ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE

Paper ID #38331

The neurocognition of engineering students designing: A preliminary study exploring problem framing and the use of concept mapping

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Abstract

Neuroimaging provides a relatively new approach for advancing engineering education by exploring changes in neurocognition from educational interventions. The purpose of the research described in this paper is to present the results of a preliminary study that measured students' neurocognition while concept mapping. Engineering design is an iterative process of exploring both the problem and solution spaces. To aid students in exploring these spaces, half of the 66 engineering students who participated in the study were first asked to develop a concept map and then construct a design problem statement. The concept mapping activity significantly reduced neurocognitive activation in the students' left prefrontal cortex (PFC) compared to students who did not receive this intervention when constructing their problem statement. The sub-region in the left PFC that elicited less activation is generally associated with analytical judgment and goal-directed planning. The group of students who completed the concept mapping activity had greater focused neurocognitive activation in their right PFC. The right PFC is often associated with divergent thinking and ill-structured representation. Patterns of functional connectivity across students' PFC also differed between the groups. The concept mapping activity reduced the network density in students' PFC. Lower network density is one measure of lower cognitive effort. These results provide new insight into the neurocognition of engineering students when designing and how educational interventions can change engineering students' neurocognition. A better understanding of how interventions like concept mapping shape students' neurocognition, and how this relates to learning, can lay the groundwork for novel advances in engineering education that support new tools and pedagogy for engineering design.

Introduction and Background

Engineering design is an iterative process that requires the co-evolution of both the problem and solution spaces [1], [2]. Tools and techniques that help students explore the problem and solution spaces in new ways can aid in their educational development as design engineers. Concept mapping as an educational tool tends to focus on measuring students' ability to think in systems [3]. Much research has focused on how to develop concept mapping as an assessment tool for student learning [3], [4]. For example, one assessment approach is to count the number of concepts, cross-links, and the level of hierarchies in students' concept maps [5]. Another approach is to use a three-point scale to rate the content on a concept map for comprehensiveness, organization, and correctness [6].

Concept mapping may also be an approach to help students explore both the problems and solutions in new ways by visualizing the representation of information and the relationships between this information [3], [7]. The graphical structure of concept maps facilitates the visualization of new relationships and elements. Less is understood about how concept mapping may be useful as a technique to expand students' ability to explore the problem and solution spaces. The process of graphically representing the connections between complex system components may help enable unique "retrieval paths" for new concepts and help students create new knowledge [8]. What these retrieval paths look like is not well understood Is the change in cognitive processing that occurs from concept mapping observable in students' brains?

Methods from neuroscience offer an approach to answer this question. Neuroimaging provides a layer of information and insight about design cognition that is underexplored [9], and holds potential to advance engineering education by adding new objective measures. For example, a prior neuroimaging study found that first-year and fourth-year engineering students use anatomically different regions of their brain when solving design problems and these differences correspond to varying levels of design performance [10]. Measuring students' neurocognition and their behavior can provide new insights into the effects of tools and techniques, like concept mapping, on students' design ability.

Research Question

The research question is what are the effects of concept mapping on students' neurocognition when developing problem statements? The expectation was that concept maps create new knowledge by focusing students' attention on the relationships between existing concepts. The use of concept maps divides the task into first thinking about the information and relationships broadly before being directed to identify a problem. Based on cognitive load theory [11], [12], this segmenting, or division, of the process may reduce the cognitive effort required by students when constructing their design problem statements and this is observable in their neurocognition.

Methods

All of the participants (n=66) in this study were engineering students (undergraduate and graduate) at Virginia Tech. Participants were recruited through their engineering courses and through university communication channels such as campus activity bulletin boards and department listservs. 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.

Once enrolled, participants were randomly assigned to the intervention or control group. The intervention group learned about concept mapping. They were shown a four-minute video about the elements and relationships in a concept map and how to construct a concept map. To practice the process, they were asked to construct a concept map about their educational experience and could ask questions while they practiced. The participants in the control group were not given instruction about concept mapping or asked to practice it.

Students in both groups were then outfitted with a functional near infrared spectroscopy (fNIRS) device. fNIRS was chosen as the neuroimaging instrument because it offers relatively good resolution in both time and space, respectively, compared to functional magnetic resonance imaging (fMRI) and electro-encephalography (EEG). fNIRS measures the change of oxygenated (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb), also called blood oxygenation level dependent (BOLD) response. BOLD response is a proxy for brain activity [13]. An increase in oxy-Hb typically mirrors neuronal activity and implies the allocation of resources and nutrients by the cerebrovascular system [14]. fMRI also measures the BOLD response. The benefit of fNIRS compared to fMRI is participants can perform tasks sitting at a desk rather than inside of a large tube laying on their backs. fNIRS was preferred over EEG because of the spatial resolution of the data. The fNIRS cap is shown in Figure 1(a). Changes in oxy-Hb were measured using the fNIRS in 22 channels placed in the 10-20 system along the prefrontal cortex (Figure 1(b)).

