shealy and Gero 2019). TRIZ requires users to decompose and analyze the problem systematically before generating new concepts. TRIZ offers engineering principles and cataloged solutions (i.e., design reference of 39 engineering parameters and 40 innovative principles).

Morphological analysis holds similar attributes to both brainstorming and TRIZ (Gero et al. 2013). Morphological analysis, like brainstorming, is an intuitive technique. It relies heavily on association rather than standardized engineering principles (Shah et al. 2003). Morphological analysis is also problem-driven, similar to TRIZ. In morphological analysis, a final design is pre-determined through decomposition, forced association, and a structured combination (Zwicky 1969).

The purpose of the research presented in this paper is to explore how these different techniques influence design cognition in the brain. Concept generation techniques shape design outcomes through their steps and procedures, for example, by increasing or decreasing abstract reasoning, memory retrieval, or uncertainty processing (Shealy and Gero 2019). These changes in cognition are observable in the patterns of activation in the brain (Alexiou et al. 2011; Hu and Shealy 2019). For instance, creative tasks rely heavily on the right prefrontal cortex (Gilbert 2010). Neuroscience offers methods to explore activation patterns in brain regions associated with critical cognitive function for design (Liang 2017; Shealy and Gero 2019). The paper begins by providing background for why variability in neurocognition is expected when using these concept generation techniques. The background is followed by the methods to measure neurocognition during concept generation. Results provide evidence of significant differences in neurocognition for brainstorming, morphological analysis, and TRIZ. The discussion offers some explanation for these differences, and the conclusion presents opportunities for future studies.

Background

Concept generation techniques like TRIZ and brainstorming often involve opposing cognitive structures (Gero et al. 2012). TRIZ tends to increase focus among designers (Gero et al. 2013) and can lead to a mental fixation on problem constraints (Gero 2011). This fixation occurs because TRIZ is problem-driven and follows logical steps guided by analysis, situational context, and constraints (Crilly 2015; Cross 2006). Such fixation can unintentionally hinder potential creative leaps that are needed during design (Storm and Hickman 2015). In contrast to TRIZ, brainstorming enables potential creative leaps by encouraging designers to suspend evaluation and relax constraints. However, the quality of design proposals that are developed through brainstorming is often doubted because of the lack of structure and lack of intermediate evaluation in its process (Howard et al., 2010; Shah et al., 2000).

Mental processes in the brain regulate the ability to generate design concepts when using TRIZ and brainstorming (Fink et al. 2009). An assumption about brain function during design is that information is stored in separate cortical modules that have not been previously associated (Alexiou et al. 2009). Composing new concepts elicits connections, and communication between disparate regions of the brain (Heilman et al. 2003). How and where activation occurs in the brain can provide new insight into concept generation (Liu et al 2016; Sweller 1994).

A critical region for new connections and communication during concept generation is the prefrontal cortex (PFC) (Gilbert et al. 2010). The PFC is the region of the brain associated with executive control functions (Schneider et al. 2012), attention (Dias et al. 1996), working memory

(Lara and Wallis 2015), planning, and inhibition (Dietrich 2004). Sub-regions within the PFC are especially necessary for creative tasks like concept generation (Beaty et al. 2016; Goldschmidt 2016; Dietrich and Kanso 2010; Dietrich 2004). The right PFC plays an active role in divergent thinking (Wu et al. 2015; Zmigrod et al. 2015; Aziz-Zadeh et al. 2013; Heilman et al. 2003) and sustained attention (Cabeza and Nyberg 2000). Designers who display high originality in solution generation exhibit strong synchronization within the right PFC (Fink et al. 2009). The left PFC plays a more active role when supporting rule-based design, goal-directed planning (Aziz-Zadeh et al. 2013), and making analytic judgments (Luft et al. 2017; Gabora 2010; Hoeft et al. 2007). The left PFC also plays a critical role in solving math problems (Poldrack et al. 1999).

The left and right dorsolateral prefrontal cortex (DLPFC) is bilaterally active when performing creativity tasks that require new associations and evaluation (Funahashi 2017). For instance, activation in the left DLPFC decreases (Tachibana et al. 2019), and activation increases in the right DLPFC during improvisation (De Dreu et al. 2012; Kleibeuker et al. 2013). The medial PFC (mPFC) and ventrolateral PFC (VLPFC), are also involved in creative design tasks. The function of the mPFC is to learn associations and is observed to play a role in the retrieval of "remote" memories (Euston et al., 2012). Increased activation in the mPFC is associated with improved ability to simulate future imaginative events (Meyer et al. 2019). The VLPFC is critical for combining existing information into new ideas (Wu et al. 2015; Dietrich 2004). The ability to detect similarity between items activates the right VLPFC (Garcin et al. 2012).

One approach to understand the relationship between patterns of activation in sub-regions of the PFC is through neural networks. Neural networks are used to describe how and where connections are made spatially between brain regions, and this is used to develop frameworks about brain processing, the activation level of these regions, and patterns of co-activation among regions during design (Martindale 1995). For example, distinct patterns of activation in the right parietal and right prefrontal cortex occurred among females during spatial-cognition tasks and left hippocampus in males (Grön et al. 2000). The difference in activation patterns by gender is expressed by their neural network connections between brain regions (Grön et al. 2000).

Identifying interconnected brain regions that are central for each concept generation technique can also provide evidence about what engineers are doing and thinking during design (Alexiou et al. 2011). For instance, TRIZ requires cognitive flexibility to switch between evaluating design principles and imagining the use of these principles with given problem constraints (Savransky 2000). Cognitive flexibility is observed in the brain by higher oscillation between left and right hemisphere dominance in the brain compared to brainstorming (Shealy et al. 2018a).

A new concept might be missed if requisite brain regions are not sufficiently engaged, and this is also observable in patterns of activation described by neural network connections (Grabner et al. 2009). For example, an increase in the connections associated with the right DLPFC corresponds to an increase in the number of solutions generated (Hu 2018). Performance in the ability to develop new associations when concept mapping is also observable in network connections. Concept maps can reduce the need for coordination in the brain because of a reduction in demand from working memory and an increase in activation in the region of the brain associated with divergent thinking (Hu et al. 2019).

