Neuroscience for Engineering Sustainability: Measuring Cognition During Design Ideation and Systems Thinking Among Students in Engineering

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ABSTRACT

Sustainability is inherently a complex problem that requires new ways of thinking. To solve grand challenges such as climate change, environmental degradation, and poverty, engineers cannot rely on the same models of thinking that were used to create these problems. Engineering education is therefore critical to advance sustainable engineering solutions. Improving education relies on understanding of cognition of thinking and designing for sustainability. In this thesis, a nascent neuroimaging technology called functional near-infrared spectroscopy (fNIRS) was used to measure cognition among engineering students thinking about sustainability. fNIRS provides an opportunity to investigate how sustainability in design influences cognition, and how different concept generation techniques help students consider many aspects related to sustainability. The first manuscript provides evidence that engineering students perceive sustainability in design as a constraint, limiting the number of solutions for design and decreasing the cognitive efficiency to generate solutions. Senior engineering students generated fewer solutions than freshmen, however, seniors were better able to cognitively manage the sustainability parameter with higher cognitive efficiency. The second manuscript investigates the cognitive difference when generating concepts using concept listing or concept mapping. The results indicate that concept mapping (i.e. intentionally drawing relationships between concepts) leads to more concepts generated. An increase in concepts during concept mapping was also observed to shift cognitive load in the brain from regions associated with process sequencing to regions associated with cognitive flexibility. This research demonstrates the feasibility of fNIRS applied in engineering research and provides more understanding of the cognitive requirements for sustainability thinking.

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GENERAL AUDIENCE ABSTRACT

Sustainability brings new challenges to engineering design. To advance the practice of sustainable engineering, engineers are expected to be able to efficiently tackle socio-technical problems using a systems perspective. Engineering education is expected to help engineering students to achieve this goal. Improving education relies on understanding of mental process of thinking and designing for sustainability. In this research, a nascent neuroimaging technology-functional near-infrared spectroscopy (fNIRS) has been used to measure the cognition of engineering students thinking for sustainability. fNIRS enables us to investigate how sustainability requirements in design influence the cognition of design process, and how different concept generation ways help students understand sustainability. The first manuscript provides evidence that sustainability in design constraint, limiting the number of solutions for design and decreasing the cognitive efficiency to generate solutions. Senior engineering students generated fewer solutions than freshmen, however, seniors showed advantage to handle sustainability requirements with higher cognitive efficiency. The second manuscript investigates the cognitive difference of two concept generation ways using concept listing or mapping. The results indicate that concept mapping leads to more concepts related to sustainability and enables the cognitive load shift from regions associated with sequencing processing to regions associated with cognitive flexibility. This research demonstrates the feasibility of fNIRS applied in engineering research for sustainability and provides more understanding of the cognitive requirements for sustainability thinking.

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List of abbreviations

BA	Brodmann Area
BOLD response	Blood Oxygenation Level Dependent response
CMS	Concept map scores
fNIRS	functional Near-Infrared Spectroscopy
HbO	Oxygenated hemoglobin
HbR	Deoxygenated hemoglobin
HbT	Total hemoglobin
IRB	Institutional Review Board
mM	millimolar
PFC	Prefrontal Cortex
PPC	Posterior Parietal Cortex
ROI	Regions of interest
STSR	Systems Thinking Scale Revised
ΔHbO	Change of oxygenated hemoglobin
µM	Micromolar

INTRODUCTION

Sustainability brings new challenges to engineering design. To advance towards more sustainable practice in engineering, engineers are expected to be able to efficiently consider and meet sustainability requirements. Sustainability is inherently a systems problem that requires a shift in thinking from individual parts to the relationships between them. Thus, enabling engineers to more quickly think in systems is vital to advance sustainable development in the future. Engineering education is expected to help engineering students achieve more sustainable design solutions in the future. Improving the engineering education relies on our understanding of design cognition for sustainability.

Until recently, measuring cognition (i.e. thinking, planning, and decision making) was limited to studying behavior and outcomes (e.g., actions taken, answers given, artifacts created). While assessment of behavior or outcomes is necessary, it is not sufficient to reveal how and what influences these behaviors and design outcomes. Outcomes may look similar but the physical thought process (localization of cognitive activation across regions in the brain) to achieve them may appear very different. The emergence of techniques to collect data on the brain have revolutionized the study of cognition because they enable the collection of objective measurable physiological data. The physiological data can provide a more detailed and quantitative explanation about how students think, and in particular, how students develop design solutions that meet sustainability requirements. Techniques to collect data on the brain allows for opportunity to congruently measure students' cognitive processing ability and design outcome. The behavioral data and physiological data about the brain, together provides a more comprehensive understanding about how students process information and develop solutions.

The nascent neuroimaging technology, functional near-infrared spectroscopy (fNIRS), was used to measure student cognition during tasks about sustainable engineering. fNIRS was used to record cognition of engineering students when completing tasks broadly about design thinking and systems thinking by measuring their Blood Oxygenation Level Dependence (BOLD) response.

To investigate how sustainability requirement in engineering design impact cognitive activities and how engineering education shapes students' cognitive abilities, in the first study, twelve freshman engineering students and eight seniors participated in an experiment completing ten brainstorming tasks related to engineering design. The tasks were subdivided, five included an additional requirement that solutions must meet sustainability parameters. The cognitive activities and behaviors of students during design, with and without sustainability requirements, among freshmen and seniors were measured and compared. The paper reports significant difference between tasks and participant groups using ANOVA.

The second paper is about systems thinking. Systems thinking is believed to facilitate decision making for complex systems problems such as sustainability. The second study investigates how different ways of thinking either using a linear list or concept maps influence cognition and number of concepts students generate. 28 engineering undergraduate students participated to develop a list of concepts and a conceptual map of concepts about four topics related to sustainability. A self-assessment survey was also given to participants to measure their tendency of systems thinking. Self-report, behavior changes, cognitive changes and brain network during the tasks were measured and compared to understand the difference between ways of thinking.

Better understanding the role of certain brain regions and cognitive change during thinking tasks related to sustainability holds promise to advance engineering education. Both experiments with engineering undergraduates in this research provide useful information about the differences in ability to generate concepts between freshman and seniors (study 1) and differences in concepts generation when using a listing technique or concept mapping (study 2). This research also demonstrates the feasibility of fNIRS used in engineering education research with implications for engineering for sustainability. I hope this interdisciplinary research integrating engineering and neuroscience generates conversation about other engineering tasks and settings in which fNIRS can be effectively used as a new tool to study cognition. fNIRS alone only provides a narrow view of understanding but combined with more familiar techniques like measuring design outcomes, behavior, think aloud protocols, fNIRS provides a new and supporting level of information that can help better understand the connection between cognition and outcomes.

1. Journal Paper 1 - Generating Creative Solutions for Sustainability: Measuring the Cognitive Advantages and Disadvantages of the Undergraduate Engineering Education during Brainstorming Tasks

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ABSTRACT

Issues such as climate change, resource constraints, and rising poverty highlight the need to pursue more sustainable solutions. Education for sustainability is necessary because of the influence on engineers' design and problem solving, their ability to make connections between complex socio-technical components, and in turn make significant and real-world implications on society. In particular, engineering design is a central and critical part in engineering education to train engineers to innovate effectively to meet societal needs. Improving design education relies on our understanding of design cognition, which includes the formulation of problems, the generation of solutions, and the utilization of design process strategies. Here, we measure the cognitive load to generate solutions for engineering design problems, with and without sustainability-related requirements, using functional near-infrared spectroscopy (fNIRS). fNIRS is a neuroimaging technique that can be used to study brain activity in more natural environments than EEG or fMRI. It therefore offers new opportunities for exploring how brain activity relates to engineering design. While there is literature describing which brain regions support particular cognitive functions, far less is known about how these are developed through learning and how they support design thinking. Twelve freshmen and eight senior engineering students participated the brainstorming tasks related to engineering design. Freshmen generated significantly more solutions than senior engineering students. During the task freshmen were found to elicit greater activation in brain regions associated with cognitive flexibility and abstract reasoning, while seniors were observed to elicit greater activation in regions involved in management of uncertainty. When an additional sustainability requirement was added to the design task both freshmen and seniors developed less solutions. Thinking about sustainability also required more cognitive effort and a shift in cognitive activation occurred from the left to

right hemisphere when sustainability was a design requirement. In many ways, this initial work serves as a proof of concept in using neuroimaging to study the processes involved in engineering design. Through a better understanding of these processes, researchers can begin to explore specific elements of the engineering curriculum that may contribute to student ability to manage complexity inherent in engineering design problems. This interdisciplinary study is meant to integrate engineering education and neuroscience and generate conversation about other engineering design tasks and settings in which fNIRS can be effectively used as a new tool.

Key Words: engineering design, education, sustainability, functional near-infrared spectroscopy, brainstorming

1.1 INTRODUCTION

Issues such as climate change, resource constraints, and rising poverty highlight the need to pursue more sustainable solutions that meet current needs without compromising the ability of future generations to do the same (Brundtland 1987). Government organizations (EPA 2007), professional societies (ASEE 1999), national academies (NAE 2008) and foundations (National Science Foundation 2009) recognize this need and call for more participation among engineers. Recent progress can be seen in new courses about sustainability added to engineering curricula (Azapagic 2005; Chau 2007; Huntzinger et al. 2007; Siller 2001). Although there is still a lack of consistent integration across engineering programs. The process of integrating sustainability into engineering education is still an active area of research (Bielefeldt 2013; Lozano 2010; Nagel et al. 2011).

Education for sustainability is necessary because of the influence on engineers' design and problem solving, their ability to make connections between complex socio-technical components, and in turn make significant and real-world implications on society. For example, consider an engineer tasked with alleviating congestion on a highway. Guided by traditional design theory, the engineer may consider adding more road lanes; a seemingly appropriate solution to address demand issues. However, such a design solution could be counterproductive, or further exacerbate the initial problem, a phenomenon called induced demand (Hymel et al. 2010; Lee et al. 1999). Adding a new road lane brings new automobile drivers, and over time (typically within five years), this leads to more traffic and worse conditions than before (Cervero 2003; Noland 2001). For another perspective on this issue, now consider Curitiba, Brazil, a city that relieved congestion by removing highway lanes rather than adding them. The solution developed out of economic necessity (the city could not afford the high cost to construct highway lanes or build an underground subway system). Repurposing existing roadway lanes to a system of buses was not only cost-effective but provided synergistic benefits for the environment and community. Residents of Curitiba enjoy the lowest per capita transportation costs and best air quality in the country (Lindau et al. 2010).

Solutions like Curitiba are more likely to emerge from a design approach that requires adding dimensions of sustainability on to the design process. Indeed, the Mayor of Curitiba credits the engineering design innovation to the additional economic dimension (one of the three pillars of sustainability), saying "…creativity starts when you cut a zero from your budget. If you can cut two zeroes, it's much better" (Lerner 2007). This is not to say that engineers working on, for instance, a water supply issue need not to know about pipes and pumps, but they also need to consider how their design affects other factors such as local development, health and downstream pollution. Just as important is when design engineers consider these additional requirements. But, starting too late in the design process creates less opportunity for change

(Gervásio et al. 2014), often resulting in “greenwashing” rather than truly radical solutions needed for the future (Kapalko 2010).

The way in which engineers’ approach design problems has important theoretical implications for understanding problem solving and engineering design education. At an applied level, problem solving processes in design are vital for devising new methods for teaching engineering and sound techniques for developing solutions that meet community needs with less. Student problem-solving and design procedures should not merely assemble solutions from existing components, but instead search for appropriate solutions using all cognitive means necessary to gain a new perspective.

Design literature refers to this searching process as the ideation phase. Designers are encouraged to brainstorm as many ideas as possible, without considering if the solutions are feasible (Osborn 1993). By generating multiple solutions for later evaluation, this increases the chance for better design because the designer is less likely to fixate upon an initial solution, or ‘satisfice’ for a previous solution (Ball et al. 1998). The goal is to cross the limits of traditional design (Kembel 2009). With all the ideas on the table, only then should designers proceed to building and testing potential solutions. There are many techniques to develop creative ideation (Goldenberg et al. 1999; Jonson 2005; Knoll and Horton 2010) and also to measure the effectiveness (Shah et al. 2003). Pedagogy for enhancing ideation is essential because design for sustainability requires pushing beyond these traditional approaches.

Design is a central and critical part in engineering education to train engineers to innovative effectively to meet societal needs (Allenby 2011; Dym et al. 2005). Parallel research investigating engineering design outcomes, and behavior, changes in neural cognition could also provide useful information for design learning (Cross 2004; Newstetter and Michael McCracken

2001). Research in design cognition successfully identifies what designers do (Eastman and Computing 2001), but typically only by self-report and observation. Understanding how designers do things is incomplete or even unreliable, requiring more research and exploration to identify how cognition leads to design outcomes.

Sustainability challenges in particular set higher requirements for engineers to satisfy not only economic, but also environmental and community needs. Yet, little is known about how these additional sustainability requirements influence design thinking and how engineers react to these parameters at both behavioral and cognitive levels. To fill the gap, the cognitive load required to generate sustainable solutions for engineering design problems will be quantitatively measured. To measure cognition, a novel approach in neuroimaging is used, called functional near-infrared spectroscopy (fNIRS). In addition to measuring engineering cognition during design tasks, the purpose is to demonstrate the feasibility of fNIRS in engineering design education research, expand its application, and provide suggestions for design learning.

