THE NEUROCOGNITION OF THREE ENGINEERING CONCEPT GENERATION TECHNIQUES

Tripp Shealy and John S Gero

Techniques and processes used for concept generation rely on composing new concepts or analysis given situational context. Composition and analysis require distinct neurocognitive function. For instance, jazz composition relies heavily on the right brain, while math relies on the left. Similar to music and math, is concept generation hemisphere dominant? What differences exist when using varying techniques? Twelve graduate engineering students were given three design tasks and instructed to use brainstorming, morphological analysis and TRIZ. A device called fNIRS measured cognitive activation. The results find left hemisphere dominance. More specifically, the left dorsolateral PFC (dlPFC), which is central to spatial working memory and filtering information. Temporal differences do exist. Morphological analysis and TRIZ reinforced the use of the left dlPFC, while brainstorming increased the use of the right dlPFC and medial PFC (mPFC) late during concept generation. The right dlPFC contributes to divergent thinking and mPFC facilitates memory retrieval. One explanation is designers relaxed rule constraints and more deeply searched for associations during brainstorming.

Keywords: Design cognition, Conceptual design, Design theory, Multi- / Cross- / Trans-disciplinary processes

1 INTRODUCTION

Engineering design is a process of problem exploration, concept generation, solution evaluation and communication (Cross, 1989). Concept generation is one of the most critical steps in this process because the quality and quantity of concepts being generated determines the outcomes of the final design (Helm et al., 2016; Bryant, 2005). Concept generation is the time to bring about problem understanding and practical knowledge to develop possible solutions (French, 1999). It can also be defined as the process of composing a desirable concept towards the future (Taura & Nagai, 2013).

Techniques and processes used for concept generation can be classified as problem–driven or inner sense–driven (Taura & Nagai, 2013). Problem–driven includes generating a new concept through *analysis*. It is the ability to develop a solution that fills a gap between a goal and an existing situation (Ball & Christensen, 2009). Typically techniques that promote a problem-driven approach are structured (Moon Sungwoo et al., 2012). Structured techniques focus on generating solutions to meet multiple functional requirements. For instance, TRIZ is a highly structured and problem-driven approach (Vidal et al., 2015). A semi-structured approach that also fits within the problem-driven classification is morphological analysis. This is partially structured because of its three-step process of decomposing a problem into several items based on functional requirements, then providing several solutions to each sub-problem and combining sub-solutions for a final design (Gero et al., 2013).

Inner sense–driven processes rely on *composition* instead of *analysis* (Welling, 2007). Whether explicitly or implicitly implied, inner sense–driven processes are intrinsically motivated and include criteria underlying the designer's mind (Shai et al., 2009). Techniques that promote an inner sense-driven approach are typically less structured (Hatchuel & Weil, 2008). Brainstorming is an example of an unstructured process (Gero et al., 2013). The main difference between inner-sense and problem-driven is the reliance on *composing* new concepts using intrinsic motivation or a focus on *analysis* guided by situational context and constraints.

Composition and analysis can be seen as opposing cognitive processes. Both require distinct neurocognitive functions. In music composition, jazz improvisation relies heavily on the right brain hemisphere (Bengtsson et al., 2007), while, for instance, math problems that require analysis are left hemisphere dominant (Poldrack et al., 1999). Similar to music composition and math, is concept generation hemisphere dominant? Do problem-driven or inner sense-driven processes rely on fundamentally different patterns of cognition or are they variations of the same underlying cognitive states?

Prior design research explains how both problem-driven and inner sense-driven methods influence design cognition. However, these prior studies offer little information about how these techniques elicit mental functions to produce results. Problem-driven approaches like TRIZ increase focus among designers. TRIZ, however, can also lead to mental fixation on problem constraints (Cross, 2006). Such fixation can be determinantal to creative leaps needed during design. Brainstorming helps relax some of these constraints but the quality of results through brainstorming are consistently doubted (Howard et al., 2010; Shah et al., 2000). The application of methods from neurocognitive science can help better describe what engineers are doing and thinking during concept generation and provide evidence of varying patterns of neurocognition (Coley, Houseman, & Roy, 2007; Howard, Culley, & Dekoninck, 2008).

2 RESEACH QUESTIONS

To understand the varying partners of neurocognition during concept generation, we ask three questions:

1. Is there a dominate brain hemisphere during concept generation?
2. What differences exist between hemispheres when using brainstorming, morphological analysis, and TRIZ?
3. What sub-region differences exist and when do these differences occur?