Neuroimaging techniques to measure design cognition

Several neuroimaging techniques are available to quantify neurocognitive activation in the brain during concept generation and build models of neural networks. These methods include electroencephalogram (EEG), functional magnetic resonance imaging (fMRI), and function near-infrared spectroscopy (fNIRS). EEG has a high temporal resolution (i.e., ability to detect quick changes on the order of milliseconds), mobility, and a relatively low initial purchase price (Hu and Shealy 2018). EEG, however, is limited in spatial resolution (i.e., ability to detect where the change in neurocognition occurs) because the electrical activity measured by EEG goes through multiple layers in the brain and is a mixture of signals from underlying brain sources. The ability to pinpoint specific brain regions with EEG is a challenge (Burle et al. 2015). For example, neurocognition of mechanical engineers and architects during design is significantly different, but where and how these differences occur in the brain is not spatially distinguishable beyond hemispherical regions in the brain when using EEG (Vieira et al. 2019).

In contrast to EEG, fMRI has high spatial resolution with the ability to display cognitive activation in the whole brain. fMRI measures the changes in blood oxygenation level, which is linked to cognitive activity (Gramann et al. 2014). The temporal resolution of fMRI is on the order of seconds due to the blood flow change over time and the time needed for net magnetization recovery before the next sampling (Eysenck and Keane 2015). Data collection with an fMRI requires participants to remain still and lay down while partially enclosed inside the fMRI scanner, and this can be constraining. For example, students completing a design experiment monitored with fMRI had to first verbally describe their design solutions and then subsequently sketch them once they were out of the fMRI scanner because drawing inside of the scanner was not possible (Hay et al. 2019).

EEG and fMRI are less than ideal for studying design cognition because of either spatial resolution limitations or lack of mobility in an unrealistic environment. fNIRS combines the advantages of EEG and fMRI. Participants can operate a computer or perform a task in an upright sitting position, similar to EEG, and it has a good spatial resolution compared to EEG and moderate compared to fMRI. fNIRS can be worn as a cap where light is emitted from sources at specific wavelengths (between 700-900 nm) into the scalp. The light scatters, before reflecting back to the light receivers. The oxy-hemoglobin (oxy-Hb) and deoxy-hemoglobin (deoxy-Hb) absorb more light than water and other tissue in the brain. The change in the difference between the emitted light and reflected light is used to calculate the change in oxygenated blood using a Modified Beer-Lambert Law. The oxy-Hb and deoxy-Hb are inversely related, but typically only oxy-Hb is reported because of its relatively higher amplitudes and sensitivity to cognitive activities (Hu and Shealy 2019).

A drawback of fNIRS is the limited power of light emitter, which makes it unable to capture sub-cortical activation in the brain, unlike fMRI. However, areas relevant for design neurocognition, such as the PFC, associated with executive function and working memory, are sufficiently accessible with fNIRS (Fuster 1988). For example, fNIRS can adequately capture the ability to think in systems (Hu et al. 2019) and make decisions (Hu and Shealy 2019; Shealy and Hu 2017).

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 relative ease of use is why fNIRS is the preferred neuroimaging instrument in this context (Shealy and Hu 2017).

Table 1. Comparison of Neuroimaging technologies

Criteria	EEG	fMRI	fNIRS
Spatial resolution	Poor	Excellent	Good
Temporal resolution	Excellent	Poor	Good
Mobility	Participants sit upright with a cap	Participants lay down in scanner	Participants sit upright with a cap
Data processing	Moderate	Intensive	Modest
Cost to operate	$0 (after purchase)	~$500 per hour	$0 (after purchase)
Ease of use	Time intensive placing electrodes	Requires technician	Less time-intensive than EEG

The research reported in this paper aimed to assess how the varying attributes associated with three concept generation techniques change how information is cognitively processed and influence the dominant use of specific regions in the brain. The use of fNIRS enabled measuring neurocognitive activation during design and provides evidence of the changes in demand patterns and functional coordination (e.g., abstract reasoning and evaluation) when designers generate concepts and how this varies across the techniques.

Research Questions

The study described in this paper aimed to assess how brainstorming, morphological analysis, and TRIZ changes how specific brain regions are activated in the PFC. The specific research questions are:

1. What is the effect of brainstorming, morphological analysis, and TRIZ on cognitive activation in the prefrontal cortex?
2. What regions within the prefrontal cortex are most central during concept generation when using brainstorming, morphological analysis, and TRIZ?
3. How does cognitive coordination across regions in the prefrontal cortex change over time when using brainstorming, morphological analysis, and TRIZ?

Methods

Experimental design

Thirty graduate engineering students (all right-handed, 22-26 years old) were recruited to participate in the study. All reported prior course work in engineering design. None of the participants indicated they had formal training with morphological analysis or TRIZ. Pre-task training was provided to introduce the three techniques to participants. Participants then received three engineering design tasks and completed each task at their own pace using one of the three techniques. The technique and design task were assigned randomly to each participant. The design tasks were not discipline-specific and previously demonstrated to require similar cognitive processes to generate a solution (Gero et al. 2013). In one of the design tasks, participants were instructed to design a device to assist the elderly with raising and lowering windows. Another design task required participants to design an alarm clock for the hearing impaired. The final design task asked participants to design a kitchen measuring tool for the blind. Participants were instructed to draw figures on paper to illustrate their design solutions. The average time to complete the task when brainstorming, using morphological analysis, and TRIZ was 7.53 minutes (SD = 3.25 minutes), 11.02 minutes (SD = 4.70 minutes), and 13.34 minutes (SD = 5.03 minutes), respectively.