The paper begins with an overview of design cognition and includes a short review about the measurement tool and brain regions of interest. Then the research questions and methods are presented. These methods follow traditional cognitive neuroscience methods using a block design approach with uniform task blocks given fixed time. Statistical methods including two-sample t-test and ANOVA were used to compare behavioral and cognitive data to examine differences between participant groups.

1.2 BACKGROUND

1.2.1 Design cognition and need for cognitive neuroscience techniques

To date, many empirical studies have investigated the cognitive processes of individuals during brainstorming or ideation (Coley et al., 2007; Cross, 2001; Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Daly, Mosyjowski, & Seifert, 2014). However, a key limitation of this previous work is the subjectivity and imperfection that comes with observational studies, participant self-reporting, and critique of the design product or rendering. For example, cognition is usually not directly measured, instead only the products of an individual's thinking (e.g., actions taken, answers given to a test, artifacts created) are observed and recorded. A design student might describe in a think-aloud protocol that they easily worked through the necessary steps without frustration when they might be mistaken, misremembering, or misinforming. Such issues are a key reason that empiricists studying human behavior prioritize directly observable objective evidence over subject-reported behavior.

A novel method from neuroscience to measure cognition is introduced in this study. This builds on the growing interdisciplinary research of neuro-education, which holds promise to link cognition researchers and educators in an effort to improve learning (Ansari et al. 2012). The emergence of neuroimaging techniques to collect data on the brain holds promise to revolutionize the study of design cognition because this type of information can help construct a more detailed understanding of the processes and the network coordination between brain regions during design thinking. Understanding the regions of activation in the brain required for is necessary to assess how learning enhances the temporal response (how fast we think) and how learning reduces the cognitive load (the energy required). This physiological data is also less susceptible to errors of self-reporting.

1.2.2 Brain data collection techniques

Two common methods used to explore cognition under laboratory conditions are electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). EEG involves a head cover (cap or net) which places electrodes on the scalp and measures electrical changes in the brain. Temporal resolution (speed of detecting changes) is very good, although spatial resolution (location where the change occurs) is poor because signals often interfere with one another and make it difficult to pinpoint specific brain regions involved in the processing. EEG methods are mainly of value when stimuli are simple and the task involves basic processes (e.g., target detection) triggered by task stimuli (Eysenck and Keane 2015).

In contrast to EEG, fMRI measures activity indirectly through changes in blood flow in the brain. As a brain region is activated, the body sends more blood to that region and fMRI detects these changes by imaging the blood oxygen level-dependent contrast (BOLD) signal in a special magnetic scanner (Eysenck and Keane 2015). Because blood flow changes happen over time, the temporal resolution of fMRI is not as good as EEG (i.e. order of seconds compared to milliseconds), but the spatial resolution is very high and thus amenable to pinpointing changes within specific regions. Data collection can be uncomfortable and constraining as participants must remain still while partially enclosed inside the MRI scanner.

The limitations of EEG (spatial recognition) and fMRI (unrealistic environment) have led to development of a third option viable to study complex processes in more realistic environments, called function near-infrared spectroscopy (fNIRS). fNIRS are unique compared to fMRI because participants can operate a computer or perform a task in an upright sitting position and is unique compared to EEG because of the spatial resolution. fNIRS technology is safe, portable and noninvasive. fNIRS is worn as a cap, similar to EEG, and emit light at specific wavelengths (700-900 nm) into the scalp. The light scatters, and some is absorbed, before reflecting back to the sensor. The deoxy-hemoglobin (HbR) and Oxy-hemoglobin (HbO) absorb more light than water and tissue in the brain. The relative concentration, indicating BOLD response, is calculated from the photon path length, based on a Modified Beer-Lambert Law.

fNIRS uses the BOLD effect, similar to fMIR. Increase in blood flow produces an increase in the ratio of oxygenated hemoglobin relative to deoxygenated hemoglobin in that specific area. Figure 1.1 shows that the deoxygenated blood (blue) is inversely related to oxygenated blood (red). Both are measured with fNIRS, though typically only one is reported.

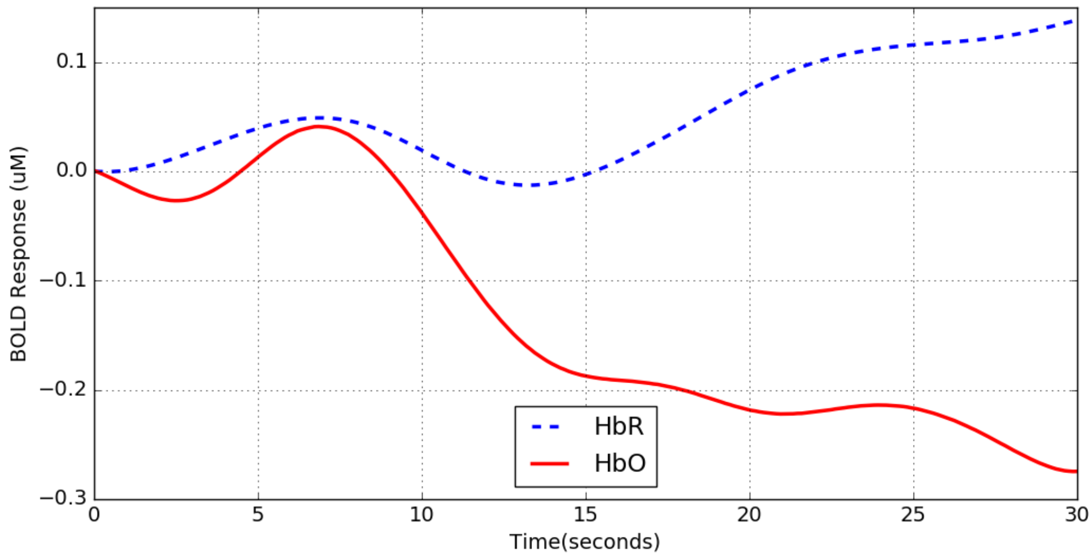

Figure 1.1: BOLD response; HbO and HbR inversely related

The drawbacks of fNIRS are its lack of high spatial resolution compared to fMRI and inability to provide information about sub-cortical brain regions. It is sufficiently effective, however, to investigate areas such as the prefrontal cortex that are associated with executive function (e.g., planning, problem solving, decision making, and design). fNIRS is thus an appropriate resource to understand design cognition in educational settings.

1.2.3 Brain regions of Interest and cognitive efficiency

The cerebral cortex (cortical regions) is the outer surface of the brain, divided into two mirrored hemispheres and four lobes. The frontal lobe is where conscious thinking seems to occur including language, attention, reasoning, decision making, planning self-regulation, learning strategies, problem solving, consciously controlled movements, and interpretation of other's behaviors. The parietal lobes receive and interpret sensory information, and are involved in attention, processing word sounds, and thinking about the spatial characteristics of objects and events. The occipital lobes are responsible for interpreting and remembering visual information and the temporal lobes interpret and remember complex auditory information and appear to be important in long-term memory. Investigating engineering design, the region of interest is the frontal lobe, more specifically the prefrontal cortex (PFC) because of its demonstrated involvement in problem solving, abstract reasoning, and decision making (Eysenck and Keane 2015; Siddiqui et al. 2008).

An indicator linking behavior and cognition is cognitive efficiency, described as the ability to achieve learning, problem solving, or instructional goals with optimal use of mental resources (Hoffman and Schraw 2009). Although there is limited consensus on the measurement of this construct, cognitive efficiency has been widely used in education and psychology fields to compare cognition and problem solving outcomes (Di Domenico et al. 2015; Hoffman 2012), and it is used in this study as a proxy to measure a ratio of effort to outcome in design.

1.3 RESEARCH QUESTIONS

By using fNIRS to quantitatively describe the change in oxygenated hemoglobin and the location of change during two different types of brainstorming tasks in freshman and senior engineering students, a more detailed understanding of the mental processes required for these types of problems is constructed. Research questions include:

Q1: Do the years of educational training in engineering influence ability to generate design concepts and does this correlate with cognitive activation in the prefrontal cortex during engineering design problems?

Q2: Does adding a sustainability-related parameter during ideation influence the number of solutions generated? Is there a significant difference in cognitive efficiency in the prefrontal cortex with and without the sustainability requirement for design solutions?

Q3: Are freshmen or senior engineering students better able to cognitively manage (measured as less cognitive activation) the sustainability parameter during the design ideation task?

The hypothesis for questions one is brainstorming tasks require both a greater diversity of brain regions to be activated as well as greater requisite intensity of activity (indexing greater cognitive load) among freshmen as opposed to seniors. Senior students with educational training in engineering will show greater ability in manage complexities than freshmen students. Greater ability to manage complexities is measured by a decrease in cognitive energy loads and more specific brain region activation (specifically the dorsolateral prefrontal cortex) as well as greater cognitive efficiency in generating solutions.

The hypothesis for questions two and three are that a sustainability related parameter during design ideation decreases the cognitive efficiency to generate solutions for both freshmen and seniors. Comparison between freshmen and seniors will reveal some pros and cons of engineering education for students to cognitively handle this parameter in design problems. Senior engineering students will show less increased activation during ideation tasks with the sustainability constraint.

The purpose of these multiple research questions is to begin to understand, and measure, how students approach design ideation and whether and how additional parameters to meet sustainability outcomes influence behavior. So broadly, are these differences measurable in cognitive processing ability? The broad hypothesis is that students with more training (i.e. seniors) are able to develop more solutions and this correlates with greater activation in the area of the brain related to creativity and abstract reasoning. In addition, sustainable solutions require more creativity not less. So, the expectation is that when students are presented this addition constraint, even greater activation occurs in the region associated with creativity and abstract reasoning.

1.4 METHODS

1.4.1 Participants

This study has been approved by the Institutional Review Board at Virginia Tech. Engineering undergraduate students (n=23) participated in the study, but due to bad signal and technical issues, three participants' data was excluded. Of the twenty individuals (average 19.5±1.64 years old, 10 females), twelve were freshman students and eight were seniors. A broad range of senior engineering students, from civil engineering, mechanical engineering, and computer engineering departments, were recruited to participate. A review of design literature did not suggest any expectation for difference in creativity, ideation, or brainstorming ability across engineering disciplines. However, this an area for potential future research and is discussed more in the conclusions. The study began by participants reviewing and signing a consent form, learning about the fNIRS machine, and participating in a brainstorming example problem in preparation for the experiment to begin.

Students were given ten engineering design problems based on Richard Smalley's list of the most pressing issues facing humanity in the next 50 years (Smalley 2003). The problems spanned topics such as renewable energy, water quality, poverty, and air pollution. Students received the engineering problems in random order. The ten problems were sub-divided into two types. Five tasks were given an additional sustainability related parameter that had to be met in their solutions. For instance, one problem asked "Prevent water body contamination in cities.

Your solutions must mimic or include processes found in nature." The other five problems did not include this requirement, for example "provide water in rural African villages." The order of problems was randomized.

Students were given 60 seconds to develop as many solutions as possible to each problem. Following each 60-second trial, students were given a 30-second rest period before the next design problem began. The timing (60 seconds then 30 seconds) was based on pilot studies to ensure neither too much or too little time for the brainstorming sessions. The purpose of the 30-second rest period is to bring the activated brain regions back to a resting state before the next task. The time frame for the resting period was chosen because this is double the length of the typical BOLD response experienced from an event onset. When collecting pilot study data students would frequently reflect on their brainstorming performance during the rest period, causing a spike in the cognitive activation in the prefrontal cortex. To correct for participants reflecting on the previous task, participants were asked to answer three arithmetic problems between each task. While these arithmetic problems do require brain activation, the region of activation is not the same. Simple arithmetic problems are often solved from memory not processing (Meiri et al. 2012; Dresler et al. 2009). In total, the experiment lasted 16.5 minutes. Figure 1.2 illustrates the block design experimental setup.

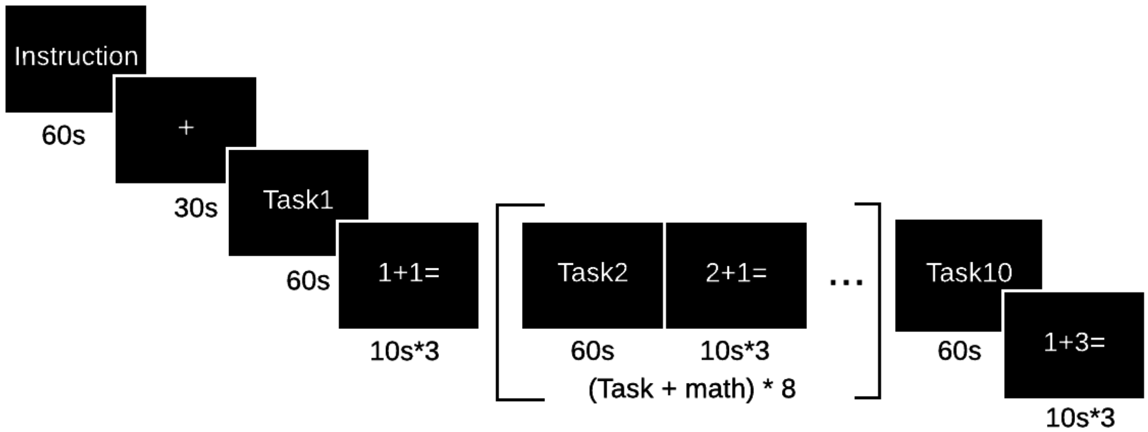

Figure 1.2: Block design in experiment

During the brainstorming tasks, students verbally called out their design solutions and a researcher tallied the number of solutions for each task. For example, a participant who suggested to reduce construction waste by integrating cut timber from the job site into the constructed building and developing a recycling program would receive two tallied solutions. Repeated answers, for example mentioning a recycling program twice for the same engineering brainstorming task was only recorded once. The degree of novelty was not included in the analysis. Experiments about brainstorming are typically based on the number or novelty of solutions generated. In this study, the number of responses was the main measurement because of its objectivity. Screening for novelty was done but future analysis could include more metrics for novelty of each solution.