3 HYPOTHESIS

Concept generation, like other cognitive tasks, likely demands bilateral coordination between the left and right hemispheres in the prefrontal cortex (PFC). The PFC functions as a filtering mechanism to optimize sensory processing and decision making. Sub-regions within the PFC are especially necessary for concept generation. Creative tasks more strongly activate right hemisphere dorsolateral PFC (dlPFC) and association tasks require the medial prefrontal cortex (mPFC) (Bhattacharya & Petsche, 2002). However, most cortical functions are laterally dominate, meaning exhibit cerebral authority in either the left or right hemisphere (Cerqueira, Almeida, & Sousa, 2008). For instance, language and motor functions are left dominant and emotion processing is right dominant (Halpern, Güntürkün, Hopkins, & Rogers, 2005). Similarly, the first hypothesis is *that one hemisphere is more dominant than the other during concept generation*.

The right PFC is accredited with episodic memory and the ability to empathize (Henson, Shallice, & Dolan, 1999). The right PFC is also generally associated with creative (Luft et al., 2017) and divergent thinking (Zmigrod et al., 2015). For instance, an intuitive idea that suddenly comes to mind is associated with increased activation in the right prefrontal cortex (Pisapia, Bacci, Parrott, & Melcher, 2016). The left hemisphere controls judgements about whether ideas generated in the right hemisphere meet constraints (Luft et al., 2017). The expectation is the *left hemisphere will dominate in the concept generation process* because previous design cognition studies find that engineers spend more time fixating on constraints than composing possible solutions (Cross, 2001).

In particular, the left dorsolateral prefrontal cortex (dlPFC) is most dominant when applying a filtering process between ideas and constraints (Blumenfeld et al., 2011). The left dlPFC also functions by applying learned rules to new problems (Luft et al., 2017). So, concept generation processes like morphological analysis and TRIZ that produce new constraints (i.e. decomposition, additional engineering parameters) lead to the second hypothesis *there will be significantly higher levels of activation in the left dlPFC during morphological analysis and TRIZ compared to brainstorming* because of the increased number of constraints and parameters that must be considered.

Another region of significance is the medial prefrontal cortex (mPFC). The function of the mPFC is to learn associations and is observed to play a key role in the retrieval of "remote" memories (Euston et al., 2012). The third hypothesis is *there will be increased activation in the mPFC during brainstorming compared to morphological analysis and TRIZ* because the cognitive steps of brainstorming involve making associations between known concepts and new ones. Similar to left and right hemisphere characterizations, the expectation is the left mPFC regulates right mPFC during concept generation. So, the fourth hypothesis is *increased activation in the right mPFC will be followed by activation in the left mPFC*. In other words, concept generation through associations are followed by some sort of filtering process in the left mPFC and this will be observable in the neurocognitive data.

4 METHODS

Twelve graduate engineering students from Virginia Tech were given instructions about how to generate concepts using brainstorming, morphological analysis and TRIZ. All participants were right handed and between the age of 22 and 26. None of the participants indicated they had formal training with morphological analysis or TRIZ prior to the pre-task training. Although, all reported prior course work in engineering design. Participants were given three design tasks and instructed to use one of the three techniques on each of them. The design tasks were not discipline specific and had previously demonstrated to require similar cognitive processes to generate a solution (Gero et al., 2013). The first task asked participants to develop a concept that would assist elderly to raise and lower windows that could get stuck due to humidity. The second design task asked participants to develop an alarm clock for the hearing impaired. The third design task asked participants to develop a concept for a kitchen measuring tool for the blind. Participants were instructed not to vocalize their design concept but instead draw their design on paper.
Prior to the design tasks, participants were outfitted with a neuroimaging device called functional near infrared spectroscopy (fNIRS) to measure cognitive activation when using each of the three concept generation techniques. fNIRS works by measuring change in the blood oxygen level-dependent (BOLD) response. The BOLD response is based on the fact that when neuronal activity is increased in one part of the brain, there is also an increased amount of cerebral blood flow. This increase in blood flow produces an increase in the ratio of oxygenated blood (also called oxy-hemoglobin) relative to deoxygenated blood (deoxy-hemoglobin) in that specific area. The relative concentration, indicating BOLD response, was calculated from the photon path length, using a Modified Beer-Lambert Law.

fNIRS is unique compared to other imagining devices like fMRI and EEG because it allows participants to operate a computer or perform a task in an upright sitting position, unlike fMRI, and is unique compared to EEG because of the spatial resolution. Previous research using fNIRS in engineering design explores cognitive differences between seniors and freshmen engineering students (Shealy et al., 2017). fNIRS is also used to study creativity during divergent thinking (Gibson et al., 2009) and free drawing (Kaimal et al., 2017). Figure 1 illustrates the sensor placement on the cap and the channels (formed by the combination of a source and a detector. The lines between the squares represent the channels of observed activation. The sensor placements (indicated by the squares in Figure 1) are associated with the dorsolateral prefrontal cortex (dlPFC), medial prefrontal cortex (mPFC) and ventrolateral prefrontal cortex (vlPFC).

