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# How the use of concept maps changes students' minds and brains

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# How the use of concept maps changes students' minds and brains

## Abstract

The research presented in this paper tested whether drawing concept maps changes how engineering students construct design problem statements and whether these differences are observable in their brains. The process of identifying and constructing problem statements is a critical step in engineering design. Concept mapping has the potential to expand the problem space that students explore through the attention given to the relationship between concepts. It helps integrate existing knowledge in new ways. Engineering students (n=66) were asked to construct a problem statement to improve mobility on campus. Half of these students were randomly chosen to first receive instructions about how to develop a concept map and were asked to draw a concept map about mobility systems on campus. The semantic similarity of concepts in the students' problem statements, the length of their problem statements, and their neurocognition when developing their statements were measured. The results indicated that students who were asked to first draw concept maps produced a more diverse problem statement with less semantically similar words. The students who first developed concept maps also produce significantly longer problem statements. Concept mapping changed students' neurocognition. The students who used concept mapping elicited less cognitive activation in their left prefrontal cortex (PFC) and more concentrated activation in their right PFC. The right PFC is generally associated with divergent thinking and the left PFC is generally associated with convergent and analytical thinking. These results provide new insight into how educational interventions, like concept mapping, can change students' cognition and neurocognition. Better understanding how concept maps, and other tools, help students approach complex problems and the associated changes that occur in their brain can lay the groundwork for novel advances in engineering education that support new tools and pedagogy development for design.

## Introduction

Concept mapping is a technique to represent complex systems [1], [2]. It provides a visual tool to illustrate the relationships between conceptual information. The use of concept maps is increasingly prevalent in both education and engineering practice. For example, concept mapping is a core principle in the Adaptable Futures guide [3]. When deciding whether a building is suitable for adaptive reuse, and how to go about designing it, the guide suggests starting with drawing a concept map including all of the possible stakeholders and making links between the reasons for hesitation to pursue the project and potential benefits from each stakeholders' perspective [3]. This conceptual process helps the designer create new knowledge by exploring the space between stakeholders, their needs, and potential risks.

Concept mapping is also a useful counter-balance to reductionist ways of thinking that often work to isolate individual components of a system. Concept mapping encourages designers to think about the interaction between components. For example, Interface Inc., a manufacturing company, was able to identify new energy efficiency gains in their mechanical systems by broadening the scope of their problem. Rather than optimizing an already efficient mechanical pump they instead recognized more prospective gains in reducing the friction within their pipes [4]. The shift in their problem statement from *create a more efficient pump* to *reduce the need for* *pumping* was a result of a more holistic systems approach that concept mapping can help stimulate. Narrowly defined problem statements can constrain ideas [5], [6].

The purpose of the research presented in this paper was to measure how the use of concept maps changes engineering students' ability to construct problem statements. Rather than concept maps being a tool for assessment [7], here concept mapping was used as an approach to help students expand the problem space being considered during design. The premise was concept mapping may help engineering students create more divergent problem statements, which in turn may lead to new design ideas. The act of constructing a concept map may provide more opportunity to continuously process the concepts in their minds, which may lead to better design outcomes [8], [9]. Illustrating the hierarchical relationships, sequential processes, and complex inter-relationships may also reduce the cognitive load in subsequent phases of design like exploring problem definition [10].

Measuring the change in cognition that occurs through concept mapping is an underexplored area of research. Novak & Cañas (2007) argued that concept mapping is an easy way to encourage very high levels of cognitive performance. The background section of this paper expands on this idea of design cognition and performance that can occur when thinking about the whole system and its interactions. The Background section also lays out an approach to more objectively measure cognition using methods from neuroscience. The Methods section provides an overview of the experiment and data analysis techniques. The results present new insight about the benefits of concept mapping and its effect on students' neurocognition. The discussion and conclusion offer several possible explanations for the observed differences and present possible future studies that bridge engineering design education and cognitive neuroscience.

## Background

Engineering design is an iterative process that usually begins with problem identification and then moves into some form of design ideation [12]. Engineering students who can expand the problem space stand to increase the subsequent production of possible solutions when ideating. Concept mapping is a tool to support students ability to expand the problem space [13].

The cognitive explanation for why concept mapping works is that it provides new and multiple retrieval paths for accessing information in their brain [14]. Designers attain new knowledge by integrating existing knowledge in new ways. What is not well understood is whether these differences in retrieval paths are actually observable in the brain and measurable in how engineering students craft their design problem statements. Design education tends to measure cognition through interviews, observational studies, and think-aloud protocols. The challenge with these methods is they infer change in student cognition when designing [15], [16]. These methods lack objectivity when measuring the underlying mechanisms of cognitive function that occur through engineering design [16]. For instance, think aloud protocols may reduce a student's ability to focus on the task and change how they perform [17].