1.4.2 fNIRS data acquisition

fNIRS sensors and detectors were placed along the frontal cortex to capture change in hemoglobin in the regions of interest. Figure 1.3 shows a graduate research assistant wearing the cap and the corresponding regions being measured. In total 18 channels (the connection between one sensor emitting the near-infrared light and one detector measuring the reflected light) were placed along the left and right hemisphere of the scalp, composed of four sensors and four detectors on each hemisphere.

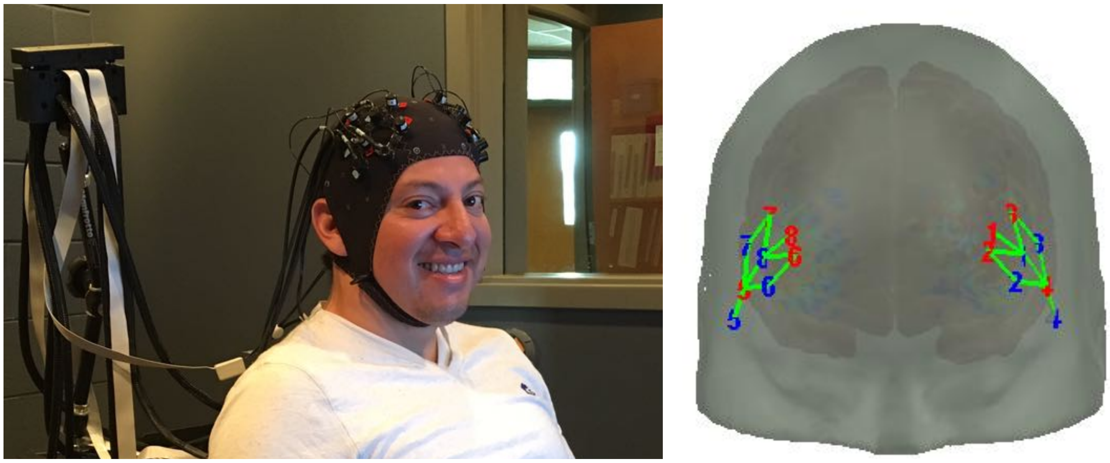

Figure 1.3: fNIRS placement along the frontal cortex

1.4.3 Statistical analyses

The data collected in the study included the behavioral data (solutions generated by the subject in tasks) and fNIRS data (BOLD response in regions of interest related to tasks). Statistical analyses were performed to test the hypotheses about the influence of education (i.e. freshmen vs senior) and sustainability requirements on engineering undergraduates.

1 .4.3.1 Behavioral data

For each participant, the number of solutions in every task was counted and the number of solutions in the group of five problems (i.e. sustainability parameter or not) for each type were averaged to obtain the average number of solutions. Two-sample t-test and ANOVA were used to compare the number of solutions by freshmen and seniors in non-sustainability parameter and sustainability parameter tasks.

1.4.3.2 fNIRS data

The raw data collected using fNIRS was processed using HomER (Huppert et al.

2009a) and filtered with a bandpass filter with a high-pass frequency of 0.03Hz and a low-pass frequency of 0.2Hz (Tak and Ye 2014; Niu et al. 2011), to remove instrument and physiological noise. The fNIRS data for the five problems without the additional sustainability parameter and the five problems with the sustainability parameter were averaged for each subject. The 30-second baseline data for each individual participant was subtracted from each channel in both parameter and non-parameter data so that the resulting process data were representative the increase in cognitive function due to the task not resting cognitive state.

Channels were averaged across different Brodmann areas (BA) in prefrontal cortex, including BA 6, BA 8, BA 9 and BA 46, split between left and right hemisphere for each participant. Change in oxy-hemoglobin (ΔHbO) was calculated by (1) the mean ΔHbO in 60 seconds, representing the average cognitive activation level; (2) the positive area under the ΔHbO Curve (AUC, area above 0) in 60 seconds, which is used as a proxy for cognitive load (AUC is justified by others to represent overall cognitive activation, for example see Karamzadeh et al. 2016; Tak and Ye 2014; Brigadoi et al. 2014) and cognitive efficiency was defined as the number of solutions divided by AUC.

1.5 RESULTS

To answer research question one, a two-sample t-test shows significantly ($p<0.05$) greater number of solutions generated by freshman (M=5.63, SD=2.14) than senior participants (M=4.10, SD=0.92) and the effect size is large with a Cohen's d of 0.93. Effect size was calculated using Cohen's d (Cohen 1992). When Cohen's d reaches 0.2, 0.5 and 0.8, the effect size can be regarded as small, medium and large, respectively (Cohen 1992). The cognitive activation during brainstorming tasks is also significantly ($p<0.05$) different between freshmen and seniors. The average BOLD response for freshmen engineering students (M=0.40, SD=0.25

micromollar, μM) is significantly greater than senior engineering students (M=0.21, SD=0.21μM), and Cohen's d is 0.82, which mean that the cognitive difference between two groups has a large effect size. To further understand where the significant difference is occurring within brain regions of interest, channels were grouped by the left and right hemispheres. The results indicate both hemispheres are significantly different ($p<0.05$) during brainstorming tasks between freshmen and senior engineering students. In the left hemisphere, the BOLD response among the average freshman (M=0.52, SD=0.24μM) is significantly ($p<0.05$) greater than seniors (M=0.18, SD=0.26μM) with a large effect size (Cohen's d = 1.36). The results are similar in the right hemisphere. The BOLD response in right hemisphere among the average freshman (M=0.27, SD=0.20μM) is approximately 1.2 times greater than seniors (M=0.23, SD=0.13μM), but the effect size is relatively small (Cohen's d = 0.24). Figure 1.4 depicts the BOLD response between freshmen and seniors in both the left and right hemisphere using HomER's image reconstruction tool (Huppert et al. 2009b).

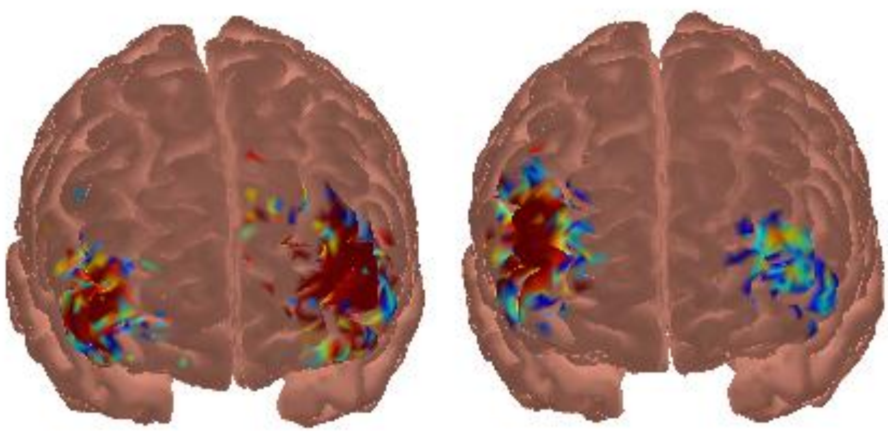

Figure 1.4: Average cognitive activation among freshmen engineering students (left) compared to seniors (right) during brainstorming task

(Higher cognitive activation is indicated by red and lower activation by blue)

Investigating further, a two-sample t-tests comparing BOLD response channel by channel suggested that all 18 channels of data were significantly different ($p<0.002$, corrected using Bonferroni) between freshman and senior engineering students. Though the average senior engineering student showed greater activation on the right hemisphere than the left and freshmen showed greater activation in the left hemisphere than the right, the results are not necessarily that straightforward.

These channels map to two known regions in the brain, defined by Brodmann's areas. These regions are the middle frontal gyrus (mFG), dorsolateral prefrontal cortex (dlPFC), and premotor cortex (PC). mFG (BA 8) is known to be involved in management of uncertainty, and executive control of behavior and planning (Burton et al., 2001; Kübler et al., 2006; Sarazin et al., 1998). dlPFC (BA 46) is known to be involved in working memory, cognitive flexibility and abstract reasoning (Bembich et al. 2014). The most significant difference between freshmen and senior engineering students occurred in the right hemisphere. Freshmen showed significantly ($p<0.05$) more activation ($M=0.26$, $SD=0.06\mu M$) in the dlPFC than senior engineering students ($M=0.10$, $SD=0.07\mu M$) with a large effect size (Cohen's $d = 2.63$). While senior engineering students ($M=0.71$, $SD=0.15\mu M$) showed significantly ($p<0.05$) more activation in the right hemisphere along mFG than freshmen ($M=0.20$, $SD=0.26\mu M$) and the effect size is large (Cohen's $d = 2.40$). The BOLD responses for both dlPFC and mFG are provided in Figures 1.5 and 1.6.

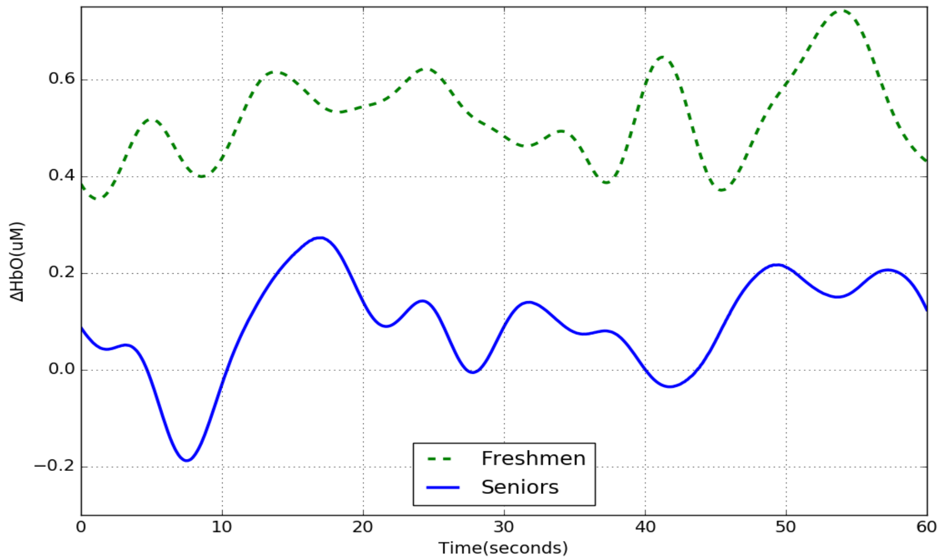

Figure 1.5: BOLD response dlPFC, right hemisphere averaged among participants during brainstorming task

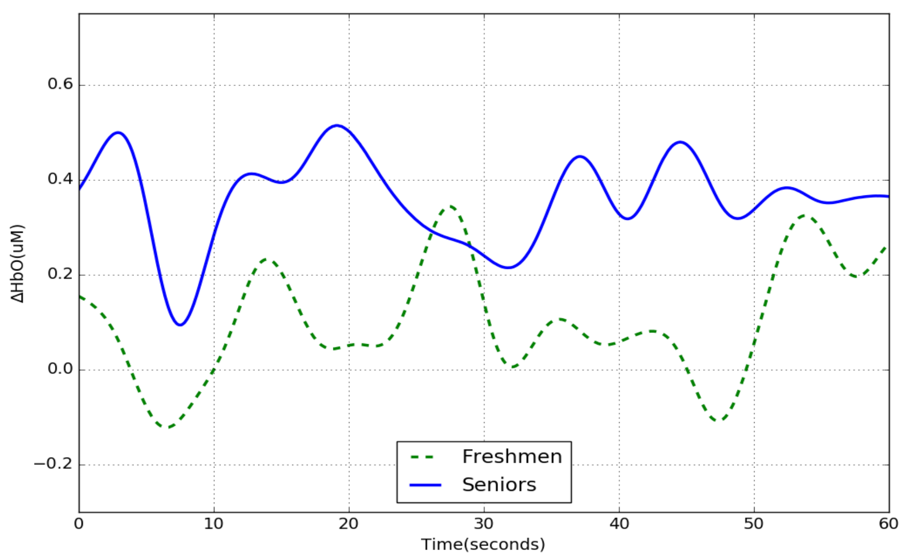

Figure 1.6: BOLD response mFG, right hemisphere averaged among participants during brainstorming tasks

The freshman engineering students sustain greater activation in the dlPFC throughout the averaged brainstorming task, as shown in Figure 1.5. While seniors show an increase in activation in the mFG early from the task beginning, shown in Figure 1.6. The BOLD response in mFG for seniors is considerably longer in length (time) compared to freshmen, indicating a longer sustained activation period. In general, the peaks above the y-axis of 0 indicate a cognitive response. The more defined Gaussian shaped curves indicate distinct times of activation. In Figure 1.5, the freshmen appear to have more distinct responses more evenly spaced along the 60 second task interval whereas the seniors' responses continue to fluctuate with less distinct Gaussian curves (i.e. BOLD responses).

