Concept maps decrease students' neurocognitive demand 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 of 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 their 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 studied for decades using observation and think aloud protocols (Dorst, 2011; Hay et al., 2017a, 2017b). 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., 2000a). What is less known is the fundamental neurocognitive functions that actually 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, 2018a).

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. The experiment was designed without a time restriction because time presented an additional variable that could have influenced how students constructed their problem statement. Without a time restriction, students had the autonomy to complete the task at their own pace. 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 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 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, 2018b; 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.

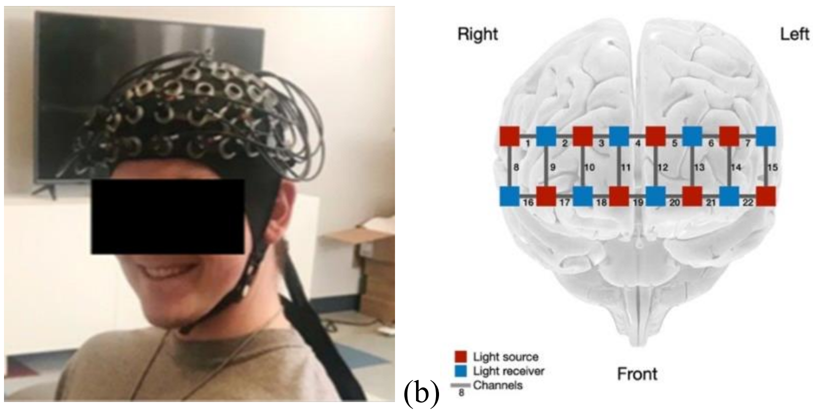
(a)


Figure 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 scripts. 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(a) shows the activation heat map for the control group, while Figure 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.

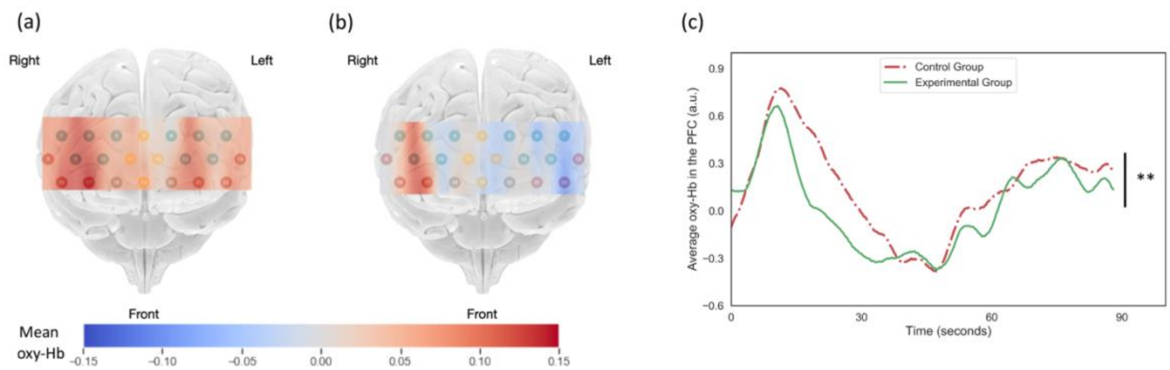


Figure 2. Brain activation in the prefrontal cortex (PFC); (a)Average brain activation heat map for the control group throughout the task; (b) Average brain activation heat map for the experimental group throughout the task; (c) Average oxy-Hb in the PFC in the first 90 seconds of the task. (Note: a.u.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

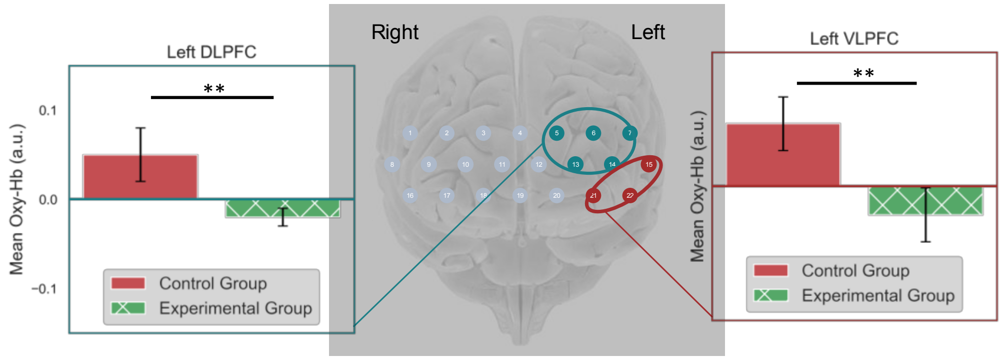


Figure 3. Brain activation in the left dorsolateral prefrontal cortex (DLPFC) and left ventrolateral prefrontal cortex (VLPFC)

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., 2000b).

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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