The Effects of Concept Mapping on Design Neurocognition: An Empirical Study Measuring Changes in the Brain when Defining Design Problems

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ABSTRACT

Grand challenges in engineering are complex and require engineers to be cognizant of different systems associated with each problem. The approach to think about these systems is called systems thinking. Systems thinking provides engineers with a lens to identify relationships between multiple components which helps them develop new ideas about the problem. Concept maps are a tool that enables systems thinking by helping engineers organize ideas and the relationship between ideas, graphically. The research presented in this thesis uses concept maps, as an intervention to help engineering students think in systems and, in turn, shape how they frame their design problem. The aim of the research was to understand the neurocognitive effects of engineering students thinking in systems. The effects of systems thinking on neurocognition is not well understood. Sixty-six engineering students were randomly chosen to either draw concept maps about a design problem or not. They were then asked to develop design problem statements for two design problems. Functional near-infrared spectroscopy (fNIRS) was used to measure changes in oxy-hemoglobin (oxy-Hb) in the prefrontal cortex (PFC) of students while they developed their design problem statements. A lower average oxy-Hb was observed in the group that was first asked to develop concept maps. The lower activation was observed in their left PFC. The group of students who first developed concept maps also demonstrated lower network connections between brain regions in the prefrontal cortex, which is a proxy for functional coordination. Using concept maps changed activation in students' brains, reducing the average neuro-cognition in the left PFC and reducing the need for functional coordination between brain regions.

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GENERAL AUDIENCE ABSTRACT

Engineering challenges require engineers to think “outside the box”. Concept mapping is a tool that encourages out of the box thinking. Concept mapping is the process of representing components of the problem and the relationship between components graphically. How the process of concept mapping changes the way engineers think is not well understood. Exploring various interconnected system components and their relationships may give rise to new ideas and this may be expressed differently in the brain. The research presented in this thesis explores how concept maps change engineering students’ brain behavior. Sixty-six students participated in the study. Half of the participants (the intervention group) were required to draw concept maps before developing two engineering problem statements. The other half (the control group) were given the same two tasks to develop engineering problem statements but without being asked to first develop concept maps. A neuroimaging tool, called functional near-infrared spectroscopy, was used to measure change in the engineering students’ prefrontal cortex (PFC) when they were developing problem statements. The PFC is generally associated with executive functions like planning, design, and creative thinking. The results indicate that concept mapping significantly changed brain behavior when developing problem statements. It reduced brain activation in the left PFC, a region generally associated with making analytical judgments and goal-directed planning. It also reduced the network complexity in the PFC, which is a proxy for functional connectivity. These results demonstrate how concept mapping can shape brain behavior when designing and lays the groundwork for future studies to explore how other interventions similar to concept mapping can help shape design thinking.

ACKNOWLEDGEMENT

I would like to express my most sincere gratitude to Dr. Tripp Shealy who has been instrumental in my journey as a researcher. He has provided constant support and guidance throughout this journey, as well as beyond, as an outstanding mentor.

I would also like to thank my committee members, Dr. John Gero and Dr. Andrew Katz for providing immense support throughout this process and encouraging me to explore new data analysis methods.

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ATTRIBUTION

The proposal submitted by Dr. Shealy was titled “Novel neurocognitive assessment of engineering education interventions applied to systems thinking,” which was funded by the National Science Foundation (NSF). Dr. Tripp Shealy is the primary investigator for this research. I started my first semester for the master’s program engaging directly with the research proposal. This master’s thesis is a result of working under Dr. Shealy’s research project funded by the NSF. I worked on this research for three semesters, starting January 2021, with several collaborators in different phases of the project. A conference paper was also produced which is co-authored by Dr. Shealy, Dr. Gero, Dr. Milovanovic and Dr. Hu. It is included as Chapter Two in this document.

My lab partner, Paulo Dias Ignacio Junior, was also an instrumental part of the research study. We worked as a team to collect data from 66 participants during the first quarter of 2021.We needed to work together to ensure timely data collection due to the impact of COVID-19. Dr. Hu also helped provide any assistance needed in terms of data collection using fNIRS (functional near-infrared spectroscopy) for the research.

Lastly Dr. Shealy, Dr. Gero and Dr. Katz provided immense support throughout to complete the thesis

CHAPTER ONE. INTRODUCTION

Grand challenges in engineering cannot be solved without fully understanding the multiple interconnected systems that are involved. The world is increasingly more connected, highlighting the importance of solving today's problems with a diverse range of approaches that account for the connections between often disparate systems and their components. For instance, engineering problems require a deeper understanding not just of the technical design issues but also the socio-political, environmental, or even economic consequences of their design choices.

Systems thinking through concept maps, can help engineers visualize, interpret, and incorporate various systems into creative and long-lasting solutions. Concept maps are a tool which helps represent complex problems graphically and develop relationships to represent systems. This technique of developing dynamic relationships visually can help engineers better organize their interpretation and understanding of the engineering problem. The process of concept mapping also teaches engineers to embrace the complexity of these systems, and not treat them as isolated elements which can help increase creative and long-lasting solutions for the diverse engineering challenges today.

Even though the contribution of systems thinking to help develop more diverse outcomes has been well established through literature review, there is very little evidence on how cognition is influenced through the process. Recent developments in neuroimaging, such as, functional near infrared spectroscopy (fNIRS), enables a more complete understanding of the cognitive activation of brain regions during designing. The research presented in this thesis explores the neurocognitive effects on engineers after they utilize concept mapping to think in systems. There are various insights that could be learned by understanding how cognition is affected. This study focused on the Prefrontal Cortex of the brain which is associated with functionalities such as

memory, planning and decision making. These are critical regions to design and problem-solving. By understanding how concept maps have supported such cognitive functions, it can open new pathways to learn more about how the problem space can be developed further in engineering education.

The experiment design for this research consisted of two different scenarios. In both scenarios, engineering students were asked to construct engineering problem statements. These scenarios were related to engineering challenges with systems that were well known to the engineering students who participated in the study. All sixty-six of the participants were either graduate or undergraduate engineering students at Virginia Tech. The first scenario consisted of asking students to develop a request for proposal to improve a familiar building on campus, Patton Hall. Half of the students were first asked to develop a concept map of the various building systems and services in the building. The second scenario asked students to develop a request for proposal to improve mobility on campus.

The master's thesis is divided into two papers that explore results of the experiment design that investigated the neurocognitive effects of the intervention. The next chapter of this paper presents the conference paper, which uses the first half of the data about Patton Hall. This conference paper includes data analysis of the first scenario and opens pathways for further data analysis, which is presented in the subsequent chapter. Chapter three further explores the neurocognitive differences between the intervention and the control groups utilizing the data from both of the scenarios. It combines the results obtained from the Conference paper for scenario 1 and adds new data analysis methods in the form of network analysis to understand the effects of concept mapping on neurocognition. The final chapter combines the learnings from working on this project in addition to reflecting on the results from both of the papers.

CHAPTER TWO. CONFERENCE PAPER

(Published while in the process of fulfilling the requirement of entirety of the master's Thesis)

Concept maps decrease neurocognitive demand on students when thinking about engineering problems

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ABSTRACT

The research presented in this paper explores the effect of concept maps on students' neurocognition when constructing engineering problem statements. In total, 66 engineering students participated in the experiment. Half of the students were asked to create a concept map illustrating all the systems and stakeholders represented in a building on campus. The other half of students were not asked to draw a concept map. Both groups were then asked to construct an engineering problem statement about improvements to the building. While performing the problem statement task, their neurocognitive activation in the prefrontal cortex (PFC) was

measured using a non-intrusive neuroimaging technique called functional near-infrared spectroscopy. The students that were asked to complete the concept mapping task required less cognitive effort to formulate and analyze their problem statements. The specific regions that were less activated were regions of the brain generally associated with working memory and problem evaluation. These results provide new insight into the changes in mental processing that occurs when using tools like concept maps and may provide helpful techniques for students to structure engineering problems.

INTRODUCTION

The world is fundamentally shifting towards becoming a complex interconnected system. Future challenges associated with our built environment cannot be solved as isolated elements. Those who design and construct our built environment need to explore the interconnection of systems including social, environmental, and economic dimensions of complex problems (Maani & Maharaj, 2004). Concept mapping is a method to help represent complex systems graphically (Novak, 1998; Novak & Cañas, 2006). Concept maps provide a visual representation of information and the relationships between this information. It is an increasingly popular technique to help both students learn, and engineering professionals visualize, the dynamic relationships between components of systems (Watson et al., 2016; J. Novak, 1998).

Teaching students and helping professionals visualize dynamic relationships between complex systems is necessary because too often engineering works to reduce, rather than embrace, complexity. For instance, engineering often breaks systems apart to optimize individual components. Optimizing the cost to deliver potable water in Flint, Michigan had disastrous consequences, causing pipe corrosion and lead exposure for residents (Erban & Walker, 2019). Reducing complexity can also lead to narrowly defining problem statements (Beamish &

Biggart, 2012), which can constrain the types of solutions that can be developed (May, 2006; Shealy & Klotz, 2014).