Research question two asked if adding a sustainability-related parameter during ideation influenced the number of solutions generated and if there is a significant difference in cognitive efficiency with and without the sustainability requirement. As expected, sustainability-related parameters significantly ($p<0.05$) limited the number of solutions generated. Solutions decreased from non-sustainability parameters ($M=5.02$, $SD=0.98$) to sustainability parameter ($M=3.41$, $SD=1.89$) with a large effect size (Cohen's $d=1.07$). When sustainability parameters were combined with years of engineering education, the reduction of solutions generated was still significant ($F(3,16)=28.8$, $p<0.05$).

The cognitive data provides supporting results. There was a significant ($p<0.05$) difference in cognitive function among all participants when sustainability requirements were required and not required for design solutions. Hemispherical differences were observed among all participants when sustainability requirements were required and when sustainability requirements were not required. Significantly ($p<0.05$) greater activation was observed in left hemisphere when sustainability requirements were required while more activation was observed in the right hemisphere when design solutions did not require sustainability. The brain image in Figure 1.7 indicates this activation shift between sustainability parameter and non-parameter tasks. In non-sustainability related design tasks, greater activation was observed in right medial prefrontal cortex (mPFC) and right dlPFC. The right mPFC is known to be associated with working memory, recall, planning, and calculation (Babiloni et al. 2005; Dehaene et al. 1996). Right dlPFC is also known to be associated with working memory and cognitive flexibility. When sustainability was a parameter for design solutions, greater activation was observed in mFG, which is involved in the management of uncertainty.

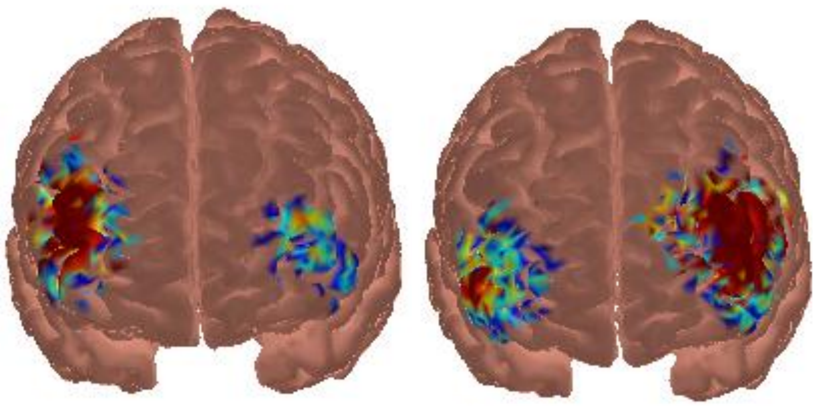

Figure 1.7: Average cognitive activation among all participants in non-parameter tasks (left) compared to parameter tasks (right)

Research question three asked whether freshmen or senior engineering students were better able to cognitively manage (i.e. measured as less cognitive activation) the sustainability requirement during the design ideation task. To answer this question, the investigation focused on left dlPFC because of its role in executive function including working memory, cognitive flexibility and abstract reasoning. Prior literature investigating decision-making and problem solving mainly focus on this region (Takano et al. 2010). The positive area under the curve (AUC) average among 10 channels located at the left dlPFC (5 channels per hemisphere) were calculated for freshmen and seniors and sub-divided into two categories, whether sustainability parameters were required for the design solution or not.

The number of solutions divided by the area under the curve (AUC) for left dlPFC was defined as the cognitive efficiency, which shows the ability to generate solutions with optimal use of cognitive energy. The cognitive efficiency of both groups (freshmen and seniors) in both tasks (without sustainability requirement and with sustainability requirement) was compared in a two-way ANOVA with repeated measure. Between subjects, seniors were significantly ($F(1,18)=14.67$, $p< 0.05$) more likely to perform with a higher cognitive efficiency than freshmen. This means, senior engineering students, while the generated fewer solutions compared to freshmen, each solution required less cognitive effort to generate. The average cognitive efficiency increased from 115.70 (SD=45.90) per solution/mM (millimolar) for freshmen to 180.48 (SD=42.34) per solution/mM for seniors with a large effect size (Cohen's d = 1.07). Within subjects, requiring solutions that meet sustainability design parameters significantly ($F(3,16)=203.8$, $p<0.05$) reduced cognitive efficiency. In other words, thinking about sustainability requires more cognitive effort, from 129.00 (SD=53.15) solution/mM when developing solutions that require consideration for sustainability to 169.18 (SD=48.45) per solution/mM when consideration for sustainability was not required. The effect size is large since Cohen's d is 0.79. Similar to the design tasks that did not require consideration for sustainability, seniors were more cognitively efficient but they also generated fewer solutions. The difference between freshmen and seniors when considering sustainability requirements is significant (($F(3,16)=37.04$, $p<0.05$) and indicates seniors appear better able to cope with the additional perceived constraints from the sustainability requirement. Another possible explanation, might be senior engineering students were satisficing (Simon 1959). Meaning, when senior engineering students generated a solution that meet the requirements and then they stopped searching for additional solutions and thus generated fewer solutions but also used less cognitive energy to do so.

1.6 DISCUSSION

Ball et al. (1998) pointed out that the more solutions generated during the ideation phase of design increase the chance of better final product. Senior engineering students generated less novel solutions than freshmen. While this is not a longitudinal study, the freshmen students are not the same senior engineering students, the results were significant, between groups. The cognitive data seems to support the design outcome results. Seniors were observed to elicit less cognitive energy in the area of the brain associated with abstract reasoning and cognitive flexibility (BA 46) but greater activation in the area of the brain associated with uncertainty and self-doubt (BA 8). When sustainability was a design consideration both freshmen and seniors were limited in the number of solutions generated. The results reveal that engineering students might not have the knowledge about sustainability to make informed design recommendations. The results also reveal that thinking about sustainability influenced the ways of thinking and this is reflected in the behavioral results. The cognitive data might suggest a cognition activation shift from right hemisphere to left hemisphere when sustainability requirements were added in the tasks. Where the activation occurred provides more insight. When sustainability requirements was not mandatory greater cognitive activation was observed in area of the brain associated with working memory, recall, planning, and calculation (Babiloni et al. 2005; Dehaene et al. 1996). and when sustainability was a parameter, greater cognitive activation was observed in the part of the brain associated with the management of uncertainty. The observed increase in cognitive activation in the area of the brain associated with uncertainty may help explain why fewer solutions were generated.

Moreover, sustainability requirements reduced cognitive efficiency, in other words, tasks with sustainability requirements require engineering students to spend more cognitive effort generating a solution. This might also be associated with the increased activation in the mFG, associated with management of uncertainty.

The results might suggest that even though students took more cognitive efforts to think about solutions, they were not able to generate solutions as many as in general design tasks without additional sustainability requirement, which might be due to their limited knowledge on sustainability. Seniors had higher cognitive efficiency, one explanation might be with more engineering training, they know better understand sustainability topics than freshmen thus leading to less uncertainty in their design solution. However, another explanation might be that seniors work to satisfice, and stop searching for additional solutions once they generate one that fits the required constraints.

1.7 CONCLUSION

The data indicate a consistent mapping between events at the neural level (greater activation) and events at the behavioral level (more solutions generated). The behavioural data, or number of concepts generated, was significantly less for seniors than for freshmen. The physiological data collected with fNIRS also indicates significant difference in cognitive activation between freshmen and senior engineering students. Freshmen have a significantly higher level of cognitive activation in the area of the brain associated with working memory, cognitive flexibility, and abstract reasoning and performed better based on the number of solutions developed. The regions of activation between freshmen and seniors most statistically different were the dorsolateral prefrontal cortex and middle frontal gyrus. Freshmen demonstrated a sustained and significantly greater activation in the right dlPFC while less in the right mFG. Right mFG is known to be invivled in management of uncertainty. To summarize, freshmen generated more solutions and demonstrated greater activation in the area of the brain associated with abstract reasoning and seniors generated fewer solutions and were observed to hold significantly higher cognitive activation in the area of the brain related to management of uncertainty. While not tested, one hypothesis for the significant difference in activation, is that seniors applied a filter or evaluation to their answer prior to verbally suggesting their solution. In fact, the shift in activation may suggest this is the case. mFG (BA8) is known to involve in management of uncertainty, thus, senior engineering students are aware of unrealistic and realistic solutions. On the other hand, this process may prevent new and novel solutions that appear outside the status quo.

A future study could ask students to narrate how they developed solutions or if they felt uncertain and second-guessed their solutions before verbally saying them out loud. And more can be done to analyze the quality of the answers students provided. The purpose of this study was for students to generate as many solutions as possible before selecting them with filters. This was explained to participants. They were told the objective was to generate as many solutions as possible. Another line of research stemming from this preliminary study is how the use of mnemonics or training related to sustainability may influence where and how engineers access information in their brain. For instance, prompting students with design heuristics may lead to more targeted ideas or refocus their solutions to options previously not considered. What is more, the seniors recruited in this study were from three distinct engineering disciplines. While there was no reason to expect one type of engineer to be more creative, or capable in brainstorming, future research could investigate the cognitive differences across engineering disciplines.

Another focus of this study was to investigate how sustainability parameters influenced engineering students along both behavioral and cognitive levels. The sustainability requirements limited the number of solutions generated by engineering students. This could be interpreted as students see sustainability as a constraint placed on the design process rather than a heuristic or aid in developing new solutions. From the cognitive level, sustainability led to the cognitive activation from right hemisphere to left hemisphere, and also decreased the cognitive efficiency for engineering students to complete the tasks. What this means is thinking about sustainability required more cognitive effort. The results appear to indicate sustainability is viewed as a barrier for engineering design rather than a heuristic to enhance design. To help students better cognitively manage sustainability, related curriculum should be designed to introduce sustainability as a tool rather than a constraint. Skills such as systems thinking and creative thinking may help facilitate more consideration for sustainability and from a different perspective. More collaboration between engineering education, engineering for sustainability, neuroscience and behavioral researchers can be done to explore how to improve students' ability to design for engineering sustainability.

Better understanding the role of certain brain regions across a range of subject groups during educational experiments like design holds promise to advance teaching and education. The purpose here is to demonstrate the potential to use fNIRS as a method for design education and as a tool to triangulate other data sources that engineering education researchers are already collecting. If design outcomes were the only data collected, the insight to the design process would be limited: freshmen engineering students generated more solutions than seniors. By also collecting physiological changes in cognitive activation the results provide a more complete understanding about why students generated fewer solutions. Students who generated more solutions were observed to have a higher increase in the area of the brain related to abstract reasoning while those who generated less were observed to have higher activation in the area associated with management of uncertainty.

Ultimately, bridging neuroscience techniques to engineering education is an area that requires the integrated understanding of both disciplines. At the same time, design education research offers opportunities to advance cognitive neuroscience more generally by addressing the data collection challenges that arise when extending methods from task-oriented problems to more cognitively complex design challenges that often lack a standardized event and take place in more real-world settings. There are numerous opportunities to advance understanding by working across these disciplines. This study demonstrates an attempt towards this goal and hopefully compels others to similarly explore complementary techniques.

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2. Journal Paper 2 - Systems versus Linear Thinking: Measuring Cognition for Engineering Sustainability

Intended Outlet for Publication:

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ABSTRACT

Sustainability is a systems problem that requires a shift in thinking from individual parts to the relationships between them. So, enabling engineers to more quickly think in systems is therefore vital to advance sustainable systems in the future. Until recently, measuring cognition (i.e. thinking, planning, and decision making) for sustainability was limited to studying behavior and outcomes (e.g., actions taken, answers given, artifacts created). However, the emergence of techniques to collect data on the brain have revolutionized the study of cognition because they enable the collection of objective measurable physiological data. By measuring the change of cognitive activation in the brain during systems and linear thinking tasks related to sustainability, a more detailed understanding of the mental processes is constructed. Using functional near-infrared spectroscopy, which measures changes in hemodynamic response in the brain, engineering students (n=28) developed both concept lists and concept maps related to sustainability topics (about energy, food, climate and water). The results show that concept mapping leads to more number of concepts generated about sustainability and requires more cognitive activation in brain regions associated with executive functions and cognitive flexibility while less activation in areas associated with sequence and visuospatial processing. Using graph theory, the brain network analysis of participants indicates that concept mapping helps engineering students reduce their brain network density and complexity. This means engineering students use more localized regions of their brain (associated with cognitive flexibility) when performing concept mapping tasks compared to when listing concepts (greater observed activation associated with sequence and visuospatial processing). A possible explanation is the concept mapping technique reduced the amount of information participants had to cognitively manage. The results also indicate that self-assessment of systems thinking ability might not be sufficient and accurate. Self-assessment scores were negatively correlated with concept map scores. This study is the first step in constructing a better model of the mental processes and brain networks of systems thinking for sustainability. This study demonstrates not only the added advantages of adopting neuroimaging technologies like fNIRS to study cognition for sustainability but how other tools like self-assessment are not sufficient. More research should be done about how to cognitively improve systems thinking ability among engineering students and the best tools for measuring its effectiveness on learning.