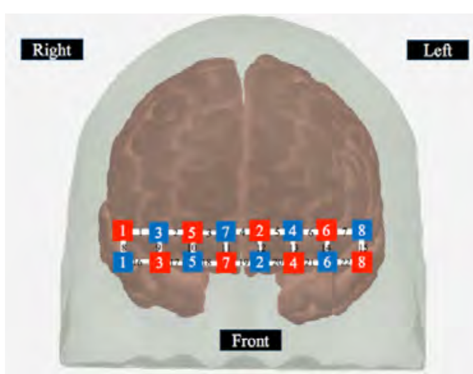

Figure 1: fNIRS placement along the frontal cortex

fNIRS data collection began during the rest period prior to each design task and continued through the design completion for each task. Raw fNIRS 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). Two participants' data were removed from analysis due to bad data signal. Ten participants data was used for data analysis. A fractioning technique was then applied to divide every design session into non-overlapping deciles (10 equal segments). The fraction technique is based on prior design cognition studies (Gero, 2010). Only oxygenated hemoglobin (HbO) is reported across these deciles.

For each participant, change in HbO measured from individual channels, denoted as the lines between sensors and detectors in Figure 1, were averaged together to describe hemispherical changes within the prefrontal cortex. The change in HbO, called the blood oxygenated level dependent (or BOLD) response for channels 5, 6, 7, 12, 13, 14, 15, 20, 21, 22 make up the left hemisphere. The average BOLD response for channels 1, 2, 3, 8, 9, 10, 11, 16, 17, 18 make up the right hemisphere. These left and right hemisphere regions were further sub-divided into the left dlPFC (channels 6, 7, and 14), left mPFC (channels 5, 12, 13, 20, and 21), right dlPFC (1, 2, and 9), and right mPFC (3, 10, 11, 17, and 18).

To investigate hemispherical difference during concept generation, Markov like states were created for each decile for each participant to describe regions (i.e. left, right hemisphere and again sub-regions dlPFC and mPFC within hemispheres). Dominant states were recorded as the region that received the highest level of oxygenated blood (HbO) for each decile. Percent frequency was used to describe the dominant hemisphere and sub-region. To describe difference in patterns of cognitive function, the percent frequencies for all ten participants were averaged to produce a typical dominant state for each decile during brainstorming, morphological analysis, and TRIZ. The percent frequency for each brain region was then plotted to observe the differences between the three concept generation techniques. To statistically describe the differences, Cohen's d was used to measure the effect size. Chi-squared tests were used to described the relationship between left and right hemisphere dominance when using each concept generation technique.

To describe sub-regions (dlPFC and mPFC) within hemispheres, the percent frequency of dominate states was compared to the expected frequency of dominate states. The expected frequency was 25 percent because four sub-regions were included (left and right dlPFC and mPFC). Instances were described when the dominate state was above 37.5 percent frequency (a 50 percent increase from the expected) or below a 12.5 percent frequency (a 50 percent decrease from the expected). Comparing the percent frequency of a dominate hemisphere by decile for each sub-region helps explain sub-regional differences and describe when these differences occur.

5 RESULTS

Higher levels of oxygenated blood (HbO) are observed in the left prefrontal cortex compared to the right prefrontal cortex in all three concept generation tasks. The increase of HbO in the left hemisphere was consistent when using all three techniques. The left hemisphere was observed to have elevated levels of HbO on average 58 percent of the time during concept generation. This elevated HbO is significantly greater than the right hemisphere and the effect size is large. Hemispherical differences for each concept generation technique and probability values are listed in Table 1.

Table 1: Percent frequency of dominant left and right hemisphere during concept generation

Concept Generation	Hemisphere		t	*p*	Effect Size (Cohen's d)
	Left	Right			
Brainstorming	57%	43%	2.5	0.02	1.10
Morphological	60%	40%	4.0	<0.001	1.78
TRIZ	58%	42%	3.03	<0.001	1.35

While the left hemisphere is dominant during all three concept generations, temporal differences do occur between the three techniques. Figures 2, 3, and 4 illustrate the average percent frequency of hemisphere dominance for each decile during the concept generation process. When brainstorming, the left hemisphere is observed as dominant early during the concept generation process. The opposite is observed when using morphological analysis. TRIZ appears to oscillate between left and right hemispheres. The circles in Figures 2-4 highlight these differences.