Participants were outfitted with the functional near-infrared spectroscopy (fNIRS). The fNIRS cap measured their neurocognitive activation during each task, and is illustrated in Figure 2(a). The fNIRS machine recorded a change in participants' oxygenated hemoglobin in their PFC as they generated a solution to each design problem. The sensor placement on the fNIRS cap is shown in Figure 2(b). 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 a nearby light receiver. It captures the change in oxygenated cortical blood in the brain. These channels cover multiple sub-regions in the PFC, including dorsolateral prefrontal cortex (DLPFC: channel 1, 2, 3, 9, 10 in the right hemisphere, and channel 5, 6, 7, 13, and 14 in the left hemisphere), ventrolateral prefrontal cortex (VLPFC: channel 16 and 17 in the right hemisphere, and channel 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: channel 4, 11, 12 and 19) in both hemispheres.

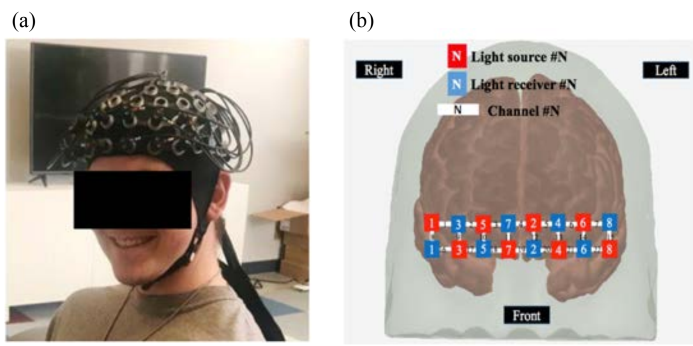


Figure 1. A participant with fNIRS cap and sensor configuration

Data analysis

Three out of the 30 participants were removed from the analysis because of a weak signal during the experiment. fNIRS raw data for the remaining 27 subjects were 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 (Huppert et al. 2009). An independent component analysis (ICA) with a coefficient of spatial uniformity (CSU) of 0.5 was applied to remove motion artifacts. The steps of noise and motion artifacts removal are critical to avoid false discovery in brain network and connectivity analysis (Santosa et al. 2017). The parameters in data processing are based on prior research (Naseer and Hong 2015; Sato et al. 2011). Only oxygenated hemoglobin (oxy-Hb) in the filtered data is reported in the results because oxy-Hb generally has a higher amplitude and is more sensitive to cognitive activities than deoxygenated hemoglobin (deoxy-Hb) (Hu and Shealy 2019).

To answer research question one, two methods were used to measure neurocognitive activation in the prefrontal cortex when using brainstorming, morphological analysis, and TRIZ. First, the positive area under the curve (AUC), as illustrated by the shading in Figure 3, was calculated for each participant when using each design technique. AUC is an indicator of cognitive load (Suzuki et al. 2018). The overall cognitive load in the PFC was then calculated using the average of all channels for comparison between the concept generation technique.

AUC was also used to compare hemisphere asymmetry between the left and right PFC (Runco 2014; Toga and Thompson 2003). The AUC of ten channels in the right PFC and ten channels in the left PFC were averaged respectively to calculate the cognitive load in the right and left hemispheres. Analysis of variance (ANOVA) was used to measure the statistical difference in the cognitive load across the PFC and the left and right PFC for each concept generation technique. Significance was defined as $p<0.05$. The effect size for the significant difference was measured by η^2 (Eta squared) for ANOVA and Cohen's d for the posthoc Tukey test. The difference is regarded as large when η^2 is greater than 0.138, or Cohen's d is greater than 0.8 (Cohen 1977).

The second measure for cognitive activation was the mean value of oxy-Hb illustrated by the dotted line in Figure 2. The design session for each design task for each participant was divided into 20 equal and non-overlapping segments, or ventiles (Gero 2010; Milovanovic and Gero 2018; Shealy and Gero 2019). Participants' mean oxy-Hb was calculated for each ventile. These ventile averages for each participant were then averaged together to create an average oxy-Hb for each of the twenty ventiles when using each design technique. ANOVA was used to measure the difference in the patterns of oxy-Hb in the PFC for the twenty ventiles (including left and right DLPFC, VLPFC, OFC, and the mPFC). Significance was defined as $p<0.05$.

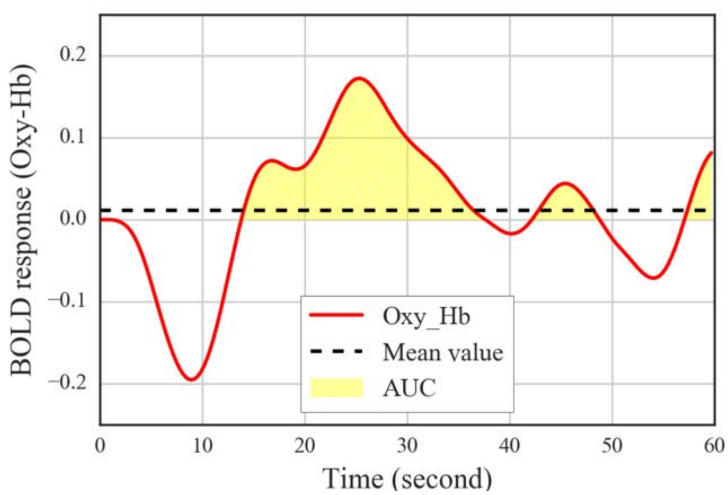


Figure 2. Area under the curve (AUC) and mean value of Oxy-Hb

To answer research question two, graph theory (Wijk et al. 2010) was applied to understand what regions within the prefrontal cortex are most central and the coordination required between brain regions during concept generation (Bullmore and Sporns 2009; De Vico Fallani et al. 2014). Pearson's correlation matrices were developed using the change of oxy-Hb in all channels during each design task for each participant. Correlation matrices were averaged across participants when using the same design technique. High correlations (incrementally from 0.6 to 0.7) were considered as connective functions (Bassett and Sporns 2017; Fornito et al. 2016; De Vico Fallani et al. 2014). A range of plausible threshold coefficients was used based on prior studies (Bressler and Menon 2010; Bullmore and Sporns 2009; Achard and Bullmore 2007). Correlations higher than the threshold coefficients indicate a functional relationship between synchronized activation of different brain regions. Links were drawn between channels when the correlation coefficient was higher than the threshold. These links are illustrated in Figure 3.