Key Words: Systems thinking, sustainability, functional near-infrared spectroscopy, concept map, engineering education, brain network, graph theory

2.1 INTRODUCTION

Sustainability is a complex systems problem with interconnected environmental, social, and economic inputs and outputs. The dynamic relationship between these systems components can act as a barrier to better decisions for sustainability if decision makers work to reduce rather than understand these complexities. A reductionist approach is, in part, a coping mechanism for bounded rationality (Gurnani and Lewis 2008; Kahneman 2003; Maani and Maharaj 2004) and, in part, due to educational training (Greer 2010). Engineers, in particular, are trained to use both tools and processes to extended their limits of rationality. However, this training may in fact further reinforce reductionism through over reliance on linear thinking models, moving from one step to another (Greer 2010). This sequential linear thinking approach, or analytical thinking, emphasizes the components in a systems problem rather than the relationships between components (Meadows 2008).

Numerous reports, academies, and foundations recognize the need for more trained engineers extending beyond the traditional linear thinking to systems thinking as an approach to meet 21st century grand challenges (Lezak and Thibodeau 2016; Groves and Vance 2015; Tejeda and Ferreira 2014; Davidson and Venning 2011; Hayden et al. 2010; Maani and Maharaj 2004). For example, engineers are expected to provide better solutions to make clean water more accessible and grow food sustainably in changing environments. To help engineering students develop an approach to conceptualize systems thinking and differentiate it from traditional linear thinking like a linear list, concept mapping, which is a diagram to organize and represent knowledge related to a system, is used by many institutions (Watson et al. 2016a; b). Yet, there is limited research explaining how students develop the needed ability to think in systems. The mental process and how different brain regions coordinate during systems thinking remain unknown and majority of psychology researchers who study systems thinking do so through self-assessment or measure of behavior change. For example, the self-report survey Systems Thinking Scale Revised (STSR) developed by Davis and Stroink (2016) is meant to provide a particpant self assessment of their ability to think in systems. No previous studies about systems thinking, or concept mapping, measure physical changes in cognitive activity. Nor do previous studies investigate cognition of systems thinking as it relates to sustainable engineering.

To fill the gap, building on previous studies that measure behavior changes through observation and self-assessment, this study measures cognition of systems thinking, in the form of concept mapping, using methods adopted from cognitive neuroscience. The purpose is to provide a deeper understanding of the cognitive underpinning that make this type of thinking distinct from linear schools of thought. Better understanding the mental process and cognitive barriers of systems thinking compared to linear thinking can help provide insight into the improvement of education on systems thinking and, in turn, better achieve sustainability goals in the future. This interdisciplinary research combines sustainability science, engineering education and cognitive neuroscience. The outcome also contributes to the evolving field of neuro-education, linking education with neuroscience in an effort to improve learning (Ansari et al. 2012). Further, this research helps demonstrate the feasibility of fNIRS, a neuroimaging technique, applied to engineering sustainability research. Eventually this type of research can help engineers make better decisions using a system thinking approach to tackle grand challenges that affect sustainability outcomes.

This paper begins with the literature review including background in four parts: sustainability, systems thinking, fNIRS and graph theory of brain networks. Then the research questions and methods are presented. The experiment was a combined block and event-related design, in which participants finished tasks in four blocks with different time length. The data analysis section includes paired t-tests, two-sample t-test and Pearson correlation coefficient to compare behavioral data (the concepts lists and maps) and cognitive data (the change of HbO). Correlation matrix and graph theory are also used to analyze brain network in concept generation tasks. The results demonstrate the cognitive differences between systems thinking and linear thinking, and then the discussion and conclusion sections offer suggestions for future research.

2.2 LITERATURE REVIEW

2.2.1 Sustainability

Over the past half century, sustainability has evolved into an interdisciplinary, complex, and dynamic science. Still, the most broad definition of sustainability includes an essentially integration of social, economic and ecological development (Adams 2006; Gibson 2006; Kates et al. 2005). Accordingly, thinking and decision making for sustainability problems require approaching the problem by holistically addressing all three (Dovers, 2005; Scrase & Sheate, 2002; Eggenberger & Partidário 2000). Non-sustainable, or less sustainable, design occurs when decision makers neglect to consider the relationship between these factors (Gibson 2006). Research about sustainability provides various solutions to the problem as different sustainability attributes including not merely the awareness and integration of factors, but also the holistic systems thinking approach to identify the interdependence and dynamic connection among these components. Education for sustainability also emphasizes the importance of these attributes. For example, the University of British Columbia (UBC) integrates sustainability throughout the curriculum, in which systems thinking is the critical first concept, followed by sustainability knowledge, acting for positive change, and awareness and integration (Sterling et al. 2013).

Applying sustainability is partly the responsibility of engineers. Although engineering practice for sustainability often works to reduce complexity by creating linear lists and processes. For example, rating systems like Leadership in Energy and Environmental Design (LEED) guides engineers to think about individual parts using a checklist of options (Azhar et al. 2011). LEED draws criticism for over simplifying, even neglecting, the potential emergent benefits of a more holistic approach for design. In the first decade of LEED, a building designed to include an efficient HVAC system would rank higher than a building designed to not need a HVAC system at all. In contrast, life cycle assessment (LCA) uses a system perspective to analyze materials using environmental sustainability metrics (Pehnt 2006) and include these results within the sustainable design process (Glass et al. 2013). With tools that reduce system complexity into a linear list and tools that help expand them, education for system thinking can help ensure those using these tolls recognize the limiting factors and rational behind them.

2.2.2 Systems Thinking

Systems thinking can help facilitate decision making in engineering (Bahill and Gissing 1998; Hayden et al. 2010), medicine (Leischow and Milstein 2006), education (Martin et al. 2005), and urban planning (Stave, 2002), among others (Lezak and Thibodeau 2016; Groves and Vance 2015; Tejeda and Ferreira 2014; Davidson and Venning 2011; Maani and Maharaj 2004). Although there are many definitions on what systems thinking actually refers to (Arnold and Wade 2015; Buckle Henning and Chen 2012), a key feature across disciplines is that systems thinking emphasizes on holism, comprehensive concepts and their interconnections. The next subsections provide a brief overview about systems thinking from two divergent points of view, sustainability and cognitive psychology.

2.2.2.1 Systems thinking for sustainability problems

Systems thinking for sustainability is broadly the study of relationships, patterns, and feedback loops (Meadows, Meadows, & Randers, 1992). Understanding the pattern in one natural or social system helps to understand other systems that manifest the same pattern (Davidson & Venning, 2011). Much of the existing research on systems thinking provides an applied analysis on fields such as corporations (Bayer 2004), management (Martin et al. 2005; Mingers and White 2010; Porter 2008), climate (Füssel and Klein, 2006), and ecosystems (Tejeda and Ferreira, 2014). A fraction of research goes further providing insight into the leverage points for change. For example, seminal work by Forrester (1969) using a systems model identified leverage points for growth in the city. Forrester discovered that improving an urban area through financial assistance may actually hurt a city's long-term health. Financial aid, job training, other job programs, along with low income housing were ineffective because they lead to other problems such as overpopulation and greater tax demands on the underemployed.

Education for sustainability should therefore strive to more closely represent the complexity of the real world. In doing so, teaching systems thinking can help decision makers find new leverage points for change (NAE 2005). Indeed, many traditional institutions, unwittingly or not, train students as specialists without the broad view of the systems in which they will work. To this end, to help develop an approach to conceptualize systems thinking is concept maps (Brandstädter et al. 2012). Concept mapping is a type of graphic organizer to help students organize and represent knowledge of a subject. Concept maps begin with a main idea and then branch out to show how that main idea can be broken down into specific topics and drawing connections between concepts at various hierarchical levels within the map. More recently, concept mapping was suggested as an adequate tool for assessing students' systems thinking (Brandstädter et al. 2012), and standard scoring exists to grade systems thinking through concept mapping (Watson and Barrella, 2016)

2.2.2.2 The cognitive psychology of systems thinking

Systems thinking is widely applied yet little is known about its psychological underpinnings. In order to promote the development of experimental research in systems thinking, previous research (e.g. Doyle, 1997) calls for collaboration between cognitive psychologists and others interested in dynamic systems such as mental modes, decision process and human-brain interaction. However, in the 20 years since this initial call, limited number of studies have investigated systems thinking through a cognitive psychology lens (Lezak and Thibodeau 2016).

Among these limited studies most evaluations of systems thinking only assess cognitive change by self-report or asking participants about their experience and describe how their systems thinking is influenced during an experimental task. For example, Choi et al. (2007)

constructed a 24-item scale called Analysis-Holism Scale (AHS) to measure the tendency of analytical or system thinking. Davis and Stroink (2016) constructed a 15-item self-report survey named Systems Thinking Scale Revised (STSR) to measure an individual's capacity to perceive the social-ecological world as an assemblage of interconnected complex systems. STSR was validated using psychometric properties with Cronbach α of 0.78, which shows its internal consistency (Davis and Stroink 2016; Thibodeau et al. 2016). Unfortunately, as Doyle (1997) pointed out, self-evaluation of cognitive change during systems thinking is necessary but not sufficient to measure cognition. Including more advanced cognitive psychology methods into systems thinking research can help eliminate the possible inaccuracy within self-report and self-evaluation of systems thinking and construct a better understanding of its cognition quantitatively. As Thibodeau et al. (2016) mentioned, the relationship between systems thinking and existing psychological constructs should be explored in effort to better understand the psychological underpinnings of systems thinking.

2.2.3 Technology to measure cognition

The most commonly used instruments to quantitatively measure cognition through imaging are functional Near-infrared Spectroscopy (fNIRS), functional Magnetic Resonance Imaging (fMRI) and electroencephalogram (EEG). fNIRS provides better temporal response than fMRI and better spatial resolution than EEG (Lloyd-Fox et al. 2010). fNIRS is also portable, which enables use in more natural settings. fNIRS can be worn as a cap and measures changes in the relative ratio of oxygenated and deoxygenated hemoglobin (HbO and HbR), which is known to be associated with cognitive activities. The sources of light in fNIRS cap emit specific wavelengths (700-900 nm) into the cortex. The light scatters, and some is absorbed, before reflecting back to the detector in the cap. The hemoglobin and Oxy-hemoglobin absorb more light than water and tissue in the brain and so the change in density, or Blood Oxygenation Level Dependent (BOLD) response in the regions of interest (ROIs) can be recorded by fNIRS machine and indicates activated brain regions and quantitatively measures cognition.

Based on the fact that cognitive activities will bring more blood flow to related brain regions (Ferrari and Quaresima 2012), fNIRS can capture change of oxy-hemoglobin and deoxy-hemoglobin in blood to describe cognitive activation. Each channel formed by the combination of a source and a detector in cap records the hemodynamic response in corresponding brain regions where the channel is located. Figure 2.1 depicts the Blood Oxygenation Level Dependent (BOLD) response measured by fNIRS, in which HbO represents oxy-hemoglobin, HbR represents deoxy-hemoglobin and HbT is the total hemoglobin. Typically, only one parameter is reported since usually HbO and HbR are inversely related. The mean value of HbO change representing the average cognitive activation level and positive area under the curve of HbO (the areas above 0) representing the cognitive load (or energy) in a specific brain region are metrics used in data analysis.

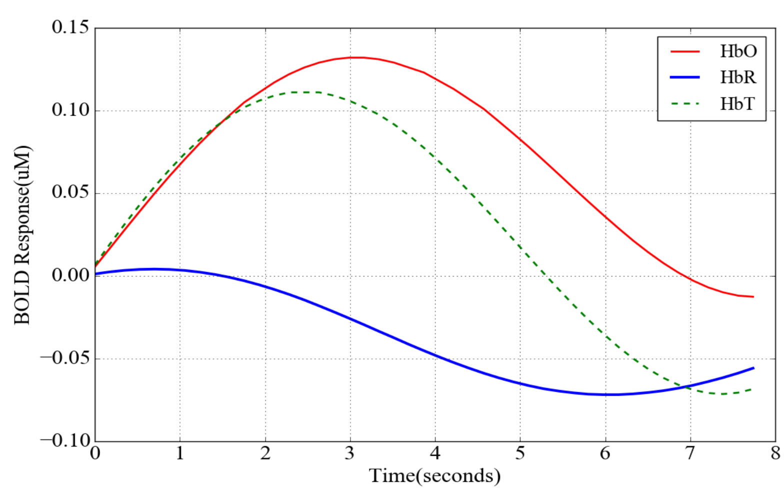


Figure 2.1: BOLD response; HbO, HbR and HbT

As a noninvasive neuroimaging technology that allows for the study of human cognition in more natural environments (Irani et al. 2007), fNIRS are used for a wide range of experimental tasks related to thinking, decision-making, problem-solving and human-brain interface. Several studies investigate the oxy-hemoglobin change in brain during arithmetic tasks within adults or school children (Dresler et al. 2009). Geometry tasks have also been study to learn about the planning and visuospatial reasoning in prefrontal-parietal networks of students (Ayaz et al. 2012). In addition, tasks about decision-making including financial decision-making (Holper et al. 2014), risky decision-making (Li et al. 2016) and moral decision making (Strait et al. 2013).