Any tool or technique that can help engineers make sense of complexity and recognize the interconnection between systems is useful to create new and novel engineering solutions to benefit society. Concept mapping can help achieve this goal (Ellis et al., 2004). It may also be useful as a tool for engineers to define and reframe the systems within which they work. Engineering design is a process of problem framing and reframing (Gero, 1990). It requires the co-evolution of the problem and solution space (Asimow, 1962; Schön & Wiggins, 1992). The purpose of the research presented in this paper was to measure the effect of concept mapping when students constructed engineering problem statements. The objective was to measure how concept maps change the cognitive processes students use when thinking about engineering problems.

BACKGROUND

The process of identifying problems is critical in engineering because it determines the types of ideas and solutions that will follow (Dorst & Cross, 2001; Schön, 1983). The activity of defining the problem and generating solutions takes place within the mental "frames" created by the engineer (Gero, 1990). Using concept maps to define systems can help extend the mental frames that students use to understand and explore problems.

How students think through complex engineering problems to arrive at solutions has been widely study for decades using observation and think aloud protocols (Dorst, 2011; Hay et al., 2017). Concept mapping is known to work by enabling unique retrieval paths for new concepts and information (O'Donnell et al., 2002). Students attain new knowledge by integrating existing

knowledge in new ways (Turns et al., 2000). What is less known is the fundamental neurocognitive functions that change as students use concept mapping to reframe and expand the problems they then work to solve. To explore the effect of concept mapping on how students conceptually frame engineering problems, this research used an approach from neuroscience that measures change in neurocognitive activation.

Neuroscience literature provides insight into how brain regions support cognitive function (e.g. visual or spatial thinking) (Dalton et al., 2015), but less is known about how these processes are used for tasks like concept mapping (Bunce et al., 2011; Rosen et al., 2016). Measuring students' neurocognitive activation can provide new understanding about how students think through problems and the effects of techniques like concept mapping to help them expand and explore new realms of the problem space (Hu & Shealy, 2018).

fNIRS to explore neurocognitive processes when students construct problem statements

To measure brain activation, the research team used a technology called functional near infrared spectroscopy (fNIRS). fNIRS combines some of the benefits of electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). fNIRS is useful to understand cognition in a more natural experimental setting compared to fMRI. fNIRS is more resistant to head movements than EEG (Grohs et al., 2017). fNIRS uses a similar setup to EEG. Participants can comfortably sit or stand while wearing a cap that is connected to a data acquisition system. fNIRS offers similar spatial resolution to EEG but lacks the high spatial resolution of fMRI. It provides little information about subcortical brains region but is sufficiently effective to investigate areas like the prefrontal cortex (PFC).

This study focused on the PFC region of the brain because of its role in decision-making and problem solving (Goel, 2014; Shealy et al., 2020). The PFC plays a role in ideation and creativity in design tasks (Fink et al., 2009; Goel & Grafman, 2000). The PFC is also required to control executive functions, such as planning, attention, and working memory (Glimcher & Fehr, 2013). Subregions within the PFC are associated with more specific cognitive functions. For example, the dorsolateral prefrontal cortex (DLPFC) tends to be associated with abstract reasoning (Pochon et al., 2002). The right part of the ventrolateral prefrontal cortex (VLPFC) is generally associated with evaluating problems rather than solving them (Aziz-Zadeh et al., 2009) and to support the generation of alternative hypotheses to explore in the problem space (Goel & Vartanian, 2005).

RESEARCH QUESTION

Drawing relationships between elements of systems might facilitate new ways students think about complex problems (Hu et al., 2019). Measuring students' neurocognitive activation when constructing engineering problem statements can lead to a more detailed understanding of the mental process used for problem framing. The research question is what is the effect of concept maps on students' neurocognitive activation when constructing an engineering problem statement?

METHOD

Experimental design

All of the participants in this study were engineering students (undergraduate and graduate) at Virginia Tech. Participants were recruited by sharing requests across engineering courses and other university communication channels such as campus activity bulletin boards.

The participants were provided with a $30 gift card for their participation in the study. The experiment procedure was approved by the Institutional Review Board.

Engineering students were asked to construct an engineering problem statement. Students were told: *"Patton Hall needs to be renovated and your role is to provide a document containing everything you think could be improved in the building. Please be as descriptive and elaborate as you can in explaining your ideas and how they would impact the systems and stakeholders."*

Participants were given as much time as they needed to create their problem statement. Sixty-six students participated in the study. Thirty-three students started the task without first being asked to create a concept map (i.e., the control group). The remaining students received a concept map intervention (i.e., intervention group). Participants were randomly assigned to one of the two groups. In the intervention group, before seeing the task about the problem statement, participants were asked to create a concept map illustrating all of the systems and stakeholders that interact in the building. Participants in the intervention group were briefed and trained to use concept maps. The pre-task training included a 4-minute introductory video on concept maps and drawing a practice concept map so that students could ask questions.

All participants were outfitted with the fNIRS cap as shown in Figure 2.1(a), before beginning the experiment. Changes in oxygenated blood were measured using the fNIRS in 22 channels placed in the 10-20 system (Figure 2.1(b)). Since the task required participants to write a response, students were also asked to first complete a word tracing task as a baseline activation in their brain. This type of baseline recording is typical among neurocognitive studies (Hu & Shealy, 2018; Tak & Ye, 2014). The experiment was conducted with PsycoPy. PsycoPy helped provide timed instructions for the participants. The time length for the experiment was similar

for both groups and lasted around 7 minutes. Participants were not given a time restriction for writing their problem statements.

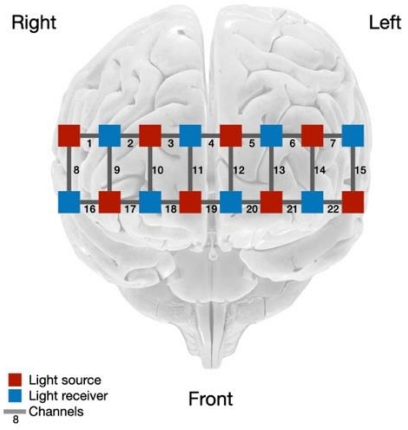
(a)  (b) 

Figure 2. 1 fNIRS cap on participant (a), prefrontal cortex channel placement (b)

DATA ANALYSIS

Ten out of sixty-six participants were removed from further analysis due to bad signals. fNIRS raw data for the fifty-six (n=28 for each group) participants were processed using a bandpass filter (frequency ranging between 0.01 and 0.1 Hz, third order Butterworth filter) which was done to eliminate low frequency physiological and high frequency instrumental noises. Additionally, an independent component analysis (ICA) with a coefficient of spatial uniformity of 0.5 was applied to remove motion artifacts. This elimination step was critical in processing the raw fNIRS data to avoid false discovery in fNIRS analysis (Santosa et al., 2017). The parameters in data processing are based on prior research (Naseer & Hong, 2015; Sato et al., 2011). Shimadzu fNIRS software was used to filter and pre-process the fNIRS data. After pre-processing, fNIRS data were analyzed using a locally developed python script. A baseline

correction and a transformation were applied to make fNIRS data comparable between subjects and between the two groups.

To address the research question, the neuro-activation in the PFC and its sub-regions was analyzed. Oxy-Hb was averaged for all channels to assess differences in activation for the whole PFC. Since sub-regions in the PFC are recruited for different cognitive tasks related to engineering, we also analyzed oxy-Hb across functional sub-regions for each participant. The mean oxy-Hb throughout the task was used as a normalized proxy for cognitive activation. Two sample t-tests were performed to compare the control group to the experimental group. The confidence interval was 0.05. Cohen's d values were used to measure effect size.

RESULTS

Concept maps change patterns of neurocognitive activation in students when constructing their problem statements

Completing a concept map prior to constructing their problem statements had a significant effect on participants' neurocognition. Significant differences were observed between groups in the average activation across students' prefrontal cortex (PFC) and in two sub-regions in the left PFC. The t-test suggests a significantly ($t = -2.08$, $p = 0.04$) lower average activation in the PFC for the intervention group ($M = 0.002$, $SD = 0.01$) than the control group ($M = 0.07$, $SD=0.02$). The effect size is large with a Cohen's d value of 3.04.

Using concept maps reduced the neurocognitive activation in the PFC during the problem framing task. Figure 2.2(a) shows the activation heat map for the control group, while Figure 2.2(b) shows the activation heat map for the intervention group. The heat maps of brain activation in the PFC highlight a difference in the left PFC. Further statistical analysis using t-

tests confirmed a significant difference in brain activation in the left PFC (t = 2.47, *p* = 0.02, Cohen's d=3.14). When participants were primed using concept maps before constructing their problem statement, they did not recruit activation from the left PFC as intensely as participants in the control group. No significant differences in brain activation were found in the right PFC (t=-1.28, p=0.14) between groups.