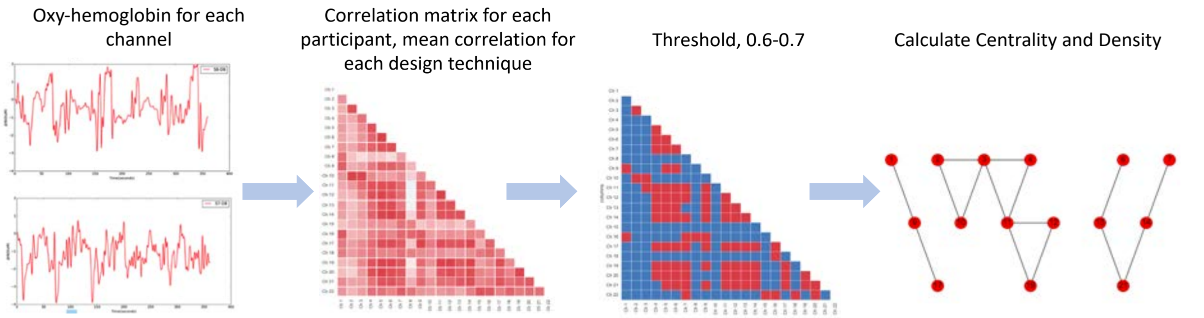


Figure 3. Brain networks and metrics

The centrality and network density were then calculated to provide descriptive measures of the network. Node centrality describes the nodes with the most edges in the network. Central nodes are critical to efficient communication for task completion (Bullmore and Sporns 2009). The density of connections was used to answer research question three. It provides an estimate of cognitive coordination within the network (Achard and Bullmore 2007). A low network density means low coordination between brain regions. Network density is the proportion of the number of actual connections to the number of possible connections in a network.

Results

TRIZ demands significantly less cognitive load in the prefrontal cortex compared to brainstorming and morphological analysis

The neurocognitive activations when generating new concepts through brainstorming, morphological analysis, and TRIZ are significantly different ($F=7.90$, $p<0.001$, $\eta^2=0.48$). The positive area under the curve (AUC) of oxy-Hb in the PFC is lower when using TRIZ compared to brainstorming ($t=3.50$, $p=0.001$, Cohen's $d=1.14$) and morphological analysis ($t=3.63$, $p<0.001$, Cohen's $d=1.57$). The effect size in AUC between TRIZ and brainstorming and TRIZ morphological analysis is large. AUC is a proxy for cognitive load. So, TRIZ reduces the cognitive load required in the PFC compared to brainstorming and morphological analysis.

These results are consistent when isolating the right PFC. TRIZ reduces the cognitive load ($F=15.61$, $p<0.001$, $\eta^2=0.65$) required in the right PFC compared to brainstorming ($t=5.26$, $p<0.001$, Cohen's $d=1.70$) and morphological analysis ($t=4.87$, $p<0.001$, Cohen's $d=1.57$). The effect size is large. TRIZ also demands significantly ($F=4.94$, $p=0.01$, $\eta^2=0.37$) less cognitive load in the left hemisphere when generating concepts. Morphological analysis elicited significantly more cognitive load in the left PFC than brainstorming ($t=2.21$, $p=0.03$, Cohen's $d=0.72$) and TRIZ (4.87, $p<0.001$, Cohen's $d=0.87$). To summarize these results, TRIZ requires significantly less cognitive load than morphological analysis and brainstorming in the right and left PFC. Morphological analysis demands a higher cognitive load in the left hemisphere compared to brainstorming and TRIZ. These results are illustrated in Figure 4.

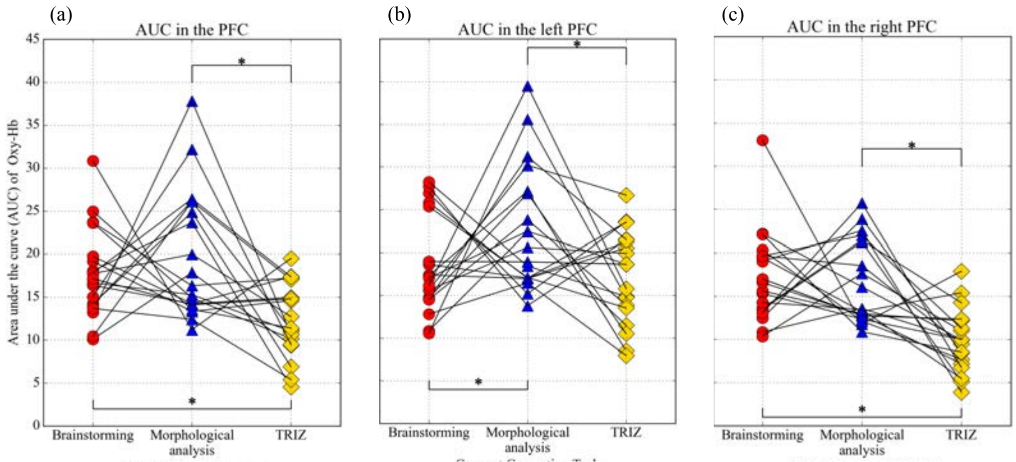


Figure 4. Difference in area under the Oxy-Hb curve when using brainstorming, morphological analysis, and TRIZ; (a) Average AUC in the left and right PFC; (2) AUC in the left PFC; (3) AUC in the right PFC

Brainstorming, morphological analysis, and TRIZ produce significantly different patterns of cognitive activation over time

Consistent with the area under the curve, mean oxy-Hb over time, which is a proxy for cognitive activation, in the right DLPFC ($F=9.14$, $p<0.001$, $\eta^2=0.52$) and right VLPFC ($F=6.24$, $p=0.004$, $\eta^2=0.52$) is significantly less when using TRIZ compared to brainstorming and morphological analysis. The effect size in the right DLPFC between TRIZ and brainstorming ($t=3.96$, $p<0.001$, Cohen's $d=1.28$) and morphological analysis ($t=3.27$, $p=0.002$, Cohen's $d=0.97$) is large. Patterns of cognitive activation are similar when using brainstorming and morphological analysis with no significant difference. TRIZ also demands significantly less cognitive activation in the right VLPFC compared to brainstorming ($t=2.93$, $p=0.006$, Cohen's $d=0.93$) and morphological analysis ($t=2.77$, $p=0.009$, Cohen's $d=0.88$). The difference in the pattern of cognitive activation over time between brainstorming and morphological analysis is also significantly different ($t=2.18$, $p=0.03$, Cohen's $d=0.74$). Figure 5 depicts the patterns of cognitive activation in both the right DLPFC and right VLPFC. Both TRIZ and brainstorming demand more cognitive activation early in the concept generation process, but this activation declines more quickly with TRIZ. Morphological analysis tends to demand more cognitive activation in the middle of the concept generation process with two distinct peaks around ventile 6 and 12.