A key point in fNIRS experimental design is choosing brain regions of interest to set the sources and detectors. As Figure 2.2 shows, each hemisphere in human brain cortex includes four lobes: frontal, temporal, parietal and occipital, each associated with different brain activities. Among these cortices, a subset is called Higher Order Association Cortex (HOAC), which combine physical information (auditory, visionary, touch, etc.) into complex thoughts and reasoning (Purves et al. 2001). In HOAC areas, the Prefrontal Cortex (PFC) involve many brain activities including reasoning, problem solving and decision making (Koechlin et al. 2003; Miller and Cohen 2001; Fuster 1991), and the Posterior Parietal Cortex (PPC) usually involve visuospatial reasoning (Constantinidis et al. 2013; Klingberg et al. 2002; Quintana and Fuster 1999). When thinking about sustainability, pertinent HOAC areas are likely activated when accessing memories, reasoning and visuospatial processing to organize concepts, sequences and relationships.

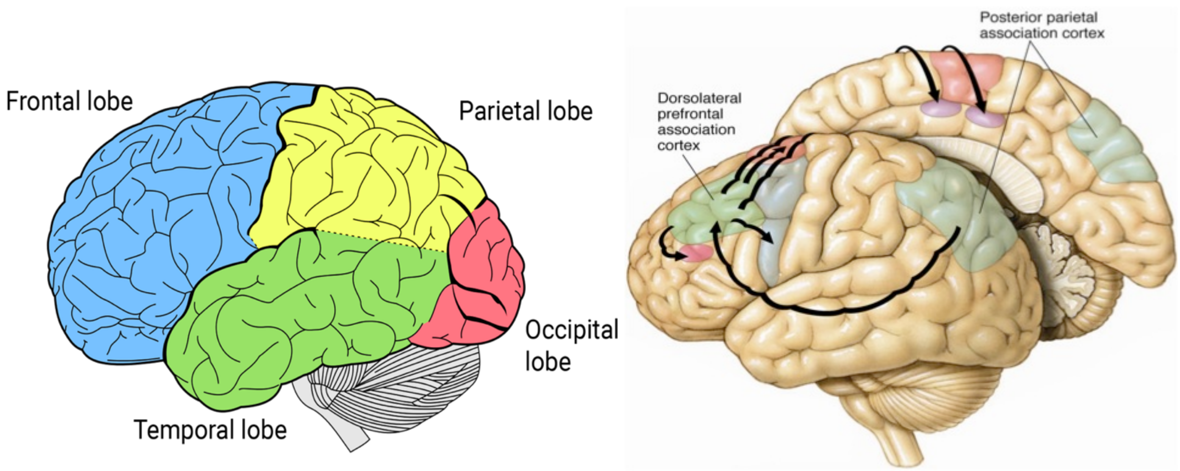


Figure 2.2: Four lobes ("Cerebral cortex" 2017)(left),

PFC and PPC (Claffey 2012) (right) in human brain

In most studies investigating problem solving and decision making with fNIRS, the region of interest is usually the prefrontal cortex (PFC), which is demonstrated to involve executive functions including abstract reasoning and working memory (Koechlin et al. 2003; Miller and Cohen 2001; Fuster 1991). Other previous fMRI studies (Schneider et al. 2012) found the posterior parietal cortex (PPC) is another region besides PFC that increase in activation during working memory tasks, especially tasks related to visuospatial and sequence processing (Constantinidis et al. 2013; Klingberg et al. 2002; Quintana and Fuster 1999). Further studies also demonstrate the function of perception to action of frontal-parietal network during mathematical or other tasks related to visuospatial reasoning (Olesen et al. 2004; Paulus et al. 2001; Quintana and Fuster 1999; Ragni et al. 2016). For example, Ayaz et al (2012) investigated the network between PFC and PPC in planning and visuospatial reasoning process when subjects solve geometry problems. Similarly, PFC and PPC were regions of interest in this study to measure concept generation for sustainability.

2.2.4 Graph theory

Graph theory is the study of graph in the form of mathematic structure describing connectivity (edge) among a set of nodes (vertices) as Figure 2.3 shows. Graph theory is wildly applied in physics, chemistry, biology and also social science to describe social networks (Foulds 2012). There are some metrics in graph theory to quantitatively describe a network such as node degree (*k*), which is the number of connections that link the node to the rest of the graph;

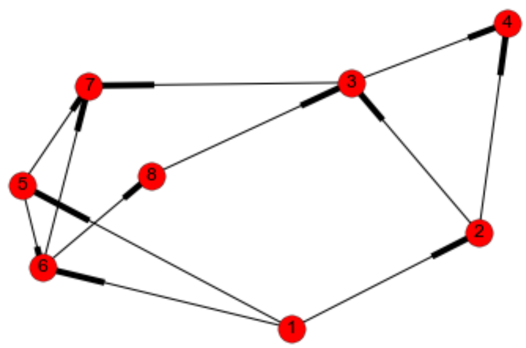


Figure 2.3: A drawing of graph containing nodes and edges

In neuroscience research, graph theory provides an approach to quantitatively analyze the structural and functional network in the human brain (Bullmore and Sporns 2009). With the quick development of neuroimaging technologies, the quantitative brain data acquired from these technologies, including fMRI (Martijn P. and Hilleke E. 2010), EEG (Demuru et al. 2013) and fNIRS (Niu et al. 2013), provide powerful new ways of complex network analysis in humans. For example, Betzel et al. (2014) studied how functional connectivity within and between resting-state networks changed with age; Ingalhalikar et al. (2014) compared the within and between hemisphere connectivity between females and males to detect gender difference in brain connectivity during language and spatial tasks.

With good spatial and temporal resolution, fNIRS has advantages to investigate brain networks. The channels located at specific brain regions can be regarded as nodes, the functional connectivity (edges) between pairs of channels can be estimated by threshold correlation between synchronized activation captured by related channels. More details about how network analysis was applied in this study is provided in the methods section.

Brain networks features were analyzed using known methods from graph theory. More specifically, network density (D) and clustering coefficient (C), two measures to describe network coordination among different brain regions were calculated using the collected cognitive data during concept generation tasks. Network density is the proportion of number of actual connections (edges) to the number of possible connections in a network. Clustering coefficient is the proportion of number of triangles formed by every three edges in a network to the possible number of triangles and representing the degree of a network in which its nodes cluster together. For example, Betzel et al. (2014) demonstrated that brain network density might decrease with age and Ingalhalikar et al. (2014) found higher clustered brain in male participants than female participants during spatial tasks.

These were applied in this study because brain network density measures the cognitive cost or resource requirement of the network (Bullmore and Sporns 2009). Thus, providing a proxy for cognitive effort required to complete the task. A low network density means low cognitive resource. Clustering coefficient can represent the complexity of brain network (Arnsten et al. 2010). Meaning, the number of connections and interaction between connections. Together, these two approaches begin to provide insight about how the brain regions coordinate together to perform and complete the concept generation tasks.

Network density (D) and clustering coefficient (E) are mathematical defined in the following equations:

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

$$C = \frac{1}{N}\sum_i \frac{1}{N}\frac{\sum_{k,j} a_{kj}a_{ki}a_{ji}}{k_i(k_i-1)} \quad (2);$$

where N is the number of nodes in the network and 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.

In summary, this research combines sustainability, systems thinking and cognitive measurement using fNIRS. Better understanding the pattern of cognitive activation required for systems thinking can begin to provide suggestions for engineering education, specifically systems thinking for sustainability. The research questions this interdisciplinary research attempt to answer are listed in the following section.

2.3 RESEARCH QUESTIONS

By measuring the cognitive activities in engineering students during concept generation using linear thinking (participants write a list of concepts) and systems thinking (participants draw a concept map) related to sustainability topics, the authors can construct a better understanding of the behavioral and mental processes that contribute to more sustainable thinking. More specifically, the research questions are:

(1) Does systems thinking lead to more concepts related to sustainability and does this correlate with an increase in cognitive activation compared to linear thinking?

(2) Is there correlation between the self-evaluation scores of systems thinking ability, the concept map scores, and BOLD response in brain regions of interest?

(3) Is there a measurable difference in brain network between linear and systems thinking tasks?

For Question 1, since increasing the number of concepts generated can improve the quality of solutions to the design problem (Yang 2009) and systems thinking requires comprehensive thinking across disciplines including social, economic and environmental aspect (Watson et al. 2016a, 2016b), the expected outcome is that concept mapping as a tool for systems thinking will facilitate concept generation and lead to more concepts. This is measured by the number of concepts generated by students in concepts maps and lists. Correspondingly, the expectation is concept mapping will require higher level of cognitive activation.

In this study only the number of solutions generated was compared not the novelty or quality. This was intentional because formalized approaches to brainstorming and ideation is a two-step process. Step one is generate as many concepts as possible and then select among concepts with filters to determine which is appropriate (Devanathan et al. 2010; Liu et al. 2003). The first step, to generate as many concepts as possible is critical to increasing the number of possible solutions. Collectively the higher number of concepts leads to improve the quality of future solutions (Yang 2009). For this reason, this study focus on the first step to generate concepts.

For question 2, the System Thinking Scale Revised survey (STSR) (Davis and Stroink 2016) was used to measure participant's self-evaluation of systems thinking ability, and the traditional concept map scores (CMS) (Novak and Gowin 1984) to grade their concept maps. We expected to find positive correlation between CMS and STSR and also between CMS and BOLD response. For question 3, the expected outcome was to find different brain networks during two types of thinking tasks for sustainability either through generating lists of concepts and concept maps. The following section provides an outline of the methods to answer each research question.

2.4 METHODS

2.4.1 Experiment process

Engineering undergraduates (n=28, age 19.54±1.52 years) from Virginia Tech participated in the study. Before the experiment, the participants finished the online STSR survey without knowing the background of the study in order to avoid biases. In the experiment, before concept generation tasks began, while wearing the fNIRS cap participants completed 60-second word tracing activities of letters 'ABCD' to control for activation as a result of writing and drawing. During data processing, the cognitive baseline data observed during the word tracing activity was subtracted from the concept generation tasks. Participants then completed four concept generation tasks related to sustainability. The topics came from the list of 14 grand challenges for engineering in 21st century (Atkins 2008), including renewable energy, food sustainability, water availability and climate change. Two of the four tasks asked participants to write a list of concepts on paper. Another two of the four tasks asked participants to draw a concept map on paper. The sequence to draw a concept map or develop a list of the four topics was randomly chosen using Psychopy, a software commonly used in psychology experiments (Peirce 2007). Students were given 6 minutes to create a list per task and 10 minutes to draw a concept map. The time limit was based on a pilot study in which three engineering undergraduates finished a list in average 5.1 minutes and a map in 8.6 minutes. Between tasks, participants were given 30 seconds to rest. The experiment process is shown in Figure 2.4.

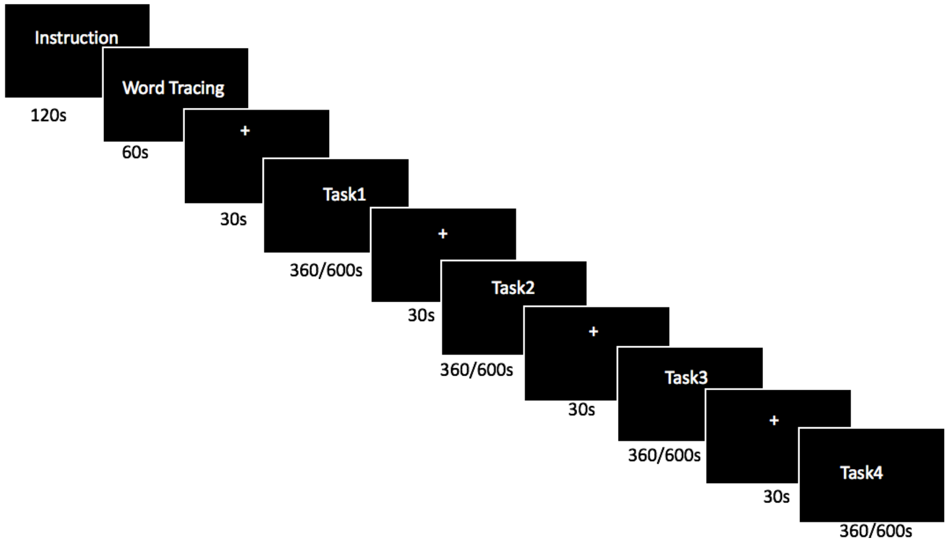


Figure 2.4: Experimental Block Design

2.4.2 fNIRS data acquisition

The NIRx fNIRS machine was used to collect cortical activation. The sensor configuration is shown in Figure 2.5. There were 26 channels recording the change of HbO (ΔHbO) in corresponding regions of the brain including PFC and PPC. More specifically, these cerebral cortices could be divided into several Brodmann areas (BA) defined by its cytoarchitecture. These channels covered BA7, BA8, BA9, BA11, BA39 and BA46. Each of these areas is associated with cognitive functions, for example, BA46 (a part of dorsolateral prefrontal cortex, or dlPFC) is an important region of interest in many fNIRS studies about cognition because of its association with executive function in working memory, abstract reasoning, decision making and problem-solving (Bembich et al. 2014; Trinh et al. 2013).