Methods from neuroscience offer additional approaches to more directly measure cognitive activity when students are learning and designing [18]. Functional magnetic resonance imaging (fMRI) is one approach to more directly measure neurocognition. It provides high spatial resolution for the whole head. A limitation of fMRI is it requires participants to lie down in a closed and confined space [19]. Electro-encephalography (EEG) is another approach. It offers high temporal resolution compared to fMRI. A downside to EEG is the challenge to accurately pinpoint the brain region where electrical activity occurs [20]. Functional near-infrared spectroscopy (fNIRS) is a third technique. It offers relatively good resolution in both space and time. The limitation of fNIRS is the measuring depth is limited to the cortex. It cannot measure deep regions within the brain [21]. However, the prefrontal cortex, which is a key area for executive functions is accessible and an important region when designing [22]. fNIRS is often used to measure change in neurocognition during tasks that require working memory [23], attention, reasoning, and evaluations [24]. fNIRS was used in this study because it provided participants a more realistic design environment compared to fMRI and better spatial resolution than low-cost EEG.

fNIRS works by measuring the change of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) in cortical regions of the brain. The change in oxy and deoxy-Hb are often referred to as the blood oxygenation level dependent (BOLD) response. BOLD response is a proxy for brain activity [25]. An increase in oxy-Hb typically mirrors more neuronal activity and implies the allocation of resources and nutrients by the cerebrovascular system [26].

The prefrontal cortex (PFC) region of the brain is divided into several sub-regions based on anatomy and function, including the dorsolateral PFC (DLPFC), ventrolateral PFC (VLPFC), medial PFC (mPFC) and orbitofrontal cortex (OFC). These sub-regions contribute to different aspects of cognitive processing [27], [28]. Activation in the left DLPFC decreased [29] and activation increased in the right DLPFC during improvisation [30], [31]. The mPFC was observed to play a critical role in the retrieval of “remote” memories [32]. Increased activation in the mPFC was also associated with improved ability to simulate future imaginative events [33]. The VLPFC was previously observed as a critical region for combining existing information into new ideas [24] and detect similarity between items [34].

There are numerous methods to analyze fNIRS data collected about the brain [35]. The change of oxy-Hb over time is a common approach [35] and used in prior engineering design neurocognition studies [36], [35]. For example, the mean oxy-Hb was observed to differ between first-year and fourth-year engineering students when design ideating [37]. First-year students recruited more oxy-Hb in the regions of the brain generally associated with cognitive flexibility and divergent and convergent thinking. Senior engineering students recruited more oxy-Hb in the brain region generally associated with uncertainty processing and self-reflection [37]. This application of neuroimaging provides an objective measure to understand student cognition when designing. Here it was used to test the use of concept maps to expand the design problem space and measure differences in engineering students’ brain.

## Research Questions

Both neurocognition and written statements from engineering students were used to measure how the use of concept maps changes engineering students’ ability to construct design problem statements. The specific questions were:

1. What is the effect of concept mapping on students framing of design problem statements?

2. What is the effect of concept mapping on students' neurocognition when developing design problem statements?

## Methods

To answer the research questions, a sample of engineering students from Virginia Tech (n = 66, age = 22.13 ± 2.93 years) participated in the study. Students were randomly assigned to one of two cohorts. The intervention cohort were asked to construct a concept map prior to receiving the design tasks. Students in the control group were asked to work on the same task but without developing any concept map beforehand. The purpose of having two cohorts was to measure the effect of the concept mapping intervention on students design problem statements and their neurocognition.

The participants included both undergraduate (n = 46) and graduate (n = 20) engineering students. Students were primarily majoring in civil engineering, industrial systems engineering, mechanical engineering, or construction engineering and management. Females represented 30% of the sample. All students were compensated with a $30 Amazon gift card for their time. All components of the study were reviewed and approved by Virginia Tech's Institutional Review Board.

The experiment began by participants in the intervention group being shown a 4-minute introductory video about concept maps. The video explained the structure of concept maps, teaching them how to use hierarchies and crosslinks to show the relationships between concepts. After watching the video, participants practiced concept mapping. They were asked to draw a concept map about the education system. This was to ensure they understood how to construct a concept map and ask questions of the research team.