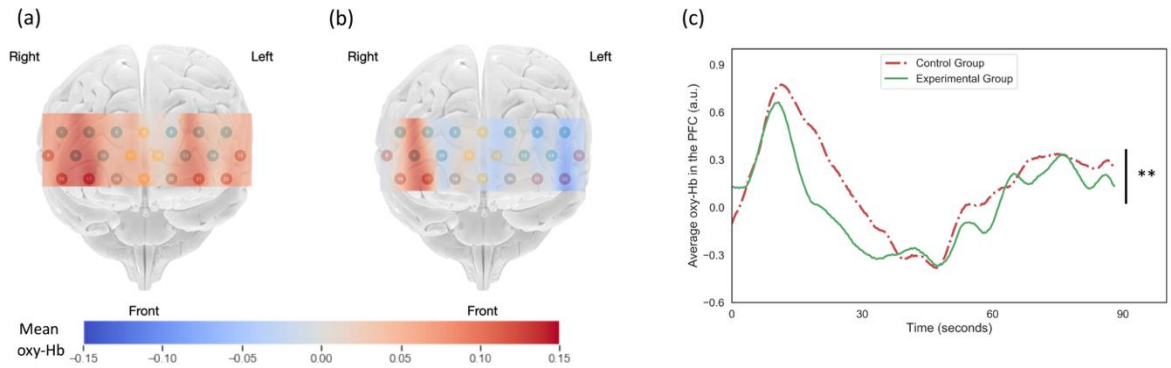


Figure 2. 2 Brain activation in the prefrontal cortex (PFC); (a)Average brain activation heat map for the control group throughout the task; (b) Average brain activation heat map for the experimental group throughout the task; (c) Average oxy-Hb in the PFC in the first 90 seconds of the task. (Note: a.u. = arbitrary unit; p*<0.1, p**<0.05)

Concept maps reduced students' neurocognitive activation in the left part of the PFC when constructing their problem statements

Activation in two sub-regions in the left PFC showed most significant differences during the engineering problem definition task. Detailed statistical analysis of the sub-regions in the PFC indicated that most significant differences occurred in the left dorsolateral prefrontal cortex (DLPFC) and left ventrolateral prefrontal cortex (VLPFC), as illustrated in Figure 2.3.

The DLPFC is usually associated with attention and working memory (Cieslik et al., 2013). The left DLPFC is generally described as involved when making analytical judgments and goal-

directed planning (Aziz-Zadeh et al., 2013; Gabora, 2010). The second sub-region with a significant difference in activation is the left VLPFC. This region tends to be associated with evaluating a problem rather than solving it (Aziz-Zadeh et al., 2013). These results suggest that generating a concept map, illustrating the systems of the problem, reduced cognitive activation in the left DLPFC and left VLPFC when constructing the engineering problem.

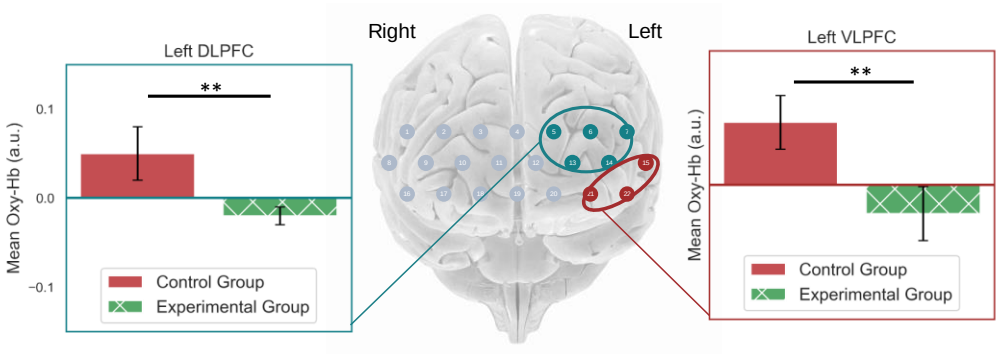


Figure 2. 3 Brain activation in the left dorsolateral prefrontal cortex (DLPFC) and left ventrolateral prefrontal cortex (VLPFC)

DISCUSSION

The results provide empirical evidence of the effects of concept mapping on students' neurocognition when developing engineering problem statements. When participants used concept maps, it reduced the cognitive effort required for them to frame their problem statements. This decreased neurocognitive activation was observed in prior neuroimaging experiments that use a similar priming intervention (Henson, 2003). The results of this study further highlight a decrease in activation in the left part of the PFC (the DLPFC and VLPFC). The left part of the PFC is known to be recruited for rule-based design, goal-directed planning of design solutions (Aziz-Zadeh et al., 2013) and making analytical judgments (Gabora, 2010). The reduction in cognitive activation in these sub-regions suggests concept mapping helps

engineering students frame the problem with lessened cognitive load particularly related to goal directed planning.

Research in design cognition provides empirical evidence of the co-evolution of the design problem and design solution space (Dorst & Cross, 2001; Maher & Poon, 1996). Such cognitive process implies a dual processing (Goldschmidt, 2016; Sowden et al., 2015) relying on exploring the problem space through the generation of solutions. In other words, the problem is framed through the ideation and conceptualize of solutions (Dorst, 2011). At a neurocognitive level, the findings from this study suggest that to construct the problem statement, students in the control group engaged both brain hemispheres. This is coherent with empirical evidence of the co-evolution of the problem-solution space that require bilateral activation. On the other hand, using concept maps reduced the activation in the left part of the PFC. The left part of the PFC tends to be engaged for goal-directed planning and deductive reasoning (Goel & Dolan, 2004). A possible explanation is that using concept maps nudged students to engage more cognitive efforts to generate solutions instead of focusing on evaluating the design problem itself. Indeed, concept maps set the problem space through the identification of elements represented in the problem statement (Turns et al., 2000).

A complementary explanation is that without concept maps, engineering students used more cognitive effort to formulate and analyze the problem-solution space that occurs in engineering design. Students in the intervention group were trained to use concept maps; therefore, they might have needed less cognitive effort to conceptually think about the problem. The lower activation in the left part of the PFC in the experimental group may suggest that students required less cognitive effort to engage in goal-oriented processes as a result of the concept mapping intervention. Furthermore, the results also provide evidentiary support for cognitive

load theory in engineering education, which could be further explored in the future, by establishing how priming students in ways that use specific regions and patterns of activation in their brain reduce subsequent cognitive effort.

This study highlights new evidence about the effects of concept maps on students neurocognition. Concept maps significantly changed students' neurocognition as they constructed their engineering problem statements. Future research could expand to include different types of tools other than concept maps to prime participants for engineering design. Future studies could begin to compare different techniques to concept maps to enrich and compare across tools to enhance engineering education. One limitation of this study is the small sample size. Although this sample size is in the range of similar previous studies that use neuroimaging methods in engineering (Hu & Shealy, 2019), a larger sample may provide more reliable results. Another limitation is the lack of evaluation of the problem statement. The research presented here is part of a wider study and our future research will include a larger dataset and more comparison between neurocognitive results and students' written problem statements.

CONCLUSION

Significant differences were observed in students' neurocognition when constructing engineering problem statements. Concept mapping changed neurocognitive behavior in students. Without concept maps, students used more cognitive effort to formulate and analyze their problem statement. Students that carried out the priming concept mapping task required less cognitive effort to conceptually think about the problem. Better understanding how concept maps, and other tools, can help frame complex problems and change students' neurocognition can lay the ground for novel advances in engineering education and new tool development for

teaching. Future research will extend the current results by measuring changes in brain behavior across time and begin to analyze what students said in their problem statements and how this differed between groups.

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CHAPTER THREE. PROPOSED JOURNAL PAPER

The Effects of Concept Mapping on Design Neurocognition: An Empirical Study Measuring Changes in the Brain when Defining Design Problems

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ABSTRACT

Concept mapping is a tool to help designers understand complex relationships between components of systems. The effect of concept mapping on design is that it aids designers through visualization and discovery of relationships between components of systems. The purpose of this study was to measure the underlying neurocognitive effects of concept mapping when designing. Whether concept mapping makes subsequent phases of design cognitively easier or changes patterns of activation in the brain is not well understood. Functional near-infrared spectroscopy (fNIRS) was used to measure the neurocognitive effects of sixty-six students asked to develop a design problem statement. Half of the participants were first asked to develop a concept map. Significant differences in the neurocognition between the groups was observed. Concept mapping decreased activation in sub-regions of the left prefrontal cortex (PFC), a region associated with memory and analytical judgement. Additional network graphs, measuring the functional connection of regions in the PFC showed that engineering students who developed concept maps had a smaller network density. Concept mapping reduced activation in the left

PFC and isolated functional connectivity in the brain. These results demonstrate the neurocognitive effects of concept mapping when designing and lay the groundwork for future studies to explore how interventions such as concept maps can help shape design thinking.