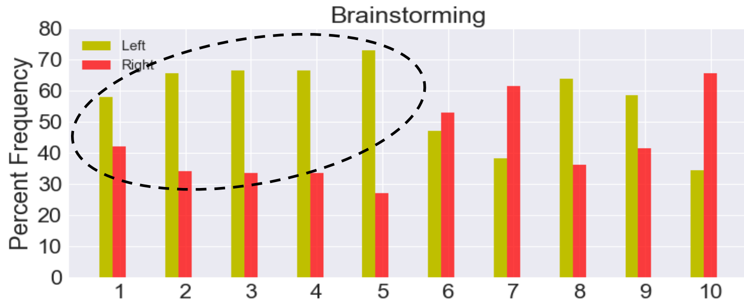

Figure 2: Percent frequency of dominant hemisphere during brainstorming

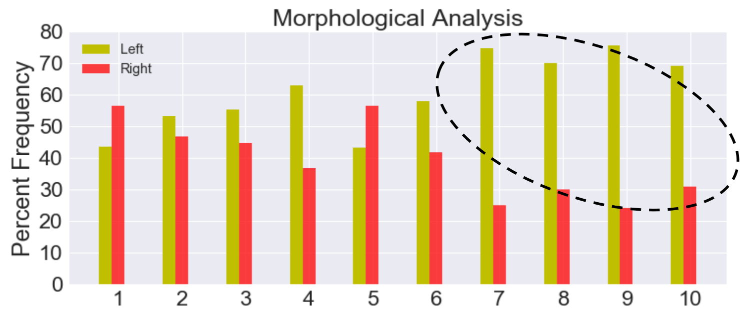

Figure 3: Percent frequency of dominant hemisphere during morphological analysis

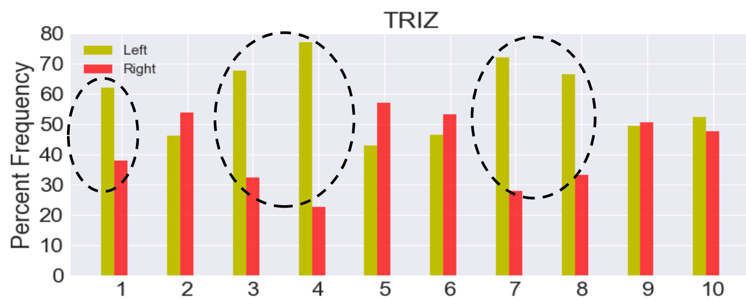

Figure 4: Percent frequency of dominant hemisphere during TRIZ

The relationship observed between dominant hemispheres when brainstorming, using morphological analysis and TRIZ are statistically different in six of the ten deciles, Table 2.

Table 2: Percent frequency and temporal differences between dominant hemispheres during concept generation

Decile	**Brainstorming**		**Morph**		**TRIZ**		**Chi-square**	***p***
	Left	**Right**	**Left**	**Right**	**Left**	**Right**		
01	58	42	43	57	62	38	8.08	*0.0175*
02	66	34	53	47	46	54	8.32	*0.0156*
03	66	34	55	45	67	33	3.79	0.15
04	66	34	63	37	77	23	5.05	0.08
05	73	27	43	57	43	57	24.09	*<0.001*
06	47	53	58	42	46	54	3.55	0.17
07	38	62	75	25	72	28	37.73	*<0.001*
08	64	36	70	30	67	33	0.81	0.67
09	59	41	76	24	49	51	15.71	*<0.001*
10	34	66	69	31	52	48	24.53	*<0.001*

The percent frequency of left hemisphere dominance is significantly greater during brainstorming in the first two and fifth deciles, but similarly high frequencies are observed in all three techniques in deciles three and four. In the second half of the concept generation process, morphological analysis is significantly more likely to lead to an increase in the reliance on the left hemisphere.

A Chi-square test indicates that these differences are very significant for deciles 1, 2, 5, 7, 9 and 10, i.e., for more than half the time. Yet, what Figures 2-4 and Table 2 fails to explain are the number of transitions between left and right hemispheres that occur during the concept generation process. In other words, how many times does a shift between left-right hemisphere dominance occur? Answering this question helps explain how varying concept generation processes produce bilateral cognitive coordination.