Participants from both groups were then asked to sit in front of a display screen that would prompt them with the experiment task. All participants were given a pen and paper to complete the task. Participants were then outfitted with the fNIRS cap and the machine was calibrated. The fNIRS cap is shown in Figure 1(a). The 22 channels on the fNIRS cap were placed in accordance with the 10-20 system, shown in Figure 1(b).

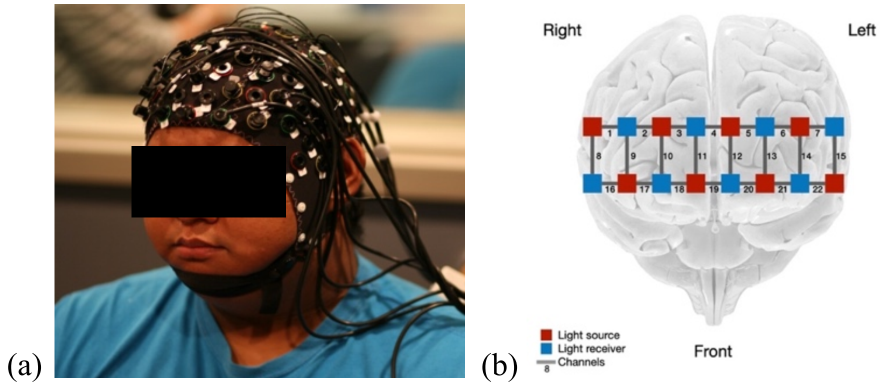
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Figure 1: fNIRS cap on participant (a), prefrontal cortex channel placement (b)

While wearing the fNIRS cap, students were asked to complete a word tracing exercise. This type of recording is typical among neurocognitive studies [38], [39]. The neuroimaging data collected during the word tracing excise was used as a baseline level of activation when writing and subtracted from the neuroimaging data when participants were writing their problem statements. Once the word tracing exercise was completed, students rested for 30 seconds by staring at a cross hair displayed on the monitor. New instructions were then given. For the intervention group, students were then asked to "Create a concept map illustrating all of the mobility systems on campus." After completing their concept maps, this group rested for another 30 seconds before receiving the next set of instructions. Both the intervention group and control group were then 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 when explaining your ideas and how they would impact mobility on campus." For both the concept mapping and problem statements, students were given as much time as needed.

Subsequent to the experiment, participants were asked to complete a brief demographics survey. The information gathered by the survey included the participants' age, gender, handedness (left or right), years of college, major and, on a scale of 1 (not familiar) to 5 (very familiar), familiarity with the mobility systems on campus. There was no significant difference ($t = 1.092$, $p = 0.28$) in familiarity between the control (mean = 3.84) and intervention group (mean = 4.06).

### *Data analysis for the problem statements*

The semantic similarity (or distance) between each of the words in students' problem statements was used as a proxy measure for difference between groups. To frame design problems, designers need to identify and describe the relationships between "seemingly remote concepts", which require the use of semantically distant words. Dumas et al. (2020) [40] argues that the body of literature on the use of semantic distance to operationalize originality in the design space justifies its use in creativity research. Semantic similarity was calculated using spaCy's "en_core_web_lg" Model in the Python programming language, which was trained using the "word2vec" family of algorithms. This model scores the similarity between two words giving them a score on a scale of zero to one. A score of one represents the maximum similarity (i.e., the same word). This approach to measuring semantic similarity was also used by Beaty et al. (2014) [41]. In the Beaty et al. study, a positive correlation was found between the semantic distance between words used in a verbal fluency test and the creative quality of responses given to an Alternative Uses Test.

### *Data analysis for neuroimaging*

Ten out of sixty-six participants were removed from analysis due to poor neuroimaging 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 [42]. The parameters in data processing are based on prior research [43], [44]. Shimadzu fNIRS software was used to filter and pre-process the fNIRS data. After pre-processing, fNIRS data were analyzed using 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 research question two (what is the effect of concept mapping on students' neurocognition when developing design problem statements?), the neuro-activation in the PFC was analyzed. Oxy-Hb was averaged over time for each channel to assess differences in activation during the problem statement task. Average activations in sub-regions of the PFC were also compared. A two-sample t-test was performed to compare the control group with the intervention group. The confidence interval was 0.05. Cohen's d values were used to measure effect size.

## Results

Responses from students in the intervention group (mean = 0.2793, SD = 0.0393)) had a significantly (t = 2.235, $p = 0.0327$) lower average semantic similarity score than the control group (mean = 0.2995, SD = 0.0393). This is illustrated in Figure 2. The students who first completed the concept maps developed more semantically diverse problem statements. The effect size was medium (Cohen's d = 0.6027, Glass's delta = 0.5137). Students that received the concept mapping intervention also wrote significantly more words in their problem statements when compared to the control group. The intervention group (mean = 99.47) wrote an average of 25 more words than the control group (mean=74.72, SD = 35.83). A *t*-test (t=2.22, p =0.034) indicated that the difference between the control and intervention groups was statistically significant ($p < 0.05$). Cohen's *d* (d = 0.61) and Glass's *delta* (0.69) indicated a medium effect size ($0.5 < d$ or $delta < 0.8$).