(a)

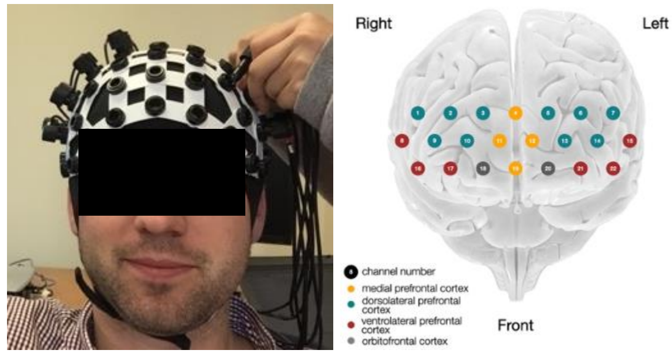


Figure 1: (a) fNIRS cap on participant, (b) prefrontal cortex channel placement

While wearing the fNIRS cap, students were asked to first complete a word tracing task to record baseline activation in their brain. This type of baseline recording is typical among neurocognitive studies [15], [16]. Subsequent to the word tracing, participants were asked to rest for thirty seconds by staring at a cross-hair.

Students in the intervention group were then prompted to construct a concept map. There were two design tasks and two associated concept maps. One of the tasks asked the intervention group of students to “create a concept map illustrating all of the systems and stakeholders that interact with each other in Patton Hall.” Patton Hall is a familiar building on campus. Following the concept mapping task students were told “Virginia Tech has hired you as a consultant. 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.” A thirty second rest period followed both the concept map and problem statement task.

The second task then prompted the intervention group of students to “create a concept map illustrating all of the mobility systems on campus.” Following the concept mapping task, students were told, “Virginia Tech has hired you as a consultant. 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”. The order of these two tasks were randomized for each participant. The control group was given the same instructions except for the concept maps. The experiment was conducted using PsychoPy. PsychoPy helped provide timed instructions and prompts on a display screen for each task.

Neuroimaging data

Ten out of sixty-six participants were removed from further analysis due to poor signals. The 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 [17]. The parameters in data processing are based on prior research [18]. Shimadzu fNIRS software was used to filter and pre-process the fNIRS data. After preprocessing, fNIRS data were analyzed using a locally developed python script. A baseline correction and z-transformation were applied to make fNIRS data comparable between subjects and between the two groups.

The neurocognitive activation in the prefrontal cortex (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, the oxy-Hb across functional sub-regions for each participant was also analyzed. The mean oxy-Hb throughout the task was used as a proxy for neurocognitive activation. Independent t-tests were performed to compare the control group to the intervention group for both tasks. The confidence interval was 0.05.

Patterns in brain networks were also compared. Brain networks are a representation of functional connectivity between different sub-regions [19]. Brain networks were created using Pearson's correlation, matrices showing the correlation between signal channels measuring the variations in oxy-Hb. A threshold was then applied to identify the connections between nodes [20]. Multiple network thresholds were used in this study, including 20%, 25%, 30% and 35% of the correlated nodes within the network. The process of developing a correlation matrix, applying a threshold, and illustrating these connections is illustrated in Figure 2. This level of thresholding was used previously when describing how brainstorming, morphological analysis, and TRIZ produce distinctly different density networks and regions of centrality [15].

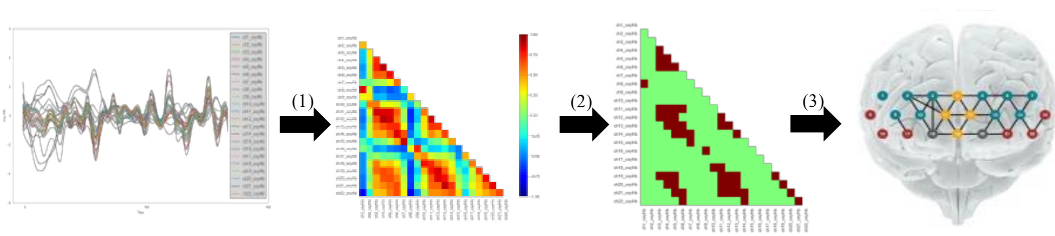


Figure 2: The process of creating brain network graphs, which is a proxy for functional coordination in the prefrontal cortex. Calculate the correlation between channels when defining the problem statement, apply a threshold, and then represent the matrix using brain network graphs. Base of brain image copyright © Society for Neuroscience.