When brainstorming, participants are observed to shift elevated levels of HbO between left and right hemispheres 27 times (SD= 16). When using morphological analysis, participants shifted 12 times (SD=10) and 16 times (SD=12.5) when using TRIZ. The difference is significant (t=2.3, p=0.03) between brainstorming and morphological analysis. Morphological analysis leads to greater sustained periods of lateral dominance compared to brainstorming. These shifts appear most prominent in the last two deciles during concept generation. Brainstorming prompts 40 and 42 hemispherical shifts between left and right brain dominance. This observed difference in hemispherical shifts describes the high variability in standard deviation of 16 during brainstorming compared to the 27 average. Morphological analysis during the same decile segments prompts just 2 and 1 hemispherical shifts. TRIZ, similar to morphological analysis, elicits just 8 and 2 hemispherical shifts.

The differences between left and right hemisphere dominance becomes more pronounced when observing sub-cortical regions of the prefrontal cortex (PFC). The left dlPFC received the highest percent frequency of elevated levels of HbO in all three concept generation techniques. Figure 5 illustrates the left and right dlPFC and mPFC. A horizontal line drawn at 37.5 percent frequency highlights the instances that cross this 50 percent increase threshold in observed HbO compared to the expected 25 percent frequency.

Morphological analysis and TRIZ most frequently rely on the left dlPFC compared to the other three sub-regions. Only brainstorming relies on each of the four sub-regions at least once during the ten segments. The least dominant sub-regions are the right dlPFC for TRIZ and left mPFC for morphological analysis.

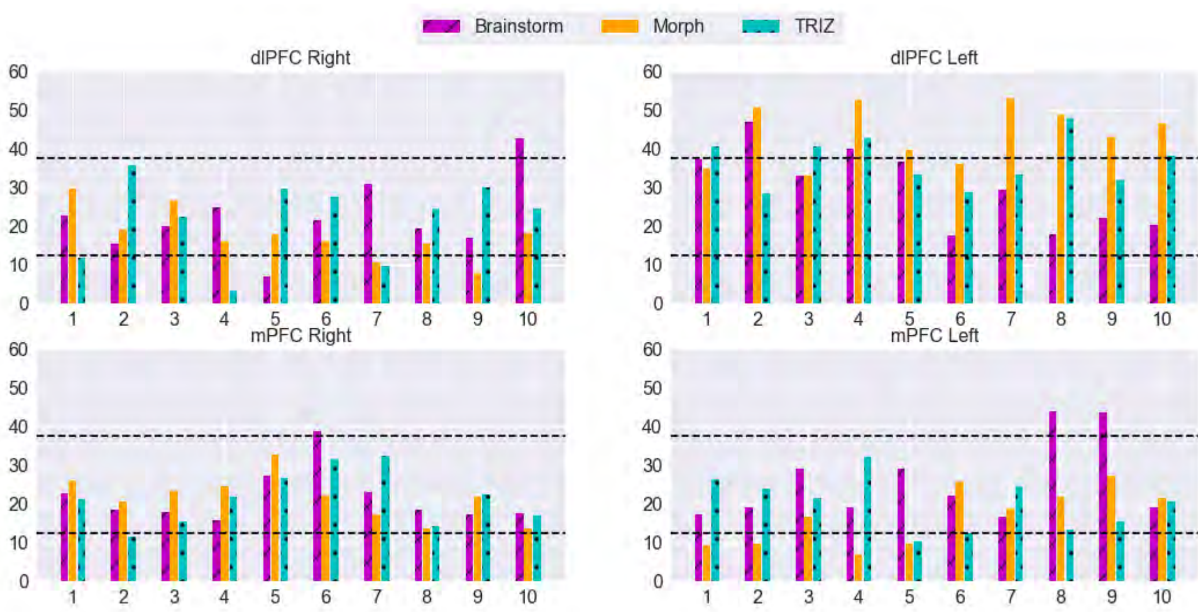

Figure 5: Percent frequency (y axis) of dominant regions of the prefrontal cortex during brainstorming, morphological analysis, and TRIZ for each decile (x-axis)

To summarize the findings, the left hemisphere is dominant in concept generation but temporal differences were also evident when using the three techniques. Brainstorming provoked a higher left hemisphere dominance early in the concept generation process while left hemisphere dominance was observed late in the concept generation process when using morphological analysis. TRIZ produced a bilateral oscillation, rotating between left and right hemisphere dominance throughout the concept generation process. The frequency of left-right hemispherical shifts is significantly greater during brainstorming compared to morphological analysis. These hemispherical differences are further pronounced when comparing sub-regions. The left dlPFC is the dominant region during concept generation. The right dlPFC appears to be the least dominant during TRIZ and the left mPFC is the least dominant using morphological analysis.