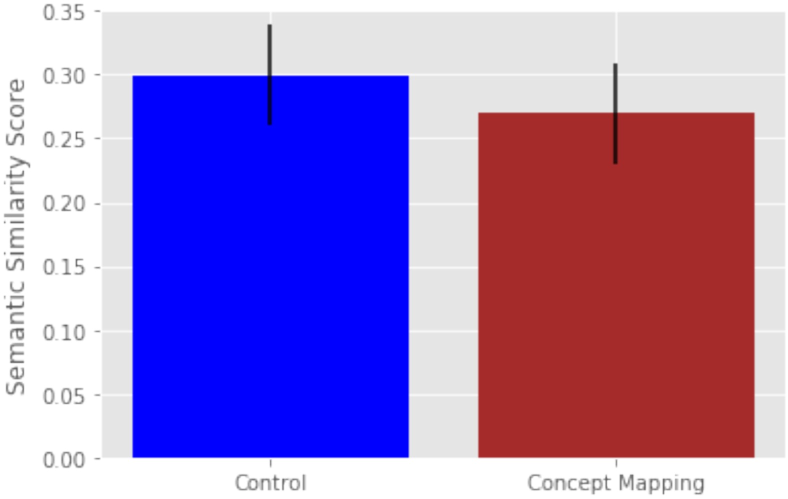

Figure 2: Semantic similarity score for words used in students' problem statements, where a score of one represents the maximum similarity (i.e., the same word)

Using concept maps also changed the average neurocognitive activation in the PFC when constructing their problem statements. The activation heat map illustrated in Figure 3, shows elevated levels of oxy-Hb for the control group across the PFC. The intervention group elicited more narrowed neurocognitive activation in the right PFC. Statistical analysis confirmed a significant difference in brain activation. The control group elicited higher activation in the left PFC compared to the concept mapping, intervention group (t=2.47, *p*=0.02, Cohen's d=3.14). The dedicated activation in the right hemisphere of the PFC could represent more focused attention [45] and this focused attention led to longer and more diverse problem statements.

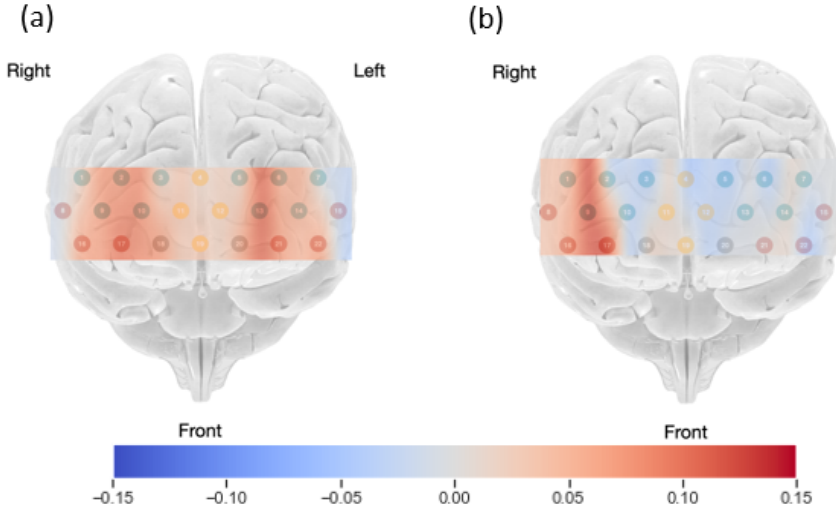

Figure 3. Brain activation in the prefrontal cortex (PFC); (a) average brain activation for the control group throughout the problem statement task; (b) average brain activation for the experimental group throughout the problem statement task

## Discussion

The group that was asked to develop concept maps used a semantically wider set of words when responding to the mobility task, which can be related to a wider consideration for the design problem space [8]. The increase in semantic distance corresponded with changes in patterns of brain activation. The intervention group had more directed activation in the right PFC and less activation in the left PFC. The right PFC plays an active role in divergent thinking [46], [47] and sustained attention [48]. Designers who display high semantic distances in solution generation exhibit strong synchronization within the right PFC [45]. The left PFC plays a more active role when supporting rule-based design, goal-directed planning [46], and making analytic judgments [49]. The left PFC also plays a critical role in solving math problems [50].