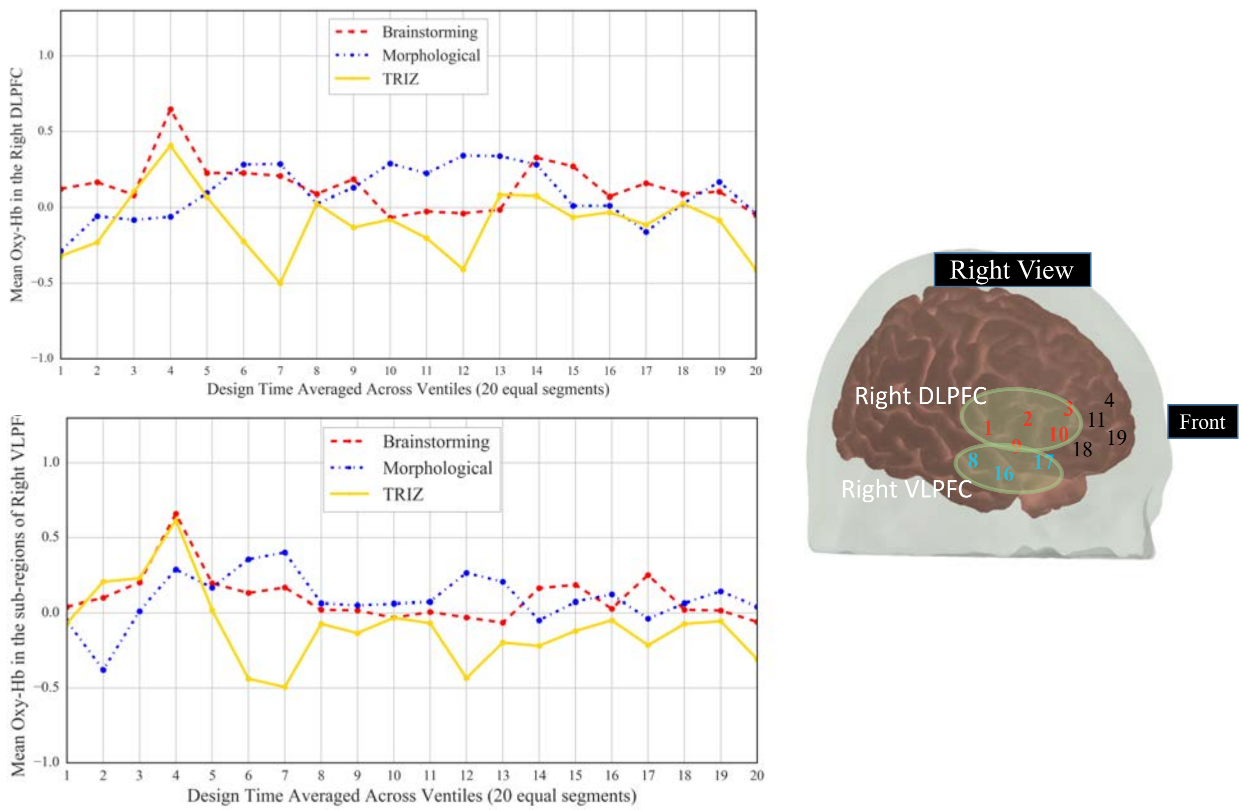


Figure 5. Differences in patterns of cognitive activation in the right DLPFC (a) and right VLPFC (b) when brainstorming, using morphological analysis, and TRZ

Significant differences ($F=10.70$, $p<0.001$, $\eta^2=0.55$) in patterns of cognitive activation when using brainstorming, morphological analysis, and TRIZ are also observed in the left DLPFC. TRIZ demands more cognitive activation compared to brainstorming ($t=4.71$, $p<0.001$, Cohen's $d=1.57$) and morphological analysis ($t=3.00$, $p=0.005$, Cohen's $d=1$) with a large effect size. TRIZ produces multiple peaks of cognitive activation in the left DLPFC that is higher in amplitude than brainstorming or morphological analysis. Brainstorming and morphological analysis elicit similar patterns of cognitive activation in the left DLPFC. Morphological analysis tends to gradually increase in the first half and then a gradual decrease in the second half of the concept generation process. Some activation is observed at the beginning and end during brainstorming, but the amplitude of activation is lower compared to TRIZ and morphological analysis, illustrated in Figure 6.

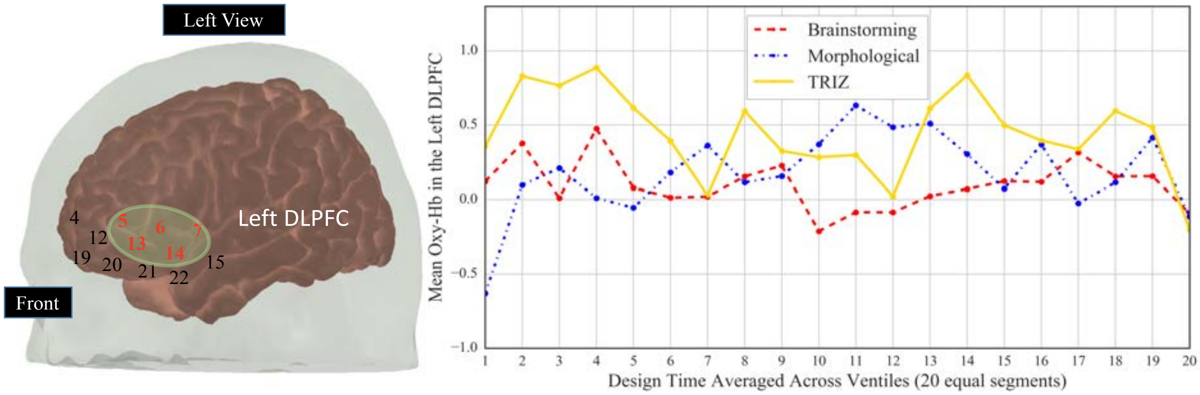


Figure 6. Differences in patterns of cognitive activation in the left DLPFC when brainstorming, using morphological analysis, and TRZ