Key Words: concept maps, systems thinking, functional near-infrared spectroscopy, network analysis

INTRODUCTION

Engineering challenges are fundamentally complex and require engineers to explore interconnected components of systems (Maani & Maharaj, 2004). Tools such as concept mapping, an approach for systems thinking, help draw relationships between the complexities of these systems and predict outcomes. However, despite wide acceptance of the benefits of the systems thinking approach, there is limited research that explores the cognitive underpinning to think in systems. Measuring the effects of a systems thinking approach is essential to better understand these complex engineering challenges.

Concept mapping is a method utilized to represent complex systems graphically (Novak & Cañas, 2006). Concept maps provide a visual representation of information and the relationships between this information. It is an increasingly popular technique to help both students learn, and engineering professionals visualize the dynamic relationships between components of systems (Novak & Cañas, 2006; Watson et al., 2016). Concept maps demonstrate the understanding of the relationships, which in turn shows how students organize their interpretation of the engineering design problem (Ellis et al., 2004). This is a valuable assessment tool that helps describe the solution approach to an engineering problem based on how students construct their map and interpret the problem (Maani & Maharaj, 2004).

Engineering problems are often narrowly defined to remove complexity, which can lead to confining problems rather than expanding them to explore the intricacy to develop innovative solutions (Beamish & Biggart, 2012). Instead of removing complex elements of the systems, in which engineering problems are nested within, concept maps help visualize the relationships between system components, which provides a comprehensive approach of thinking and developing solutions. For example, the government of Togo, in west Africa, installed wells for the villagers in the village of Ayole to use, but after several years, these wells broke down and villagers started consuming contaminated water (Monat & Gannon, 2018). While the initial wells were helpful, their long-term success failed because of the lack of systems understanding, such as supply chain planning, socio-economic systems, psychological factors, and even political systems. This was not a purely technical problem that could be solved by designing a well to provide water. Eventually, utilizing systems thinking, the local villagers were trained to maintain the well, how to generate sales to fund repairs, provided the logistics of supplying spare parts, and awareness about drinking other sources of contaminated water (Monat & Gannon, 2018).The use of ways of thinking in systems, that concept mapping helps encourage, can create an overarching perspective towards solutions that can create long lasting and sustainable impact.

What happens in both the mind and brain of engineers when they use concept maps, and similar tools and techniques that encourage systems thinking, is not well understood (Turns et al., 2000). The cognitive mechanisms that create associations and can how specific techniques encourage more of these associations are not well explored (Hu & Shealy, 2018) The ability to see the underlying neurocognitive mechanisms can help understand how these associations are developed . This will also help challenge the traditional approach to reduce complexity and encourage ways of holistically problem solving (Hu & Shealy, 2018).

The motivation for the research presented in this paper was to establish a direct and objective measurement of how concept mapping changes neurocognition. Understanding the underlying neurocognition will provide deeper insight into the cognitive processes, networks and connections between different brain regions and how techniques like concept mapping can shift these patterns of activation in the brain (Dorst, 2011). Techniques like concept mapping can help encourage systems thinking and breakdown complexities through the process of illustrating connections between system components (Ellis et al., 2004.). By measuring neurocognition and understanding how neurocognition changes by using concept maps can enable a deeper understanding of students' design processes to enable better outcomes.

BACKGROUND

Concept maps

Engineering problems require understanding the bigger picture and organizing information that facilitates the construction of relationships between existing and new knowledge (Ellis et al., 2004; Hu et al., 2019). Concept maps help designers create a platform to construct these relationships which is crucial for problem solving. For example, after utilizing concept maps, students were able to formulate more diverse perspectives for a defined problem, which suggests, comes from attaining better organizational skills through concept mapping (Ellis et al., 2004b). By allowing designers to play with different systems and ideas of interconnectivity, this tool also enables designers to engage in new pathways to solve problems. Concept maps also help designers avoid tunnel vision and become more inclusive of dynamic systems, making them better problem solvers to meet increasingly complex interconnected and global challenges.

Additionally, concept maps help expand "mental frames" by increasing the existing knowledge domain, creating new frameworks by connecting new information, and moving

systems towards new solution spaces (Gero, 1990). For example, to achieve new iterations, designers need to be aware of different frameworks that could exist, and concept maps help devise those frameworks for engineering design. This helps reinforce previous knowledge as well as increases the likelihood of utilizing new relationships of these systems. This is powerful and effective since it pushes the limits of traditional problem-solving methods.

Priming and neurocognition

Concept mapping becomes useful as a design aid when it is coupled with subsequent stages of design. In other words, priming designers to think in systems can inform how they perceive the problem, which may influence how they define the problem, what solutions they develop during ideation, or how they critique existing ideas. Priming involves introducing a new material that can change the person's response to a task due to the encounter with that material or a related one (Schacter et al., 2004). For priming to be effective, it should be specific and pertinent to the scenario of the task given to designers (Alexander, 2016). For example, giving designers the opportunity to explore the system in which the design problem exists before prompting them into solving the problem could assist with the use of reflection-in-action (Schon, 1983). Concept mapping, as a priming intervention, could help engineers frame and reframe the problem and expand the exploration of the design problem and solution spaces (Jiang et al., 2014).

Neurocognitively, priming is different than recalling or recognition (Schacter & Badgaiyan, 2001).. The neurocognitive effect of concept maps as a primer for subsequent phases of design is not well understood. Broadly, there is not enough research that explores the effects on the cognitive underpinning of engineers' thinking (Bunce et al., 2011; Hu & Shealy, 2019). Understanding the cognition behind how designers develop

connections and relationships of systems and interconnected systems prior to problem identification may help expand how designers explore the problem and solution space and this may be observable in the brain. There is not much evidence that supports how cognition activation changes when concept maps are used for priming students to solve problems (Bunce et al., 2011) and the research presented in this paper provides new insight into understanding the different neurocognitive functions that are affected when priming designers to think in systems.

RESEARCH QUESTION

The research question is what is the effect of concept maps on designers' neurocognition when framing an engineering problem statement? The expectation is drawing relationships between elements of systems might facilitate new ways for designers to think about complex problems (Hu et al., 2019). Measuring designers' neurocognitive activation when constructing engineering problem statements can lead to a more detailed understanding of the mental process used for problem framing.

METHODS

The first part of this section describes the equipment used to measure neurocognition. The second sub-section describes the design of the experiment, including the design scenarios given to participants. The third subsection provides an overview of the data analysis techniques used to answer the requestion question.

Functional near infrared spectroscopy (fNIRS) to measure neurocognition

There are multiple instruments available to measure neurocognition, including electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and Functional

near infrared spectroscopy(fNIRS). EEG uses a head cap (or a covering) that measures the electrical brain signals (Hu & Shealy, 2019). fMRI uses magnetic resonance imaging (MRI) scanner that measures brain activation with good spatial resolution, that directly measures the blood-flow in different regions of the brain and produces the Blood Oxygen Level Dependent (BOLD) response, which is used to observe different areas of the brain (Menon & Crottaz-Herbette, 2005). One of the major disadvantages of fMRI is that the data can only be collected when the participant is enclosed in a MRI scanner (Hu & Shealy, 2019).

This research used Functional near infrared spectroscopy (fNIRS) for the data collection which combines the benefits of electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). It has revolutionized the ease of data collection and analysis in an educational setting (Grohs et al., 2017). fNIRS provides increase in mobility as well compared to the other equipment. One of the challenges of fNIRS is that it only measures cortical activation whereas fMRI provides measurements for all brain regions. fNIRS can detect changes in neurocognition during mental arithmetic tasks, imagery detection tasks, detecting emotions as compared to other techniques (Naseer & Hong, 2015). fNIRS is commonly used in design and decision making studies (Hu & Shealy, 2019). Additionally, fNIRS is also minimally invasive and easier to use in the laboratory setting which provided comfort for the participants to perform the tasks.

The region of interest for this study was the prefrontal cortex (PFC) because of its link to decision making, abstract reasoning and problem-solving (Goel, 2004; Hu & Shealy, 2019). The PFC region is necessary for learning strategies in addition to planning and organization skills. The PFC region is also associated with planning and working memory (Goldschmidt, 2016.). Understanding the neurocognitive activation of the PFC region would expand understanding of

decision and design studies.

Experiment design

Sixty-six engineering undergraduate and graduate students from Virginia Tech were recruited to participate in this study. Recruitment was conducted through advertising in engineering classes at Virginia Tech. The participants were provided with a $30 Amazon gift card for their participation. The experiment procedure was approved by the Institutional Review Board at Virginia Tech. Thirty-three students participated in each cohort (i.e., the control group and intervention group) and were randomly assigned. There was no significant difference in age or gender between the two cohorts. The median age of the students was 22 years and a standard deviation of 2.9 years. The students who participated were primarily from the Civil and Environmental Engineering Department. Twenty students were female, and forty-six students were male students.

After consenting to participate in the study, participants were randomly assigned to one of two groups: the intervention or control group. Participants in the intervention group learned about concept mapping through a four-minute video that showed an example of a concept map and how to draw cross links to create and highlight meaningful relationships between different concepts. After the video, participants in the intervention group drew a concept map about the educational system in the United States. This was a part of their training, and they were allowed to ask questions about concept mapping. Participants in the control group were not shown the video, nor provided practice techniques about concept mapping.