6 DISCUSSION

Left hemisphere dominance during concept generation may appear contradictory given prior neurocognitive studies about creativity that suggest creative problem solving is largely driven by the right hemisphere (Finkelstein et al., 1991). However, creativity and design are not the same. Design is goal-directed, often relies on past experience or domain knowledge, and requires planning of novel solutions.

In problems more indicative of design, the left hemisphere appears to play a critical role. For instance, using an fMRI scanner, architecture students were observed while developing new figures by mentally rearranging a circle, the letter C, and the number 8. Among these students, cognitive activation was observed to increase more frequently in the left hemisphere than the right (Aziz-Zadeh et al., 2013).

Left hemisphere dominance could also be a result from the time reflecting on given constraints and parameters. The percent frequency between left and right hemisphere dominance during brainstorming compared to morphological analysis and TRIZ seems to support this explanation because it required the fewest set of constraints and had the smallest effect size. High left hemisphere dominance early during brainstorming might suggest cognitively processing constraints and parameters prior to the searching and associations process beginning. Whereas, morphological analysis first requires searching for individual solutions to the decomposed functions and then assessing how these functions fit within the given parameters. These differences in design process appear to be observed in the results.

An explanation for the significantly lower number of hemispherical shifts during morphological analysis compared to brainstorming is functional fixedness (Camarda et al., 2018). Generating concepts to solve the design problems requires an understanding of various functions in the context of artifacts being designed or created. Morphological analysis forces functional fixedness through decomposition of the constraints. TRIZ also forces functional fixedness but the difference might be that TRIZ requires viewing and selecting principles and parameters compared to morphological analysis that requires independently developing these functions without assistance.

When investigating sub-regions within the prefrontal cortex, the differences in patterns of cognitive function become more pronounced. The left dlPFC clearly plays a critical role in concept generation and this is evident in all three techniques. The left dlPFC is central to spatial working memory tasks and also as a filtering mechanism for sensory information. The dominance of this region is not surprising given its associated cognitive function and the types of design tasks being performed. However, the difference in homogenous versus more heterogenous patterns of dominance between the three concept generation tasks was not expected. Morphological analysis and TRIZ appear to reinforce or elevate the use of the left dlPFC, while brainstorming included all four sub-regions at least once above the 50 percent increase from the expected frequency. The dominance of the right dlPFC and mPFC could indicate designers trying new mental approaches to find solutions. All three of these dominant regions were in the second half of the concept generation process. The right dlPFC is known to contribute to exploration (i.e. without rules) and improvisation. Electric stimulus to the right dlPFC increased performance of novice jazz musicians (Rosen et al., 2016). Perhaps designers relaxed rule constraints in order to continue searching for possible solutions. Observing increased activation in both the left and right mPFC during brainstorming might also suggest deep memory retrieval in order to continue the searching process.

7 CONCLUSION

The results presented in this paper demonstrate varying neurocognitive patterns when using three distinct concept generation techniques and provides neurocognitive evidence for the difference between inner sense-driven processes (like brainstorming) and problem-driven processes (like morphological analysis and

TRIZ). With all three techniques, the left hemisphere was dominant. More specifically the left dlPFC. The function of this region controls spatial working memory tasks and also works as a filtering mechanism for sensory information. The left dlPFC remained dominant when using morphological analysis and TRIZ but brainstorming provoked varying dominance that included the right dlPFC and mPFC late in the concept generation process. This variability in dominance may be indicative of changing cognitive approaches to continue the searching process for new ideas.

For concept generation, both creative thinking (right hemisphere) and rule-based problem solving (left hemisphere) are needed to generate novel concepts and insure they meet given constraints. However, the frequency of hemispherical shifts between left and right hemispheres was significantly greater during brainstorming compared to morphological analysis. This suggests bilateral coordination increases when constraints are lowered. Using a more structured approach helps to increase attention (Gero et al., 2013) but also fixation (Cross, 2006) and these results provide supporting neurocognitive evidence for these claims.

New questions have emerged through these findings. First, when and to what degree should one hemisphere or region be dominant during concept generation? How does this affect the quality and novelty of design outcomes? If designers are aware of the cognitive patterns that produce various design outcomes does this affect their cognitive ability to shift regions? Can increased bilateral coordination be trained? Biofeedback is a well-developed technique in medicine. It enables an individual to learn how to change physiological activity to improve individual performance. Is the same true for neuro-feedback and design? By adopting both theory and instruments from neurocognitive science, we can begin to provide answers to these types of questions and in the process improve tools that support engineers to more effectively innovate radically new engineering solutions.