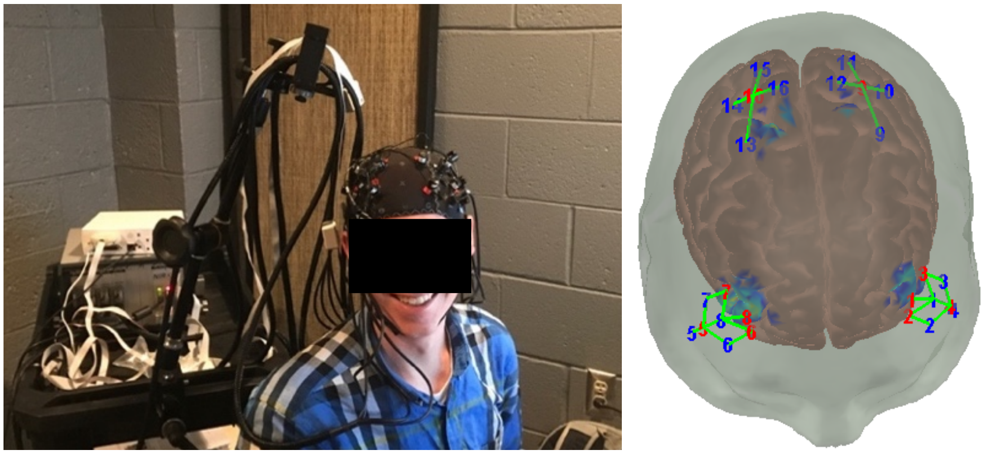


Figure 2.5: Placement of fNIRS sensors along PFC and PPC

2.4.3 Data analyses

2.4.3.1 Behavioral data analysis

The behavioral data, including the STSR survey and concept generation in lists and maps, were collected in the experiment. STSR survey contains 15 items stating the relationship in social-ecology-economic systems and participants have 7-level choice from strongly agree to strongly disagree for each item. Based on the choice of participants, a mean score for all the items ranging from 1-7 was calculated to represent their self-evaluation of systems thinking ability. The concept map scores (CMS) were graded using the traditional concept map scoring method by counting the number of concepts (NC), the highest hierarchy (HH) and the number of cross links (NCL) in the map, and using the equation CMS = NC + 5*HH + 10*NCL.

Increasing the number of concepts generated in first step helps to improve the quality of solutions to the design problem (Yang 2009). Hence the number of concepts in the lists and maps was counted for comparison. The Pearson correlation coefficient was used to describe the correlation between CMS and STSR among all participants.

2.4.3.2 fNIRS data analysis

Raw data from fNIRS were filtered using a bandpass filter with a high-pass corner frequency of 0.01Hz and a low-pass corner frequency of 0.1 Hz (Trinh et al. 2013) to remove high-frequency instrument noise and low-frequency physiological noise. The block average of ΔHbO in two list tasks were averaged together for each channel and similarly, the two concept map task blocks were averaged together. The baseline data from word tracing was subtracted from the tasks data for each participant in each channel. To compare the cognitive activation, paired t-tests were conducted to analyze ΔHbO difference by channels and by Brodmann areas during concept mapping and listing. The Pearson correlation coefficient was also used to detect the relationships between CMS and cognitive activation in specific regions among all participants.

To compare brain network between concept mapping and concept listing, the network topology and metrics were created following the steps illustrated in Figure 2.6. The first step was to develop a correlation matrix for ΔHbO in 26 channels for each participant. Then a threshold was applied to transfer the data into a binary matrix (also called adjacency matrix in graph theory). When the correlation coefficient (CC) was greater than the threshold, data was set as a 1, below the threshold was set as a 0. Three threshold coefficients were used (0.7, 0.75, 0.8). These threshold coefficients are based on previous research (Worsley et al. 2005). From the binary matrix, links were drawn between channels where CC was 1 to get the topology of brain network. There were 26 nodes representing 26 channels and links between nodes representing connectivity between channels in the network topology in this study. According to this topology, the network metrics including density (D) and clustering coefficient (C) could be determined based on the equations in the background section.

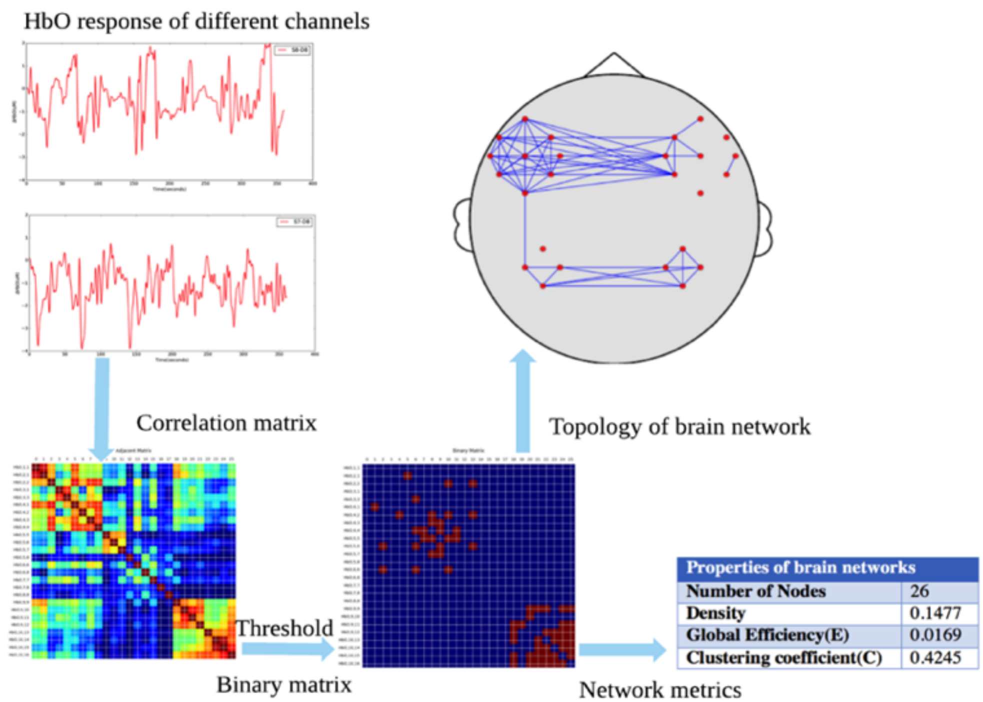


Figure 2.6: Brain networks and metrics

In brain network research, density measures the cognitive cost or resource requirements of a network (Bullmore and Sporns 2009), and clustering coefficient as the complexity of the network (Barzegaran et al. 2012; Niu et al. 2011; Arnsten et al. 2010). With these two, the energy requirement and complexity of brain network during concept mapping and listing for sustainability were compared with paired t-tests among all participants.

2.5 RESULTS

The behavioral and cognitive data provide insight into the differences between concept generation using concept maps and more general linear lists. The results are divided into 4 sub-sections to show the results of research questions including the number of concepts in maps and lists, the cognitive activation during the task, the correlation among CMS, STSR and cognitive activations, and the brain networks during different concept generation tasks. The significance level in this study is 0.05.

2.5.1 The number of concepts, concept map scores and Systems thinking Scale Revised

The number of concepts generated by participants were averaged for the concept map tasks and listing tasks. The numbers of concepts generated by participants were normally distributed. A paired t-test among all participants showed that engineering students generated significantly ($p=0.006$) more concepts in concept maps ($M=22.88$, $SD=6.53$) than linear lists ($M=19.21$, $SD=5.42$), and the increase has a medium effect size (Cohen's $d = 0.61$. A follow-up contrast was investigated comparing the number of concepts generated in maps again that in lists, and the result that $F (1, 54) =5.20$, p-value=0.027 also indicated that significant difference and average 3.66 more concepts were generated in maps than lists ($SE=1.60$). One possible reason why more concepts were generated during the concept mapping tasks is the hierarchical structure that concept mapping provides might enable participants to more quickly recognize interconnections between different components related to sustainability with wider and deeper knowledge.

Using the traditional concept map scoring method, all concept maps were graded and the average score is $M=67.59$, $SD=12.26$. The mean score of the 15 items from STSR survey for each participant was also calculated (for one participant it was the mean of 14 items because of a missing item in the response), and the average score of all participants is $M=5.28$, $SD=0.45$, which is close to the score $M=5.30$, $SD=0.69$ in previous study (Davis and Stroink 2016).

2.5.2 Cognitive activation during concept generation tasks

In two types of concept generation tasks, different cognitive activations were found in different brain regions specified by Brodmann areas including BA 7, BA 39, BA 9 and BA 46. In both tasks, ΔHbO in ten channels located between BA9 and BA46 were averaged as cognitive activation in BA 9 and BA 46 and four channels located between BA7 and BA39 were averaged as cognitive activation in BA 7 and BA 39 respectively. BA7 and BA39 are located along the parietal cortex, which is known to be involved in sequence and visuospatial processing (Crozier et al. 1999; Köhler et al. 1995). BA9 and BA 46 (also called dorsolateral prefrontal cortex), part of the prefrontal cortex, are known to be involved in executive functions, cognitive flexibility and abstract reasoning (Bembich et al. 2014).

The mean value of ΔHbO, which describes the average cognitive activation level during the whole task, were analyzed using a paired t-test between concept listing and concept mapping tasks. HbO mean values of all participants met the normal distributed assumption. Table 2.1 indicates the significant difference between tasks in different brain regions. The mean HbO of every 30 seconds in these regions during concept generation tasks were calculated and plotted in Figures 2.7 and 2.8. More activation in BA 7 and BA 39 when concept listing and more activation in BA 9 and BA 46 when concept mapping is clearly shown in two Figures. BA 7/39 means average of channels located between BA 7 and BA 39 and BA 9/46 means average of channels located between BA 9 and BA 46 in the following figures, tables and paragraphs.

Tasks **ΔHbO Metrics**	**Concept mapping**	**Concept listing**	**P-value (p* <0.05) (paired t-test, n=28)**
Mean Value(μM) in BA 9/46	0.313	-0.171	0.008*
Mean Value(μM) in BA 7/39	-0.473	-0.121	0.049*

Table 2.1 ΔHbO mean value during concept generation tasks

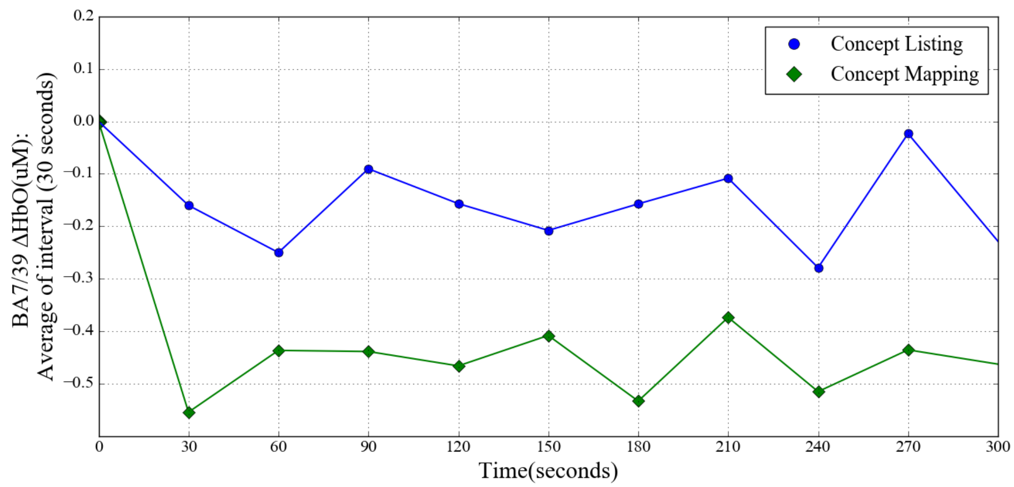


Figure 2.7: ΔHbO in BA 7 and BA 39 in concept generation tasks (participants average)

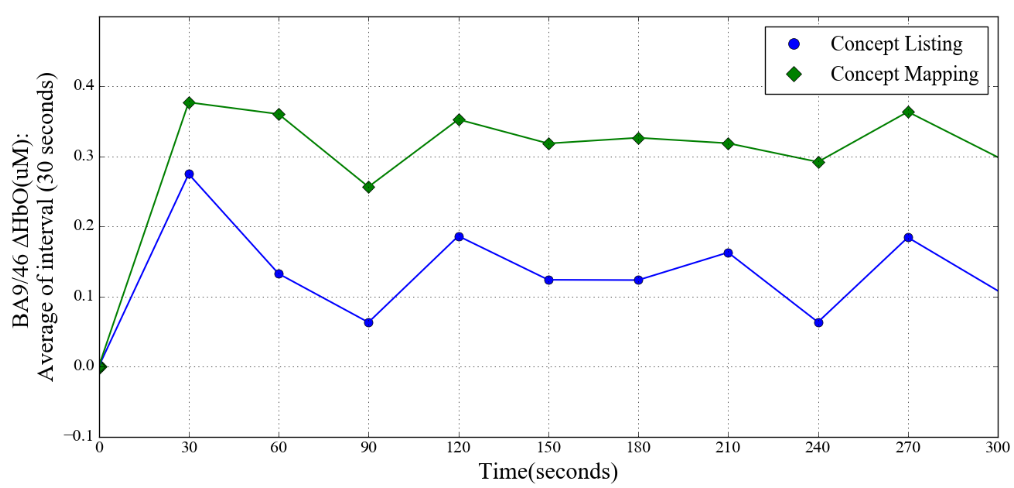


Figure 2.8: ΔHbO in BA 9 and BA 46 in concept generation tasks (participants average)

The positive area under the curve (AUC) for HbO in BA 9/46 can represent the cognitive energy consumed during concept generation tasks. The mean of HbO in BA 9/46 was also compared with a paired t-test. The activation of BA 9/46 was analyzed because of its executive functions. Table 2.2 shows that significantly ($p<0.05$) more cognitive activation in BA 9/46 were required in concept mapping tasks compared to listing tasks. This means during concept mapping tasks participants were observed to increase cognitive activity to complete the tasks in the area of the brain associated with cognitive flexibility and abstract reasoning.