Once inside the lab, participants were outfitted with the fNIRS cap as shown in Figure 3.1a. The participants were also given sheets of paper and pen and were seated in front of a TV

screen shown with the instructions. The fNIRS cap was adjusted such that the frontal area of the head was covered as shown in Figure 3.1a. The data collected was the change in oxygenated blood (Δ HbO) measured across all 22 channels listed in Figure 3.1b. A word tracing activity was conducted in the beginning of the experiment to measure the baseline activation of the brain. This type of baseline recording is typical among neurocognitive studies (Tak & Ye, 2014). Figure 3.2 shows the order of the resting phase, concept mapping phase, and problem statement phase. The resting phase presented "cross hairs" on the screen for 30 seconds and a prompting asking students to rest. The sequence of the scenarios was randomized. The experiment used PsycoPy to provide each prompt and the timed crosshairs.

The design task comprised of constructing two engineering problem statements as listed below (scenario 1 and scenario 2). The order of the problem statements was randomized. Participants were given as much time as they needed to create their problem statements for the two scenarios.

Scenario 1:

"Patton Hall needs to be renovated and your role is to provide a document containing everything you think could be improved in the building. Please be as descriptive and elaborate as you can in explaining your ideas and how they would impact the systems and stakeholders."

Scenario 2:

"*Mobility on campus needs to be redesigned and your role is to provide a document containing everything you think that could be improved. Please be as descriptive and elaborate as you can in explaining your ideas and how they would impact mobility on campus."*

These scenarios were designed around known surroundings such that the participants were familiar with the systems that they needed to construct the problem statements for. scenario 1, Patton Hall was chosen since this is a familiar building for Civil Engineering students on campus, with the convenience of the location of the lab. All students have used the building space through their undergraduate or graduate careers. For scenario 2, mobility was chosen because transportation needed to be improved on campus and participants could use their personal experiences to construct the problem statement.

Before receiving these scenarios, the participants from the intervention groups were tasked with constructing concept maps as the priming intervention. They were given as much time as needed to construct their concept maps. The instructions asked:

Concept Map 1: "*Create a concept map illustrating all of the systems and stakeholders that interact with each other in Patton Hall.*"

Concept Map 2: "*Create a concept map illustrating all of the mobility systems on campus.*"

(a)

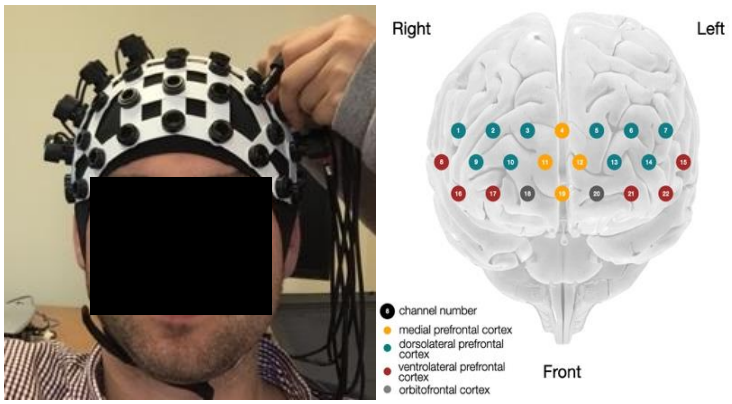

Figure 3.1 (a) fNIRS cap on a participant, (b) prefrontal cortex channel placement

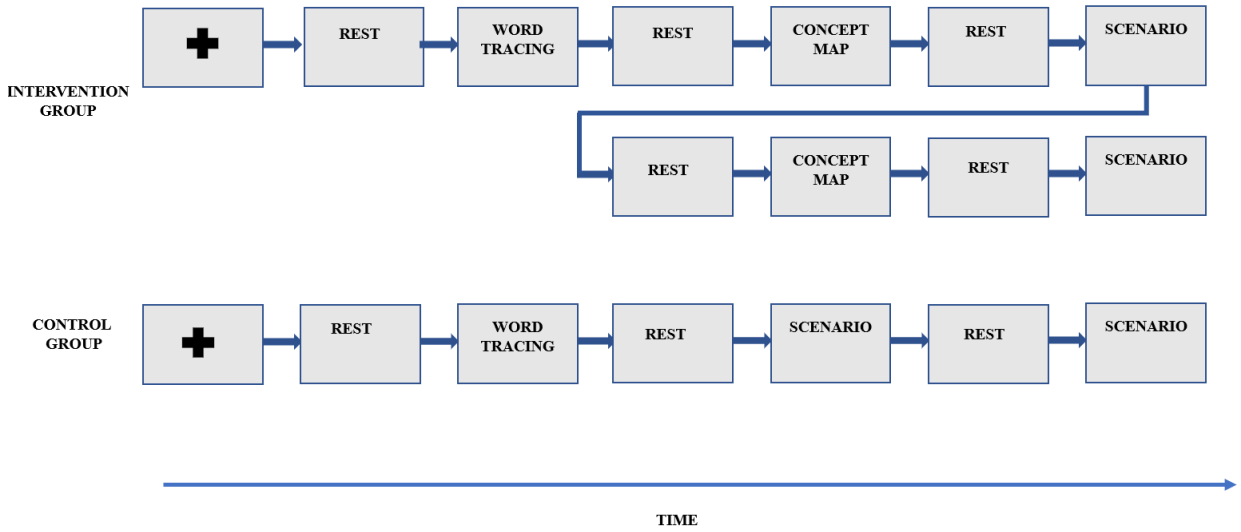

Figure 3.2 Diagram representing the order of tasks for the control and intervention groups

After the experiment, the participants completed a survey that included demographic information. The questions on the survey asked for the age, gender, handedness (left or right), years of college, major and, on a scale of 1 (not familiar) to 5 (very familiar) with Patton Hall and familiarity with the mobility systems on campus from the participants.

DATA ANALYSES

Processing of the fNIRS data

The raw fNIRS data was first screened using a bandpass filter with a frequency ranging between 0.01 and 0.1 Hz (Hu et al., 2019; Tak & Ye, 2014). An independent component analysis (ICA) with a coefficient of spatial uniformity of 0.5 was then applied to remove other motion artifacts from the raw data (Santosa et al., 2017). These parameters in data processing are based on protocols from prior studies related to fNIRS data processing methods (Naseer & Hong, 2015). These screening steps were done using the Shimadzu fNIRS software, which is a critical

step to ensure the data is filtered for any high frequency instrument or physiological noises. The HbO was analyzed for the participants for the two scenarios. Ten out of sixty-six participants were removed due to bad signals. After the elimination there was a total of 56 (n=28 for each group) participants. The word tracing activity was also conducted at the beginning of the experiment for baseline corrections and z-transformation. After this correction, the data was comparable between two groups and represented the change in cognitive state while conducting the problem framing tasks, and not the cognitive state while resting. Using this data from the fNIRS, two data analysis methods were used that are described below.

Measure change in the prefrontal cortex

The average change in Oxyhemoglobin (Oxy-Hb) throughout the problem framing tasks represent neurocognitive activation in the PFC region. To understand the differences in neurocognitive activation between the two cohorts, the average change in Oxy-Hb was analyzed for the problem framing tasks. The Oxy-Hb was averaged across the 22 channels for each participant in the control and intervention groups. This was followed by an independent t-test to measure if there was any significant difference between the two groups. Additionally, sub-regions of the PFC were also analyzed using an independent t-test to measure significant difference between the two groups. The data obtained from fNIRS cap sensors represented different regions of the Prefrontal Cortex (PFC) as shown in Figure 1b). The sub regions of interest were Right Dorsolateral PFC (DLPFC) represented by channels: 1, 2, 3, 9 and 10, Left DLPFC are represented by channels: 5, 7, 13 and 14, Right Ventrolateral PFC (VLPFC) are represented by channels 16 and 17, whereas the left VLPFC are represented by 21 and 22. Lastly, the Orbitofrontal Cortex (OFC) is represented by channels 18 and 20. The confidence interval was 0.05. Cohen's d values were also calculated to measure effect size, which is a

quantitative measure of the experimental effect (Ialongo, 2016). The larger the effect size, the stronger the relationship between two variables (Ialongo, 2016). The control and intervention groups for the building renovation task and the mobility task were analyzed separately and compared between the two groups

Patterns of oxyhemoglobin in prefrontal cortex were measured using network analysis

Brain networks are a representation of functional connectivity which can be used to study complex structural and functional activation between brain sub-regions (Bassett & Sporns, 2017). A combination of nodes in brain networks represent different brain regions (Rubinov & Sporns, 2010). The nodes are represented by the channels as shown in Figure 3.1b that correspond to different sub-regions of the PFC. Graph based representation of brain networks help provide a detailed understanding of the structure and function of the complex brain systems (Fornito et al., 2016). Brain network graphs provide a medium to understand how these nodes interact with each other that represent functional connectivity of these nodes. Functional connectivity between nodes implies that these regions have coherent and synchronized dynamics (Fornito et al., 2016). Using networks, this approach can help understand how functionally one sub-region of the brain is connected to other regions.