REFERENCES

Aziz-Zadeh, L., Liew, S.-L., & Dandekar, F. (2013). Exploring the neural correlates of visual creativity. *Social Cognitive and Affective Neuroscience*, *8*(4), 475–480. https://doi.org/10.1093/scan/nss021

Ball, L. J., & Christensen, B. T. (2009). Analogical reasoning and mental simulation in design: two strategies linked to uncertainty resolution. *Design Studies*, *30*(2), 169–186. https://doi.org/10.1016/j.destud.2008.12.005

Bengtsson, S. L., Csíkszentmihályi, M., & Ullén, F. (2007). Cortical regions involved in the generation of musical structures during improvisation in pianists. *Journal of Cognitive Neuroscience*, *19*(5), 830–842. https://doi.org/10.1162/jocn.2007.19.5.830

Bhattacharya, J., & Petsche, H. (2002). Shadows of artistry: cortical synchrony during perception and imagery of visual art. *Brain Research. Cognitive Brain Research*, *13*(2), 179–186.

Blumenfeld, R. S., Parks, C. M., Yonelinas, A. P., & Ranganath, C. (2011). Putting the pieces together: The role of dorsolateral prefrontal cortex in relational memory encoding. *Journal of Cognitive Neuroscience*, *23*(1), 257–265. https://doi.org/10.1162/jocn.2010.21459

Bryant, R. B. S. C. R. (2005). CONCEPT GENERATION FROM THE FUNCTIONAL BASIS OF DESIGN. *DS 35: Proceedings ICED 05, the 15th International Conference on Engineering Design, Melbourne, Australia, 15.-18.08.2005*.

Camarda, A., Salvia, É., Vidal, J., Weil, B., Poirel, N., Houdé, O., … Cassotti, M. (2018). Neural basis of functional fixedness during creative idea generation: An EEG study. *Neuropsychologia*, *118*, 4–12. https://doi.org/10.1016/j.neuropsychologia.2018.03.009

Cerqueira, J. J., Almeida, O. F. X., & Sousa, N. (2008). The stressed prefrontal cortex. Left? Right! *Brain, Behavior, and Immunity*, *22*(5), 630–638. https://doi.org/10.1016/j.bbi.2008.01.005

Coley, F., Houseman, O., & Roy, R. (2007). An introduction to capturing and understanding the cognitive behaviour of design engineers. *Journal of Engineering Design*, *18*(4), 311–325. https://doi.org/10.1080/09544820600963412

Cross, N. (2001). Design cognition: results from protocol and other empirical studies of design activity. In *Design knowing and learning: cognition in design education* (pp. 79–103). Elsevier.

Cross, Nigel. (1989). *Engineering design methods*. Wiley.

Cross, Nigel. (2006). *Designerly Ways of Knowing*. Retrieved from //www.springer.com/us/book/9781846283000

Euston, D. R., Gruber, A. J., & McNaughton, B. L. (2012). The Role of Medial Prefrontal Cortex in Memory and Decision Making. *Neuron*, *76*(6), 1057–1070. https://doi.org/10.1016/j.neuron.2012.12.002

Finkelstein, Y., Vardi, J., & Hod, I. (1991). Impulsive artistic creativity as a presentation of transient cognitive alterations. *Behavioral Medicine (Washington, D.C.)*, *17*(2), 91–94. https://doi.org/10.1080/08964289.1991.9935164

French, J. M. (1999). *Conceptual Design for Engineers | Michael J. French | Springer* (3rd ed). Retrieved from //www.springer.com/us/book/9783662113646

Gero, J. S. (2010). Generalizing design cognition research. In K. Dorst, et al. (Eds), DTRS8: Interpreting Design Thinking, DAB documents, Sydney, pp. 187-198.

Gero, J. S., Jiang, H., & Williams, C. B. (2013). Design cognition differences when using unstructured, partially structured, and structured concept generation creativity techniques. *International Journal of Design Creativity and Innovation*, *1*(4), 196–214. https://doi.org/10.1080/21650349.2013.801760

Gibson, C., Folley, B. S., & Park, S. (2009). Enhanced divergent thinking and creativity in musicians: A behavioral and near-infrared spectroscopy study. *Brain and Cognition*, *69*(1), 162–169. https://doi.org/10.1016/j.bandc.2008.07.009

Halpern, M. E., Güntürkün, O., Hopkins, W. D., & Rogers, L. J. (2005). Lateralization of the Vertebrate Brain: Taking the Side of Model Systems. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *25*(45), 10351–10357. https://doi.org/10.1523/JNEUROSCI.3439-05.2005

Hatchuel, A., & Weil, B. (2008). C-K design theory: an advanced formulation. *Research in Engineering Design*, *19*(4), 181. https://doi.org/10.1007/s00163-008-0043-4

Helm, K., Jablokow, K., McKilligan, S., Daly, S., & Silk, E. (2016, June 1). *Evaluating the impacts of different interventions on quality in concept generation*.