Results and discussion

Students who first completed the concept mapping task recruited less oxy-Hb to their left PFC compared to the control group. The reduction of oxy-Hb in the left PFC was consistent for both tasks, illustrated in Figures 3 and 4. This implies that the use of concept mapping reduced cognitive load in the left hemisphere of the PFC. This may occur because of the segmenting of the task into first thinking about concepts associated with the problem before being asked to identify an define the problems.

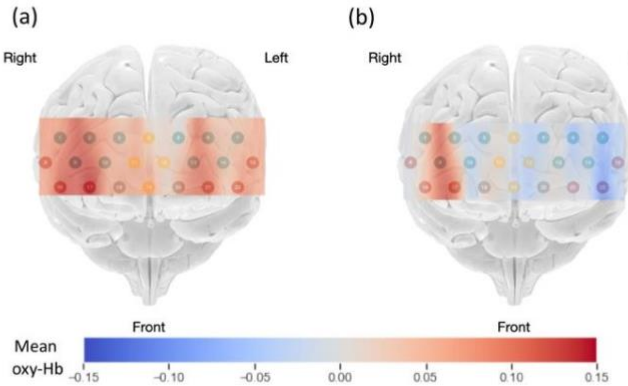


Figure 3: Building system task; (a) Average brain activation for the control group; (b) Average brain activation for the intervention group.

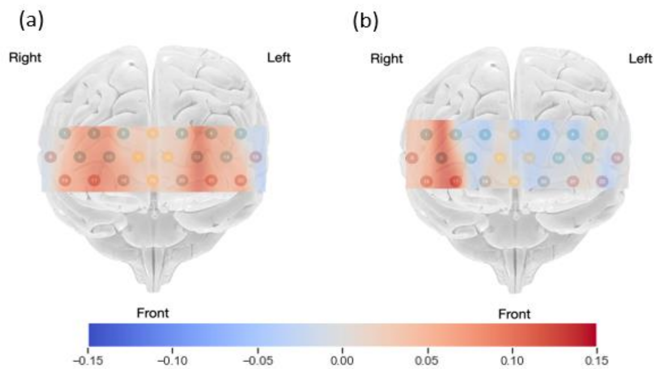


Figure 4: Mobility system task; (a) Average brain activation for the control group; (b) Average brain activation for the intervention group.

The differences observed between groups was significant. Statistical analysis using t-tests found that the oxy-Hb recruited specifically to the left dorsolateral PFC (DLPFC) was significantly less for students who completed the concept mapping task about the building system ($t=-2.08$, $p=0.04$; intervention group: $M = 0.002$, $SD = 0.01$; control group: $M=0.07$, $SD=0.02$) and the mobility system task ($t=2.01$, $p=0.04$; intervention group: $M=0.01$, $SD=0.15$; control: $M=0.05$ $SD= 0.02$). The left DLPFC is generally described with its involvement in making analytical judgments and goal-directed planning [21], [22]. This deactivation of the left PFC as a result from concept mapping is consistent with prior research [23]. It may suggest concept mapping aids students' understanding of the purpose and goals of the task before being asked to identify associated problems. The concept mapping activity created an opportunity for the intervention group to think about the concepts and relationships involved with the topic prior to developing a problem statement. Thinking about the problem for longer, not necessarily the use of concept maps, may be the reason differences were observed in students' neurocognition. Future research should use an active control, or additional techniques to focus students' attention on potential problems and solutions.

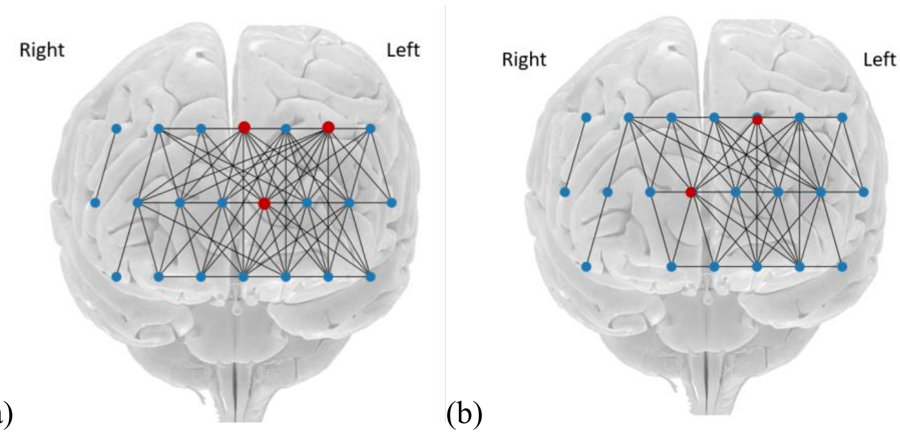
The right PFC, a region that was recruited for both the intervention group that was asked to develop a concept map and the control group, is known to play an active role in divergent thinking [21], [24] and sustained attention [25]. Designers who display high semantic distances in solution generation exhibit strong synchronization within their right PFC [26]. Goel and Grafman [27], investigated concept generation abilities of a designer with lesions in the right hemisphere and a designer without brain damage. They found the right DLPFC is critical for ill-structured representation and computations.