In this study, the networks were created to understand the topological centrality of the brain, which shows how one node can influence other nodes. Graph-based networks were created using correlation matrices. These matrices help understand topological relationships between brain regions. The construction of these networks helped identify correlations between brain regions and characterize interactions in the brain.

In this analysis, as shown in Figure 3.3, by utilizing Pearson's correlation, matrix demonstrating the correlation between signal channels for the change in Oxy-Hb was produced for each participant. While using the Pearson's correlation, a threshold was applied which is a critical step of this type of analysis. There is no consensus on any local threshold to be used for a matrix (Fornito et al., 2016).Typically, networks representing top 21% have the best network efficiency (Achard & Bullmore, 2007). For this data analysis, a threshold of 35% (0.65) was chosen based on previous studies.

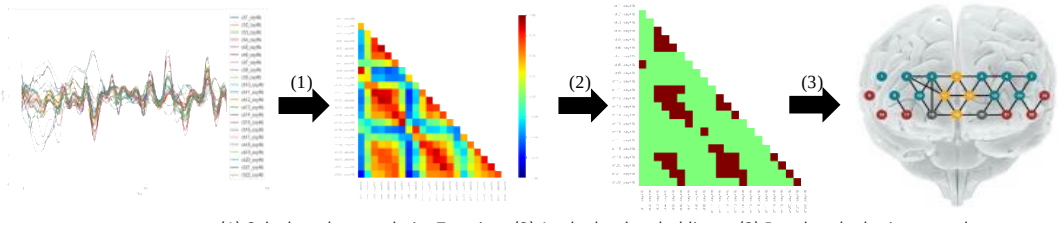

Figure 3.3 Network generation from the correlation matrix of HbO values from each channel. Base of brain image copyright © Society for Neuroscience

After the Pearson correlation's matrix was generated for each participant, the matrix was averaged across the total number of participants to produce a single matrix for the control and intervention groups for the two scenarios. Using the data from the matrices, as shown in Figure 3.3, network graphs were generated using Python for each of the groups.

After creating the network graphs, Network Centrality, Network Density (D) and Clustering (C) coefficients were calculated. These metrics provide a proxy to interpret the functional connection between regions required for the intervention and control groups to complete the problem framing tasks (Hu et al., 2019). The following equations below (1 and 2),

were used to calculate these proxies, where N is the number of nodes, $a_{ij}$is 1 if there is an edge between node i and j or else it would be 0, and $k_i$is the degree of node I (Hu et al., 2019).

$$D = \frac{2\sum_i a_{ij}}{N(N-1)} \quad (1)$$

$$C = \left(\frac{1}{N}\right)\sum \frac{1}{N}\frac{\sum_{kj} a_{kj}a_{ki}a_{ji}}{k_i(k_i-1)} \quad (2)$$

The functional and temporal connectivity of the regions can be understood by measuring Network density. Network density is the ratio of number of actual edges to the number of possible edges in a network (Hu et al., 2019). Lower density of a network refers to lower cognitive effort(Hu et al., 2019). Network centrality can be associated by identifying the central nodes in a network. The central nodes are the nodes with highest connections in the network (Borgatti, 2005). Identifying central nodes provides an understanding of high functioning regions while performing the design task (Borgatti, 2005). The clustering coefficient represents the interactions between brain nodes and the degree with which the nodes cluster together (Hu et al., 2019).These metrics provide further understanding of the functional connectivity required to complete the problem framing tasks. Additionally, they provide a better understanding of the activation of the different regions of the PFC.

RESULTS

Concept maps reduced students' neurocognitive activation in the PFC when constructing their problem statements

Scenario 1

Using concept maps reduced the neurocognitive activation in the regions of the PFC during the problem framing task for both tasks. For scenario 1 (building renovation), Figure 3.4 a

and b shows the activation heat map for the control group and intervention groups. This heat map highlights a higher activation in the left PFC of the control group compared to the intervention group. Statistical analysis using t-tests confirmed a significant difference in brain activation in the left PFC (t = 2.47, *p*= 0.02, Cohen's d = 3.14) between the two groups. Participants primed using concept maps demonstrated lower activation in their left PFC compared to the control group. No significant differences in brain activation were found in the right PFC (t = -1.28, p = 0.14) between groups for scenario 1 (building renovation).

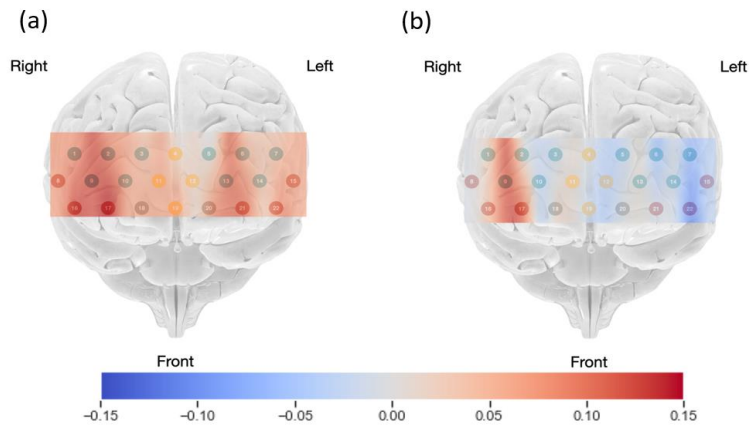

Figure 3.3 Brain activation in the prefrontal cortex (PFC); (a)Average brain activation heat map for the control group throughout the problem framing task for scenario 1(building renovation) ; (b) Average brain activation heat map for the experimental group throughout problem framing task for scenario 1(building renovation)

Further evaluation was done to check for significant differences in different sub-regions of the PFC. For scenario 1 (building renovation), there was activation in two sub-regions in the left PFC that showed significant differences during the engineering problem definition task. Detailed statistical analysis of the sub-regions in the PFC indicated that most significant differences occurred in the left dorsolateral prefrontal cortex (DLPFC) and left ventrolateral prefrontal cortex (VLPFC), as illustrated in Figure 3.5.

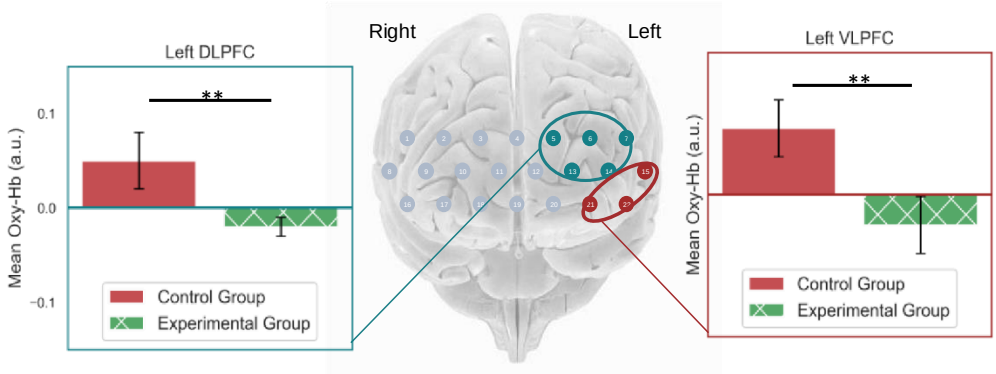

Figure 3.4 Brain activation in the left dorsolateral prefrontal cortex (DLPFC) and left ventrolateral prefrontal cortex (VLPFC) for scenario 1(building renovation) (Note: a.u. = arbitrary unit; p*<0.1, p**<0.05)

Scenario 2

For engineering problem scenario 2 (mobility), as shown in Figures 3.6 a and b, the heatmaps showed a higher activation for the control group compared to the intervention group. This suggested higher cognitive load for the participants of the control group. These participants spent more cognitive load while conducting the engineering problem defining task. Both heat maps in scenarios 1 and 2 for the problem framing task showed reduced average oxy-Hb in the intervention group compared to the control group. A possible explanation could be that concept maps did aid the participants towards creating mental organization, which reduced the activation for the intervention group and helped them transition more quickly into the problem framing task. There were no significant differences found in the right PFC region.