A possible explanation for why more focused activation in the right PFC and less activation in the left PFC was observed among students who completed the concept mapping exercise was that concept mapping aided the students' mental organization of information before the problem statement task and enabled them to spend more time on the creation of new ideas. When designers are able to spend more time reflecting on a design problem, they can enable more creativity [51], [52] and the results presented in this paper support this idea.

Concept mapping prior to defining the design problem may have helped facilitate a quicker transition from thinking about one concept to another, which seems to correspond to divergent thinking that is known to elicit activation in the right PFC. The deactivation of the left PFC as a result from concept mapping is also consistent with prior research [53]. Amadieu et al. [54]

found that the hierarchical structure of a concept map facilitated navigation through system components and reduced the overall self-reported cognitive load by participants.

Another possible explanation is the design process involves the co-evolution of the design problem and solution space [55], [56]. This co-evolution implies a sort of dual processing [57], [58], relying on exploring the problem space through the generation of solutions. At a neurocognitive level, the findings from this study might suggest that to construct the problem statement, students in the control group engaged both brain hemispheres and this bilateral activation is related to the co-evolution of the problem-solution space. Using concept maps reduced the bilateral activation, resulted in more well-defined problems, and this may also correspond with more emphasis on the problem space than the solution space when developing their problem statements.

### *Limitations and future work*

A 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 develop a problem statement. So, just thinking about the problem for longer, not necessarily the use of concept maps, may be the reason differences were observed between students' problem statements and their neurocognition. However, neither group was constrained in the time they were given to think about the task.

Not all concept maps are created equal. The variability in task performance within the concept mapping group may offer additional insights about the differences that occur in students' neurocognition when designing. A well-developed concept map is able to enhance the representation of connections among the components and enable multiple retrieval paths for accessing concepts [14]. Future research can begin to score concept maps and correlate how these scores measuring the number of concepts and their cross links relate to students' problem definitions and their brain behavior. A potential hypothesis is that students with higher concept map scores produce greater semantic differences in their problem definitions and this will correspond with further increased right hemisphere activation in their PFC.

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. For example, measuring the change in functional coordination in brain networks between groups [59]. Network analysis can be used to assess the functional connectivity between brain regions [35]. Network features, like the network density, clustering coefficient, and efficiency, present new characteristics of what is happening in the brain [60]. Central regions, or nodes, in the brain may facilitate functional interaction and act as a control for information flow as it interacts with other brain regions [61]. The network characteristics (e. g., density, clustering coefficient) that best correlate to design performance is not known [62]. Future research can begin to look for default networks and central brain regions that are relevant to "retrieval" paths during design.

Understanding how concept mapping performance correlates with neurocognition can begin to help inform pedagogy. The research presented in this paper demonstrates how using concept maps can improve performance and reduced cognitive effort. Helping students further segment the design task into components and how these components build on each other and change neurocognition can help contribute new insight into theories about cognitive load and learning [63]–[65]. While this paper is a step in that direction, 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. More qualitative-quantitative analysis, for example, about the co-evolution of the problem and solution space, how activation and deactivation in the brain correlate with performance, and potential brain networks that represent retrieval paths in the brain is still needed.

## Conclusion

Defining problems is a critical early step in the design process, so identifying techniques that can assist students to define problems has the potential to help them improve as designers. Concept mapping is often used as a type of assessment tool to measure what students have previously learned. Concept mapping may also be useful as a technique for creating new knowledge by exploring the space between concepts and their connections. Sixty-six engineering students participated in a study to measure the cognitive and neurocognitive effects of concept mapping on problem identification. Concept mapping led to longer written problems statements and statements with greater semantic distance between words.

Concept mapping also changed patterns of activation in students' brains. Students who first used concept maps had more directed cognitive activation in the right hemisphere of their prefrontal cortex and less activation in their left prefrontal cortex (PFC). The right PFC plays an active role in divergent thinking [46], [47] and designers who display high originality in solution generation previously exhibited strong synchronization within the right PFC [45]. The left PFC plays a more active role when supporting rule-based design, goal-directed planning [46], and analytic decision making [49]. This neuroimaging data provides new insight into how concept mapping can aid in students' mental organization of information and how more localized right hemisphere activation in the prefrontal cortex corresponds to more semantically diverse problem statements. This triangulation of cognitive and neurocognitive data highlights the opportunity for more research at the intersection of engineering design education and neuroscience to demonstrate how tools and techniques can change students' minds and brains.

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