A possible explanation for the more 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 and enabled them to spend more time on the creation of new ideas associated with their problem statements. Being 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 the elicitation of activation in the right PFC.

Network analysis

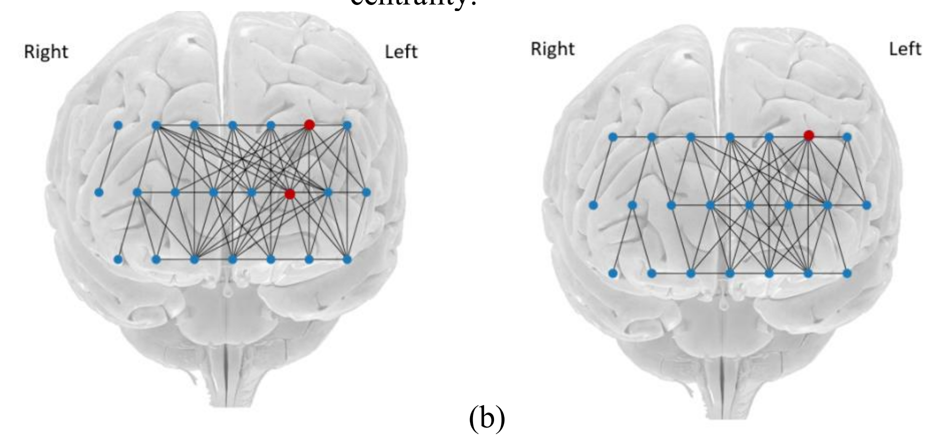
Functional connectivity between nodes representing the prefrontal cortex also varied between groups. The control group, in both tasks, produced more dense networks with more connections across regions of the PFC, represented in Figures 5 and 6. This is consistent with prior research about the effects of concept mapping on students' neurocognition. Concept mapping alleviated brain network complexities and required less coordination between different brain regions in a prior study [28]. Concept mapping seems to focus subsequent activation to specific regions of the brain.

There is consistency in node centrality in all of the network graphs. Sub-regions in the middle and left DLPFC, in Figures 5 and 6, are regions with high centrality. High central nodes are highlighted in red. The medial PFC (mPFC) is believed to be an essential region for neural networks relevant to perspective taking [29]. Prior neuroscience literature also suggests the mPFC is recruited in memory retrieval, association learning, and simulating future imaginative events [30], [31]. A possible explanation for the high centrality of this region is that students cognitively made associations between ideas during the problem statement process and this is coordinated through the mPFC.



(a) (b)

Figure 5: 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 high centrality.



(a) (b)

Figure 6: 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 high centrality.

Further research is needed to provide the basis for more complete explanations about the meaning of these network differences. The central region, or 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 help facilitate functional interaction and act as a control for information flow as it interacts with other brain regions, but 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 future research [32]. The intersection of engineering design education, neuroscience, and network analysis as a measure for functional connectivity should be the subject of future investigation to better develop an understanding of how information flows through the brain.

Conclusion

Concept mapping appears to make designing easier to cognitively manage [11]. Concept mapping led to deactivation in the region of the brain associated with analytical judgement [21], [22] and it focused activation in the region of the brain associated with divergent thinking [21],

[24]. Concept mapping also produced less dense networks. These networks are a representation for functional connectivity in the brain [19]. Network density is a measure of the cognitive resource requirement of the network, and a lower network density is another measure for lower cognitive effort.

The brain region with the highest centrality across both groups and both tasks is in the left PFC. This consistency offers opportunity for future investigation. It may suggest it is important for controlling information flow in the brain during design. The medial PFC (mPFC) also tended to be of high centrality (three out of the four groups had nodes with high centrality in this region). The location of this region, between the left and right hemisphere, may help explain its high degree of centrality. The association of this region with future thinking and the type of design task students were completing may also help explain why this area is of high centrality.
The research reported in this paper presents one aspect of the development of the neural underpinnings of students' design cognition. Measuring brain activation during design activities provides an objective result that is independent of the measurer. There is still considerable research needed to connect brain activations and their resultant networks to the cognitive activities that occur during design. Methods for analyzing brain activity requires further development if it is to capture the higher order cognition involved when students design.

Acknowledgements

This material in this paper is based on research supported by the National Science Foundation under Grant Nos. 1929892 and 1929896. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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