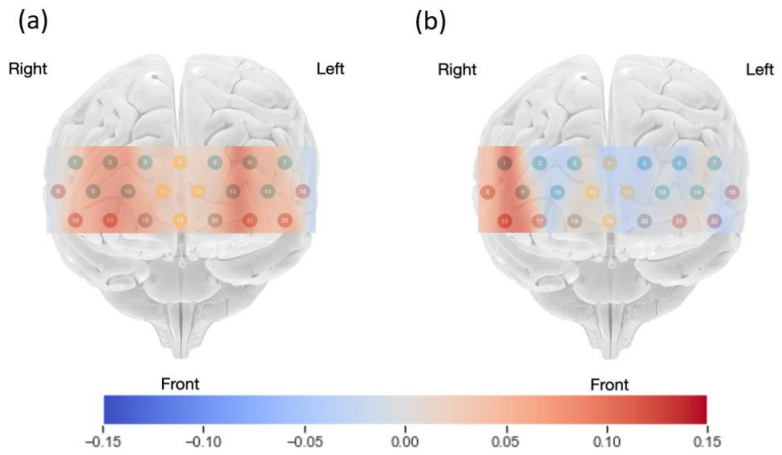

Figure 3.5 Brain activation in the prefrontal cortex (PFC); (a) Average brain activation heat map for the control group throughout the problem framing task for scenario 2 (mobility); (b) Average brain activation heat map for the experimental group throughout the problem framing task for scenario 2 (mobility)

After further evaluation, significant differences were found in the left region of the PFC for scenario 2 (mobility) as well. The left dorsolateral prefrontal cortex (DLPFC) showed a significant difference with a higher activation in the control group than the intervention group. The t-test suggested the significant ($t = 2.01$, $p = 0.04$) difference between the two groups. Figure 3.7 shows the statistical analysis of the sub region that shows the control group had a higher activation than the control group.

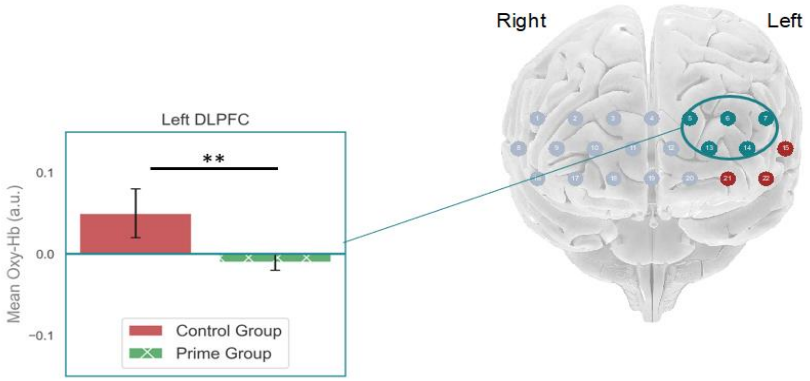

Figure 3.6 Brain activation in the left dorsolateral prefrontal cortex (DLPFC) for scenario 2 (mobility). (Note: a.u. = arbitrary unit; p*<0.1, p**<0.05)

The DLPFC is associated with attention and working memory (Cieslik et al., 2013; Hay et al., 2017). The left DLPFC is generally involved when making analytical judgments and goal directed plans (Aziz-Zadeh et al., 2013; Sowden et al., 2015). The second sub-region with a significant difference in activation is the left VLPFC. This region tends to be associated with evaluating a problem rather than solving it (Aziz-Zadeh et al., 2013). These results suggest that generating a concept map, illustrating the systems of the problem, reduced cognitive activation in the left DLPFC and left VLPFC when constructing the engineering problem.

Functional connectivity

Node centrality varied for scenario 1 (building renovation) and scenario 2 (mobility) tasks across different subregions of the Prefrontal cortex (PFC). Throughout both tasks, the central nodes were found to be either in left DLPFC and medial PFC. In all the network graphs, there were more than one central node in the PFC for both control and intervention groups. For instance, in Figure 3.8a, there are three Central nodes scattered across three sub-regions for the

control group for scenario 1 (building renovation). There were also multiple other nodes that corresponded to centrality values very close to the high central node across different sub-regions. Since constructing the problem statements constituted of multiple cognitive functions such as memory, analytical thinking, and decision-making, there were nodes that represented different sub-regions with high centrality values. The network density was also higher in the control group compared to the intervention group for both scenarios.

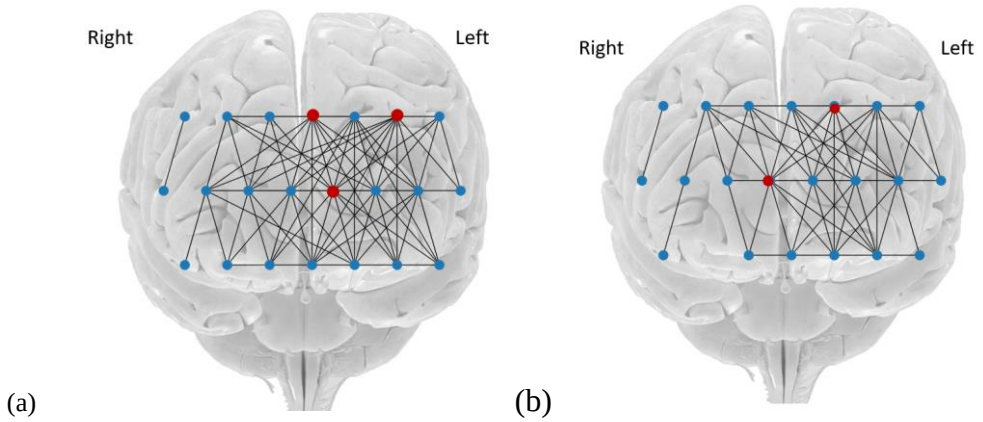

Figure 3.8 Network graph for the building systems task for the (a) control group and (b) intervention group using a threshold for the correlation matrix of 0.65. Red nodes represent the nodes with the highest centrality.

For scenario 1 (building renovation), the control group had more nodes with the high network centralities compared to the intervention group. In Figure 3.8a, the left DLPFC (channel 6) and medial PFC (channels 4 and 12) on the network graph had the highest centrality value of 0.762. For the intervention group, as seen in Figure 3.8b, the left DLPFC (channel 6) and medial PFC (channel 11) are the nodes with the highest centrality value of 0.650. Both the groups had the same sub-regions with the highest centrality values; however, the centrality values were higher for the control group compared to the intervention group. The control group also had four additional nodes in the left DLPFC (channels: 5, 13 and 14) with centrality values, all greater

than 0.6 and less than 0.7. The intervention group had three nodes (Channels 13, 20, 21 and 22) with second highest centrality values, between 0.5 and 0.6. The other sub regions with the second highest centralities for the intervention group were in the left DLPFC (channel 13), left VLPFC (channels 21 and 22) and orbitofrontal cortex (channel 18).

The average network density for the control group (0.44) was higher than the intervention group (0.32). This depicts that there was more functional connectivity on the control group participants compared to the intervention group. The higher density also suggests that there is higher cognitive coordination (Hu et al., 2019), which meant that concept maps did help reduce the mental effort needed to conduct the problem solving task. The clustering coefficient was also higher for the control group (0.69) as compared to the intervention group (0.59). The lower clustering coefficient also shows that there were more lesser centrality regions which also signifies reduced cognitive load (Hu et al., 2019).

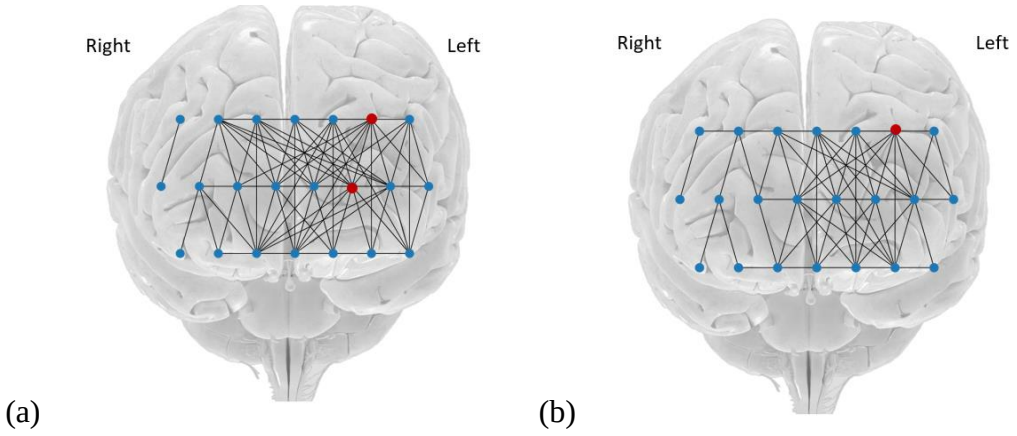

Figure 3.9 Network graph for the mobility systems task for the (a) control group and (b) intervention group using a threshold for the correlation matrix of 0.65. Red nodes represent highest centrality for the graph.