A significant and large (F=4.52, p=0.01, η^2=0.35) difference is also observed in the medial PFC (mPFC) (Channels 11 and 19). Brainstorming demands more (t=3.15, p=0.003, Cohen's d=1.01) cognitive activation over time in the mPFC than TRIZ, and the difference is large. Brainstorming demands more cognitive activation both at the beginning and end of the concept generation process. Neurocognitive activation gradually increases when using morphological analysis for the first fifteen ventiles. TRIZ demands more neurocognitive activation early and late in the concept generation process, but the amplitude of activation is less than both brainstorming and morphological analysis, illustrated in Figure 7.

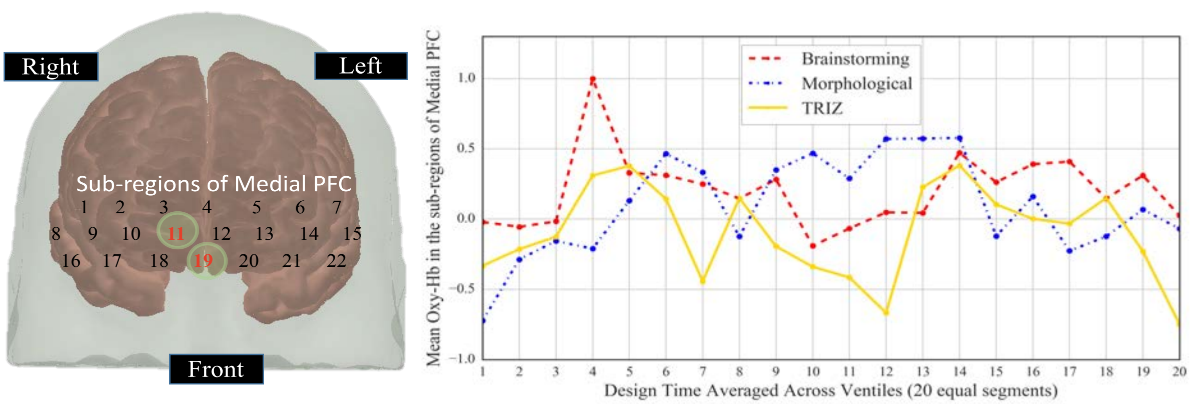


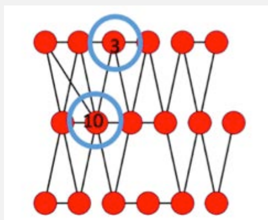
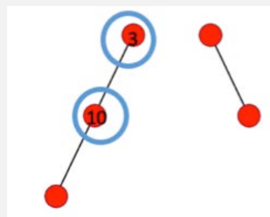
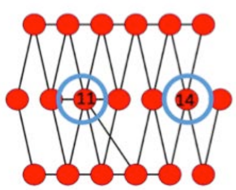
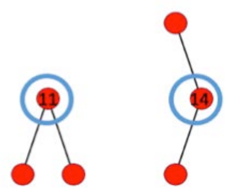
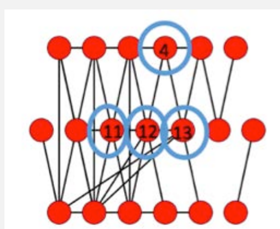
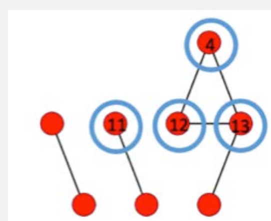
Figure 7. Difference in patterns of cognitive activation (mean value of Oxy-Hb) in the sub-regions of Medial PFC among techniques

Node centrality varies by hemisphere between brainstorming, morphological analysis, and TRIZ

Brain network analysis suggests that node centrality varies when using brainstorming, morphological analysis, and TRIZ. A sequence of increasing threshold coefficients within the range of 0.6 to 0.7 was used to measure node centrality. The channels with the highest centrality (average under all thresholds) and their associated regions are shown in Table 2. The network graphs in Table 2 illustrate the brain network with a threshold of 0.6 and 0.7 when using brainstorming, morphological analysis, and TRIZ.

When brainstorming, the most central node is in the right DLPFC. When using morphological analysis, the most central node is in both the right and left DLPFC. When using TRIZ, the most central nodes are in the right DLPFC, left DLPFC, and medial PFC. TRIZ also elicits the most network connections compared morphological analysis and brainstorming. Morphological analysis elicits more network connections than brainstorming. Network connections are one proxy for coordination between brain regions.

Table 2. Network graphs and centrality when concept generation

Technique	Network graph, Threshold = 0.6	Network graph, Threshold = 0.7	Channel: Central regions
Brainstorming			Channel 10: 0.351 (Right DLPFC) Channel 3: 0.253 (Right DLPFC)
Morphological			Channel 11: 0.310 (Right DLPFC) Channel 14: 0.230 (Left DLPFC)
TRIZ			Channel 12: 0.344 (Left DLPFC) Channel 11: 0.307 (Right DLPFC) Channel 10: 0.270 (Right DLPFC) Channel 4: 0.264 (Medial PFC)

Coordination between brain regions increases when using morphological analysis and TRIZ compared to brainstorming

The network density was calculated for each ventile when using brainstorming, morphological analysis, and TRIZ to understand the coordination between brain regions over time. Figure 8 shows the change in density for each ventile. There are significant ($p<0.001$) differences in the network density when using brainstorming, morphological analysis, and TRIZ. The density when brainstorming is significantly lower than morphological analysis (e.g., $t=-12.78$, $p<0.001$ when threshold=0.7) and TRIZ (e.g., $t=-11.01$, $p<0.001$ when threshold=0.7). Morphological analysis and TRIZ have no significant difference in network density. TRIZ and morphological analysis significantly increase the brain regions that are in coordination during concept generation compared to brainstorming.