Henson, R. N., Shallice, T., & Dolan, R. J. (1999). Right prefrontal cortex and episodic memory retrieval: a functional MRI test of the monitoring hypothesis. *Brain: A Journal of Neurology*, *122 (Pt 7)*, 1367–1381.

Howard, T. J., Culley, S. J., & Dekoninck, E. (2008). Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies*, *29*(2), 160–180. https://doi.org/10.1016/j.destud.2008.01.001

Howard, T. J., Dekoninck, E. A., & Culley, S. J. (2010). The use of creative stimuli at early stages of industrial product innovation. *Research in Engineering Design*, *21*(4), 263–274. https://doi.org/10.1007/s00163-010-0091-4

Huppert, T. J., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2009). HomER: a review of time-series analysis methods for near-infrared spectroscopy of the brain. *Applied Optics*, *48*(10), D280-298.

Kaimal, G., Ayaz, H., Herres, J., Dieterich-Hartwell, R., Makwana, B., Kaiser, D. H., & Nasser, J. A. (2017). Functional near-infrared spectroscopy assessment of reward perception based on visual self-expression: Coloring, doodling, and free drawing. *The Arts in Psychotherapy*, *55*, 85–92. https://doi.org/10.1016/j.aip.2017.05.004

Luft, C. D. B., Zioga, I., Banissy, M. J., & Bhattacharya, J. (2017). Relaxing learned constraints through cathodal tDCS on the left dorsolateral prefrontal cortex. *Scientific Reports*, *7*(1), 2916. https://doi.org/10.1038/s41598-017-03022-2

Moon Sungwoo, Ha Chideok, & Yang Jinkook. (2012). Structured Idea Creation for Improving the Value of Construction Design. *Journal of Construction Engineering and Management*, *138*(7), 841–853. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000491

Pisapia, N. D., Bacci, F., Parrott, D., & Melcher, D. (2016). Brain networks for visual creativity: a functional connectivity study of planning a visual artwork. *Scientific Reports*, *6*, 39185. https://doi.org/10.1038/srep39185

Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *NeuroImage*, *10*(1), 15–35. https://doi.org/10.1006/nimg.1999.0441

Rosen, D. S., Erickson, B., Kim, Y. E., Mirman, D., Hamilton, R. H., & Kounios, J. (2016). Anodal tDCS to Right Dorsolateral Prefrontal Cortex Facilitates Performance for Novice Jazz Improvisers but Hinders Experts. *Frontiers in Human Neuroscience*, *10*. https://doi.org/10.3389/fnhum.2016.00579

Shah, J. J., Kulkarni, S. V., & Vargas-Hernandez, N. (2000). Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments. *Journal of Mechanical Design*, *122*(4), 377–384. https://doi.org/10.1115/1.1315592

Shai, O., Reich, Y., Subrahmanian, E., & al, et. (2009). *Creativity Theories and Scientific Discovery: A Study of C-K Theory and Infused Design*.

Shealy, T., Grohs, J., Hu, M., Maczka, D., & Panneton, R. (2017). *Investigating Design Cognition during Brainstorming Tasks with Freshmen and Senior Engineering Students using Functional Near Infrared Spectroscopy*.

Taura, T., & Nagai, Y. (2013). Perspectives on Concept Generation and Design Creativity. In *Concept Generation for Design Creativity* (pp. 9–20). https://doi.org/10.1007/978-1-4471-4081-8_2

Vidal, R., Salmeron, J. L., Mena, A., & Chulvi, V. (2015). Fuzzy Cognitive Map-based selection of TRIZ (Theory of Inventive Problem Solving) trends for eco-innovation of ceramic industry products. *Journal of Cleaner Production*, *107*(Supplement C), 202–214. https://doi.org/10.1016/j.jclepro.2015.04.131

Welling, H. (2007). Four mental operations in creative cognition: The importance of abstraction. *Creativity Research Journal*, *19*(2–3), 163–177. https://doi.org/10.1080/10400410701397214

Zmigrod, S., Colzato, L. S., & Hommel, B. (2015). Stimulating Creativity: Modulation of Convergent and Divergent Thinking by Transcranial Direct Current Stimulation (tDCS). *Creativity Research Journal*, *27*(4), 353–360. https://doi.org/10.1080/10400419.2015.1087280

To appear in ICED2019