For, scenario 2 (mobility), the nodes with the highest centrality was in the left Dorsolateral PFC for both control and intervention groups. For the control group there were two channels (6 and 13) with the highest centrality value of 0.714 as seen in Figure 3.9a. Whereas, for the intervention group, there was only one channel (6) with the highest centrality value of 0.619 as seen in Figure 3.9b. The nodes with the highest centrality values for the control group were greater than that of the intervention group. Additionally, the control group resulted in four additional nodes (channels: 4, 12, 18 and 14) with higher centrality values, all greater than 0.6 and less than 0.7. For the control group, the second highest node centrality regions were in the left DLPFC (channel 14), medial PFC (channels 4 and 12) and orbitofrontal cortex (channel 18) on the network graph. The intervention group resulted in three additional nodes (Channels 12,11 and 14) with second highest centrality values, all greater than 0.5 and less than 0.6. The other sub regions with second highest centralities for the intervention group were in the left DLPFC (channel 14) and medial PFC (channels 11 and 12).

The network density for the control group was higher (0.42) for scenario 2 as compared to the intervention group (0.31). Additionally, the clustering coefficient was higher for the control group (0.66) compared to the intervention group (0.55). This was similar to scenario 1, where the density and clustering coefficients were lower which meant that the cognitive load was higher in the control group compared to the intervention group.

To further explore the network densities, average network density for each of the 28 participants was calculated for both the control and intervention groups for the two scenarios. Then independent t-test was conducted but there were no significant differences found for both the tasks, scenario 1 ($t = -0.5$, $p = 0.58$) and scenario 2 ($t = -0.6$, $p = 0.52$). However, there was

greater average network density across both the scenarios for the control group compared to the intervention group.

DISCUSSION

The results provide evidence that concept mapping decreases neurocognitive activation when framing engineering problems. Concept mapping made defining design problem statements cognitively easier. The regions of the prefrontal cortex with reduced activation were the left DLPFC and VLPFC. The left DLPFC is generally involved when making analytical judgments and goal directed plans (Aziz-Zadeh et al., 2013; Sowden et al., 2015). The left VLPFC tends to be associated with evaluating a problem rather than solving it (Aziz-Zadeh et al., 2013). One explanation for this reduction in brain activation is the concept mapping activity helped the design students evaluate the problem prior to having to define it. They understood the components of the problem because they had already thought about it, which made the problem definition phase cognitively easier. The deactivation of the left PFC as a result from concept mapping is also consistent with prior research (Hu et al., 2019). Amadieu et al. (2009) found that the hierarchical structure of a concept map facilitated navigation through system components and reduced overall cognitive load self-reported by participants.

The right PFC plays an active role in divergent thinking (Aziz-Zadeh et al., 2013; Zmigrod et al., 2015). Goel and Grafman (2000), evaluated that the right DLPFC plays a crucial role in terms of configuring the concept generation abilities.A possible explanation for the directed activation in the right PFC and less activation in the left PFC among the students who completed the concept maps is the process of creating concept maps aided students' mental organization of information. They were already familiar with the information, and the relationships between this information,

may have helped facilitate a quicker transition from thinking about one idea to another, which seems to correspond to divergent thinking and sustained elicitation of activation in the right PFC.

Functional connectivity between sub regions of the PFC also varied. The control group, in both tasks, produced more dense networks with more connections across regions of the PFC. This is consistent with prior research about the effects of concept mapping on students' neurocognition. Concept mapping alleviated brain network complexities and required less coordination between different brain regions in a prior study (Hu et al., 2019). Concept mapping seems to focus subsequent activation to specific regions of the brain. Brain regions in the right PFC seem to work independent without coordination between regions in the left PFC.

While network density varied, the highest centrality nodes were somewhat consistent between the control and intervention groups for both scenarios. The nodes with the highest network centrality were generally located in the medial and left PFC sub regions. The medial PFC (mPFC) is believed to be an essential region for neural networks relevant to perspective taking (Seitz et al., 2006). Studies also suggest that the mPFC plays a vital role in memory retrieval, association learning, and simulating future imaginative events (Euston et al., 2012), (Meyer et al., 2019). A possible explanation for the high centrality of this region is that students cognitively made associations between systems during the problem statement process, and this is coordinated through the mPFC. The central node in the medial and left hemisphere of the PFC, might be relevant to the coordination of "retrieval" paths during design. These regions appear to also ensure functional interaction between other brain regions. Network characteristics in neuroscience is an emerging field and how characteristics (e. g., density, clustering coefficient) are correlated to design performance is an area of needed future research (Beaty et al., 2015).

The study overall provides evidence that there is significant change in the neurocognition of design students engaged in concept mapping. Though the sample size was small in this study, there is still significant evidence of higher cognitive activity in the control group compared to the intervention group. The size of the group is also consistent with prior studies applying neuroimaging to engineering design (Hu & Shealy, 2019). Replicating the study with a larger sample and varying the population could help provide redundancy to support to these findings.

Another limitation of this study was the lack of an active control group. The concept mapping activity created an opportunity for the intervention group to think about the concepts and relationships involved with the topic prior to the task to define the problem statement. This was necessary because the literature on problem solving suggests that to be effective, the priming intervention should be specific and pertinent to the scenario of the task given to the subjects (Alexander, 2016). However, just thinking about the problem for longer, not necessarily the use of concept maps, may have contributed to the observed difference between students' neurocognition. However, neither group was constrained in the time to think about the problem. No time limit was imposed on the control group when working on the task. The students in the control group were allowed to develop concept maps, just were not prompted to do so.

The variability in task performance within the concept mapping group may offer additional insights about the differences that occur in students' neurocognition. A well-developed concept map is better able to enhance the representation of connections among the components and may elicit more retrieval paths in the brain for accessing concepts (O'Donnell et al., 2002). Future research can begin to score concept maps and correlate how these scores relate to neurocognition. An expectation is that students with higher concept map scores produce elicit greater activation in their right PFC.

CONCLUSION

The purpose of this paper was to understand the change in neurocognitive activation as a result of using concept maps. Design students were given two design problem tasks. The design students were randomized into a control group or intervention group. The intervention group was asked to develop concept maps prior to defining their problem statements. The results from both scenarios showed that using concept maps reduced subsequent cognitive effort to complete the problem statement task. The reduction in effort occurred specifically in the left and medial PFC. These regions are generally associated with perspective taking (Seitz et al., 2006), memory retrieval, association learning (Euston et al., 2012; Meyer et al., 2019), goal directed planning (Aziz-Zadeh et al., 2013; Sowden et al., 2015) and evaluating problems (Aziz-Zadeh et al., 2013). The reduction in activation may suggest that concept mapping enables these aspects to occur sooner and thus reducing the need when developing their problem statements.

Further analysis also revealed that there were significant differences in the brain networks between the groups. The network analysis highlighted that the density of the intervention group's network was lower in compared to the control group. Concept mapping not only reduce the cogntive effort but reduce the number of functional connections in the brain. While more nodes were central in the control, the regions with high central in the brain networoks tended to be in the left and medial prefrontal cortex. Consistent subregions of node centrality begin to suggest a possible default network of functional connectivity. The central node in the medial and left hemisphere of the PFC, might be relevant to the coordination of retrieval paths during phases of design. These regions appear to help facilitate functional interaction and act as a control for information flow as it interacts with other brain regions.

The research presented in this paper presents one aspect of the development of the neural underpinnings when students are designing. There are numerous additional methods and opportunities for analyzing neurocognitive data and more needs to be done. However, it is also important to understand that this is only a single aspect of understanding the underlying changes that occur in cognition from interventions to the design process. More qualitative-quantitative analysis techniques that offer new triangulation of data between neurocognition and student performance is still needed. Measuring design cognition is better developed with several approaches whose results potentially map onto observations and assessments produced by students. Including measurements of brain activation during design provides an additional objective result that is independent of the measurer. There is still considerable research needed to draw conclusions about brain activations and what this means for cognitive activities that occur when students are designing. This paper is a step in that direction.

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CHAPTER FOUR. CONCLUSION AND REFLECTION

The research provided new evidence that shows that there were differences observed between the intervention and control groups after the use of concept maps. Even though the sample size of the participants was small, there was enough evidence gathered to open new opportunities for further understanding of this study. However, there is also room for improvement in terms of the scope of the research, where new data analysis methods could be studied as well as the old ones could be further evaluated. For example, the network graphs could be broken into deciles to understand how the graphs change over time. The results currently report the brain regions with highest centrality, there could be more in-depth analysis of how these regions impact problem solving and performance of the participants, which further explores into neuroscience and cognitive studies. Additionally, there could also be more analysis done in terms of how the high centrality regions change over deciles and the impact of it in terms of functionality of the brain.

After conducting the data analysis, one of the improvements that could be done in future studies is the use of triggers. My experiment design was such that there were many triggers incorporated to collect data for two scenarios, which included several “rests” as well as word-tracing activity to get the baseline correction. Some participants were feeling a little agitated when the data collection ran over 40 mins in a few cases. This could be considered while designing future experiments. This would additionally help with data filtration and processing since there would be less room for mistakes while identifying the correct trigger counts while conducting the analysis.

Additionally, this research provided a better understanding of concept maps used as a tool for systems thinking approach. This goal could be further evaluated by also comparing how

concept maps changed through time in addition to how the relationships were formed between systems by comparing between scenarios. This would also allow to understand how the design space changes over time when participants construct more than one engineering design problem using concept maps.

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