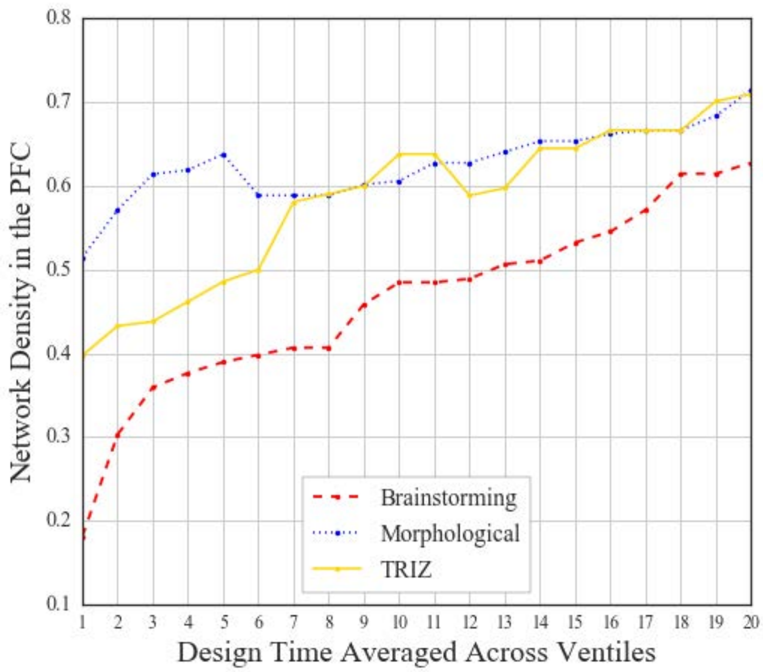


Figure 8. Network density change over time during concept generation (correlation threshold equals 0.6)

Discussion

These results offer empirical evidence about the neurocognitive differences when using brainstorming, morphological analysis, and TRIZ. The results relate to the drive, the structuredness, and the intuitiveness of each technique. A fundamental cognitive function of the PFC is working memory (Funahashi 2017; Lara and Wallis 2015). The cumulative cognitive activation (described in the results as the positive area under the curve for oxy-Hb) in the PFC is a proxy for cognitive load in working memory. The results indicate that the use of TRIZ demands less cognitive load in the PFC than brainstorming and morphological analysis. This trend also appears in the right and left PFC. This trend is consistent with prior research that says TRIZ is likely to occupy less space in students' short-term memory based on self-report surveys and student reflections (Belski 2011; Belski and Belski 2015). A reason why TRIZ demands less cognitive load might be that the structuredness of TRIZ offers strong cues and an organized information retrieval process between short-term and long-term memory systems. With reference to the 39 Engineering Parameters and 40 Innovative Principles in TRIZ, students can break down the problem, focus on a single principle at a time, and attend to one possible solution before moving to the next parameter and principle. This process of shifting attention between principles and solution reduces cognitive complexity in design and seems to align with human cognitive structures as cognitive load theory suggests (Jong 2010).

Conversely, the lack of cues while brainstorming might result in less focused attention. When brainstorming, students expressed significantly higher cognitive load in their PFC. The excess of information or distractions from other thoughts could be the result of the un-structuredness of this technique (Kohn and Smith 2011). Cognitive resources are limited in short-term memory (Artino

2008). Brainstorming appears to consume more of these resources (Kirschner 2002; Santanen et al. 2000), and this is consistent with prior literature (Gabora 2010; Lara and Wallis 2015).

Using morphological analysis also appears to result in a higher cognitive load than TRIZ. Morphological analysis follows a process of breaking down the problem and then concept association, which can stimulate more concepts than brainstorming (Keong et al. 2012). However, without any engineering parameters or principles like in TRIZ, each step of morphological analysis requires intuitive thinking, likely demanding more cognitive resources. To summarize these findings, the logical rule-based technique of TRIZ provides a design tool that reduces cognitive load compared to the intuitive techniques of brainstorming and morphological analysis.

The second finding is that each technique relies on specific subregions of the PFC. Previous studies about creative tasks find limited evidence of differential activation between hemispheres and subregions (Colombo et al. 2015). Brainstorming and morphological analysis demand more cognitive activation (described as the mean value of oxy-Hb) in the right lateral PFC compared to TRIZ. The right lateral PFC (including DLPFC and VLPFC) plays an active role in divergent thinking tasks (Wu et al. 2015). The right DLPFC is generally associated with divergent thinking (Zmigrod et al. 2015; Aziz-Zadeh et al. 2013) and maintaining divergent ideas with sustained attention (Cabeza and Nyberg 2000). Intuitive ideas that suddenly come to mind are also associated with increased activation in the right DLPFC (Pisapia et al. 2016). The right DLPFC is a critical region for ill-structured design cognition (Gilbert et al. 2010).

The right VLPFC plays a critical role related to hypotheses generation and maintenance of divergent thinking (Goel and Vartanian 2005). A possible explanation for the higher activation in the right DLPFC and right VLPFC when using brainstorming and morphological analysis compared to TRIZ is that students tend to continually rely on divergent thinking during brainstorming and morphological analysis to generate multiple new, unconnected concepts. This reliance on divergent thinking appears to lead to higher sustained activation in the right lateral PFC to maintain these isolated small chunks of information in the working memory (Gilbert et al. 2010).

Another possible explanation for the higher activation in the right DLPFC when using brainstorming and morphological analysis is that the problem appears to be more ill-defined for brainstorming and morphological analysis. A design study found that the right DLPFC showed significantly higher activation in ill-structured problems than well-structured problems (Gilbert et al. 2010). Brainstorming begins with a random and intuitive exploration of the solution space without explicit identification of the design problem, and morphological analysis provides no parameters or principles for designers to formulate a problem like TRIZ. This explanation seems consistent with prior findings that reasoning about the design problem is increased when applying TRIZ compared to brainstorming and morphological analysis (Gero et al. 2013).

Patterns of high cognitive activation in the right lateral PFC occur at the beginning of concept generation when using TRIZ. Students might think divergently to generate many ideas, but the pattern of neurocognitive activation shifts from the right DLPFC to the left DLPFC later in the concept generation process when using TRIZ. The left DLPFC is generally associated with making judgments (Birdi et al. 2012), and fixation (Cross 2006). The left DLPFC is associated with controlling convergent judgments about whether ideas generated in the right hemisphere meet constraints (Luft et al. 2017). This region also shows more activation in goal-directed planning of novel solutions (Aziz-Zadeh et al. 2013). The higher activation in the left DLPFC when using TRIZ compared to brainstorming and morphological analysis might indicate that students reserve cognitive attention to evaluate concepts by applying filters and affirm solutions to satisfy the constraints or meet the design goals. This shift from right to left DLPFC enables cognitive flexibility and might lead to increased attention (Goldschmidt 2016), which seems to support the claim that TRIZ can increase attention (Gero et al. 2013).

On the contrary, when using brainstorming and morphological analysis, more cognitive resources are allocated to the right DLPFC. Possibly, maintaining divergent thinking in the right hemisphere means fewer resources are available for convergent thinking and evaluating concepts in the left DLPFC. Of course, this result might not be surprising since the general instruction for brainstorming is to suspend or delay judgments when generating solutions (Keong et al. 2012). For morphological analysis, students might not have had adequate cognitive resources for concept evaluation allocated to the left DLPFC, which is suggested by the lower activation in this region.

Higher cognitive activation was also observed in the medial PFC (mPFC) when using brainstorming. The function of the mPFC is to learn associations and is observed to play a critical role in the retrieval of "remote" memories (Euston et al., 2012). The higher activation in this region when brainstorming might suggest more cognitive resources are required to make associations between divergent ideas or linking known concepts with new ones. In the case of morphological analysis, students decomposed the problem based on functions, so the association processing could seem more manageable and require less activation in the mPFC than brainstorming. The fewest cognitive resources were required when using TRIZ. Similar to morphological analysis, this logical process relies on decomposition and analysis.

In addition to the changes in cognitive load and patterns of activation in sub-regions, the brain network analysis revealed potential connections between the structuredness of each concept generation technique and the central regions for cognitive coordination. The right DLPFC is the most central region needed for communication across brain regions during brainstorming. The right and left DLPFC are the two most central regions for communication across the brain during morphological analysis, and the right and left DLPFC and the medial PFC are the most central for communication across brain regions during TRIZ. The same regions were also detected with high centrality for concept generation in a prior study investigating design cognition (Shealy et al. 2018b).

The common brain region with high centrality when using all three techniques is the right DLPFC. The right DLPFC plays a crucial role in efficient communication (i.e., coordination) during concept generation. This finding is consistent with previous research, which finds coordination in the right DLPFC is crucial to design cognition (Gilbert et al. 2010). The differences found in this study, compared to previous studies, is the cognitive coordination (described in the results as the network density) across the PFC is more for TRIZ and morphological analysis than brainstorming. In other words, using the problem-driven approaches that require decomposition and analysis activate more communication across regions in the brain. This might be because these techniques direct more reasoning about the problem, binding of different knowledge sets, and information retrieval from long-term memory (Heilman et al. 2003).

The results presented in this paper provide new insights to better understand the relationship between concept generation techniques and cognitive processes through the analysis of neurocognitive activation, and coordination. Brainstorming, morphological analysis, and TRIZ change engineering students' neurocognitive behavior. There are several limitations to this study that are worth mentioning. fNIRS data only includes the change of oxygenated hemoglobin in the PFC. Other brain regions (e.g., parietal cortex) might also contribute to creative design cognition. This limit is characteristic in all neuroimaging studies that do not capture whole-brain activation (Ayaz et al. 2011; Cazzell et al. 2012). Another limitation is that this study focused on neurocognitive differences and did not include a comparison of the behavior of engineering students and their design outcomes. The 27-person sample size is another limitation (Schönbrodt and Perugini 2013). Although the number of participants does meet the average sample size of 27 in similar studies (Hu and Shealy 2019), and the posthoc analysis also indicates a strong power. Future research should replicate the results with a larger sample size (Shrout and Rodgers 2018).

Conclusion

The neuroimaging methods adopted in this study explored how concept generation techniques influence neurocognition during design. Significant differences are observed in neurocognition when using brainstorming, morphological analysis, and TRIZ. Brainstorming and morphological analysis induce more cognitive load across the prefrontal cortex (PFC) compared to TRIZ. Higher cognitive activation associated with divergent thinking and ill-defined problem-solving is observed in the right dorsolateral PFC and ventrolateral PFC when using brainstorming and morphological analysis. TRIZ demands more cognitive activation in the left dorsolateral PFC. This region is associated with controlling judgments and convergent thinking.

Centrality and coordination between regions in the PFC also varied with each technique. The right DLPFC plays a central role in communicating across brain regions when using all three techniques. The left DLPFC also plays a central role in communicating across brain regions when morphological analysis and TRIZ are used, and the mPFC also plays a role when using TRIZ. Morphological analysis and TRIZ significantly increase the number of brain regions in coordination during concept generation.

These multiple analyses indicate that TRIZ, compared to brainstorming and morphological analysis, increases coordination between brain regions and decreases the cognitive load during concept generation. This insight about the neurocognitive benefits of using TRIZ offers new supporting evidence for the use of structured and goal-direct concept generation techniques. It motivates the development of new techniques and offers a more in-depth explanation about how these techniques inform creative thought and behavior. Future research should explore the correlation between the neurocognitive response, design behavior, 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 science by providing a framework and methods to enhance concept generation.

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