Tasks Metrics	Concept mapping	Concept listing	P-value (p* <0.05, p**<0.01) (paired t-test, n=28)
Mean Value(μM)	0.1696	-0.025	0.024*
AUC(μM·s)	99.133	-18.465	0.010**
Positive AUC(μM·s)	282.414	148.009	0.001**

Table 2.2 Cognitive activation in different tasks

2.5.3 Correlation analysis among CMS, STSR and cognitive activation

The premise was participants who self-evaluate as better at systems thinking (defined as a higher systems thinking scale revised, or STSR, scores) would make better concept maps (defined as a higher score using traditional concept mapping scoring techniques) and better concept maps require more cognitive energy (defined as increased HbO specifically in BA 9/46). In particular, BA 9/46 were the region of interest because of its known association with abstract reasoning and cognitive flexibility. A significant (p=0.018) negative correlation was found between STSR and concept map scores (CMS). This seems to contradict the purpose of STSR, which was designed to measure individual's capacity or tendency to think in systems for social-economic-environment elements by self-report. In other words, participants who self-reported high tendency or ability to think in systems were more likely to perform poorly on concept mapping, which is another approach to measure ability to think in systems. Figure 2.9 illustrates the negative correlation (Pearson correlation coefficient = -0.44, p=0.015, n=28) between STSR and CMS.

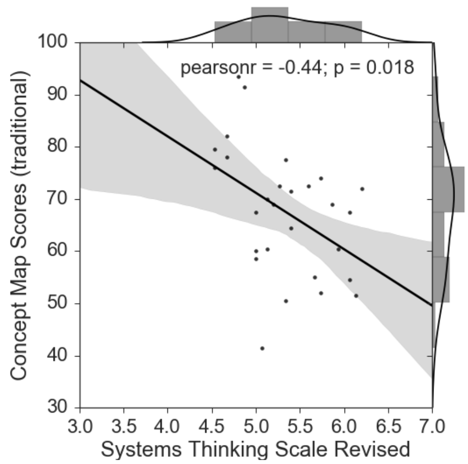


Figure 2.9 Negative correlation among CMS and STSR

The correlation between CMS and cognitive activation in BA9/46 is positive. The significantly positive correlation only occurred, however, between AUC in one of the channels located between BA 9 and BA 46, not across the averaged channels. Indicating, localized activation within BA 9 and BA 46 appears to significantly influence concept mapping ability. The number of concepts and links (two key features in concept maps) were also found positively correlated to the activation in the localized channel. Figure 2.10 illustrates these significantly positive correlations. Noted in the figure, S4-D1 is the channel between source 4 and detector 1 that was positively correlated.

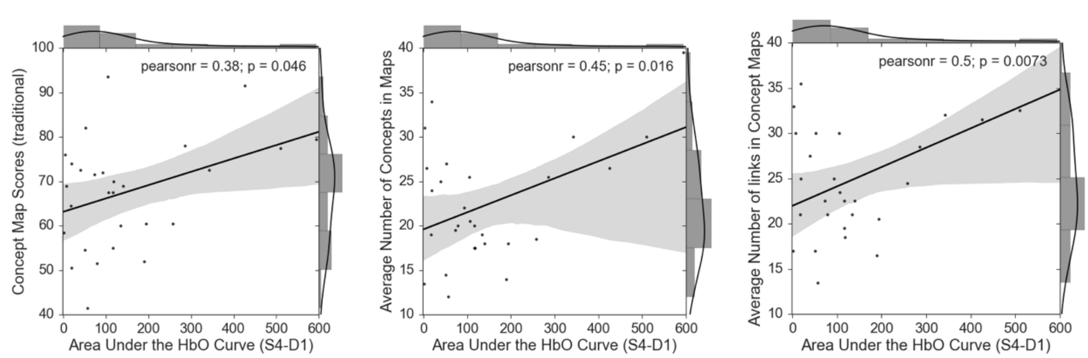


Figure 2.10: Positive correlation among CMS, number of concepts/link and area under the curve for HbO in concept mapping tasks

2.5.4 Brain networks

For each participant, in both concept listing and mapping tasks, their ΔHbO correlation matrixes, binary matrixes and brain networks with thresholding 0.7, 0.75 and 0.8 were created. The network metrics including density (D) and Clustering coefficient (C) were calculated using Python package NetworkX. Table 3 shows the graph and these metrics of brain networks in different tasks from one participant.

Table 2.3 illustrates one participant's network graph during concept listing and concept mapping tasks. Across all participants, there were more brain connections between different channels, greater network density and higher clustering coefficient during concept listing tasks than concept mapping tasks. When thresholding increased, these metrics decreased.

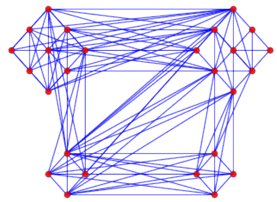
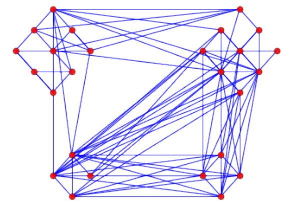
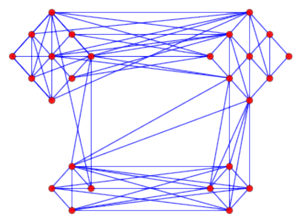
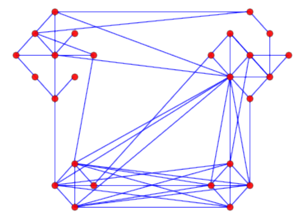
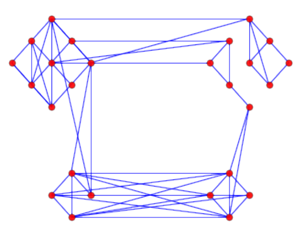
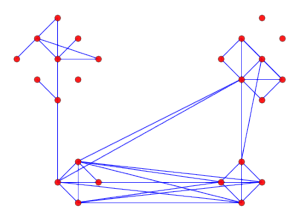
Thresholding	0.7	
Tasks	Concept listing	Concept mapping
Graph		
Density (D)	0.377	0.311
Clustering coefficient (C)	0.734	0.688
Thresholding	**0.75**	
Tasks	Concept listing	Concept mapping
Graph		
D	0.286	0.196
C	0.708	0.447
Thresholding	**0.8**	
Tasks	Concept listing	Concept mapping
Graph		
D	0.193	0.126
C	0.568	0.404

Table 2.3 Example of brain network graph and metrics

Wilcoxon signed rank tests was used for analysis since these metrics were not normally distributed. Significant differences were found between tasks as Figure 2.10, Figure 2.11 and Table 2.4 illustrate. Table 2.4 includes the density, clustering coefficient averaged among all participants and the p-value from Wilcoxon signed rank test between concept mapping and listing tasks. The results indicate that there were significant differences in network metrics between concept mapping and listing tasks. An average of 28% higher network density was found during concept listing than mapping. Greater network density during linear tasks might suggest more cognitive resources, or cognitive load (Martijn P. and Hilleke E. 2010), was required to generate concepts using a list, while concept mapping appears less cognitively taxing. The brain network when developing concepts as a list was more complex, with more closed loops between neighboring nodes, and average 24% higher clustering coefficients. In other words, concept mapping appears to alleviate complexities in brain connectivity.

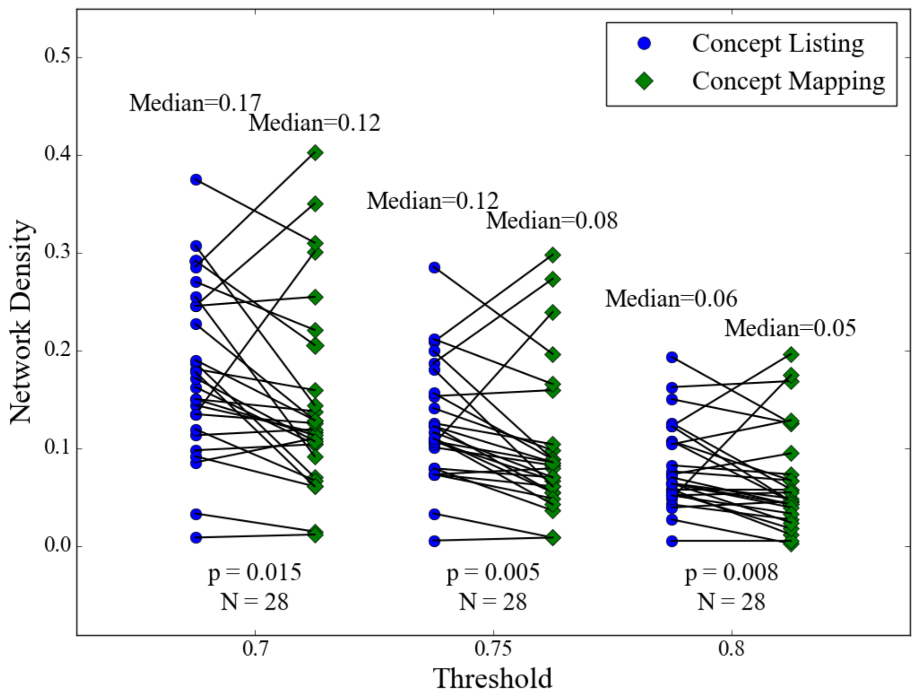


Figure 2.11: Brain network Density

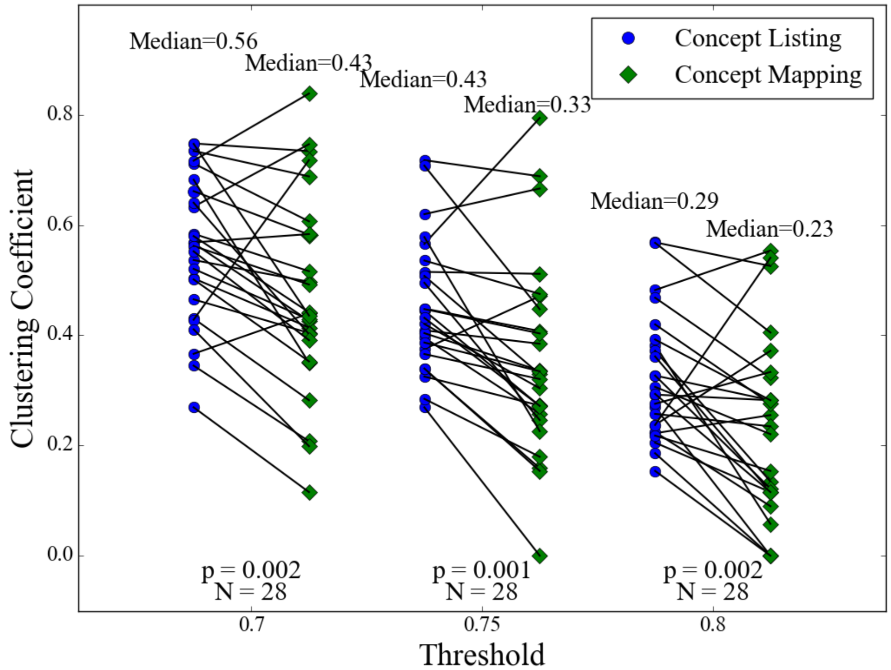


Figure 2.12: Brain network Clustering Coefficient

T=Thresholding; L = Concept Listing, M = Concept mapping; p*<0.05, p**<0.01
D=network density, C=clustering coefficient

T	0.7			0.75			0.8		
Tasks	**L**	**M**	**p**	**L**	**M**	**p**	**L**	**M**	**p**
D	0.18	0.15	0.025*	0.13	0.10	0.012*	0.08	0.06	0.037*
C	0.54	0.46	0.002**	0.44	0.36	0.001**	0.31	0.23	0.002**

Table 2.4 Average brain network metrics in different tasks

These results suggest that the cognitive advantage of concept mapping to think in system is that it might relieve the cognitive cost and network complexity, so that it require less network coordination between different brain regions. One possible explanation is concept mapping offers participants a tool to record and organize relationships between ideas so this information is not needed to be stored in the brain.

2.6 DISCUSSION

As expected, significantly more concepts were generated when using concept maps compared to concept listing averaged among all participants. Requiring participants to consider the relationships between system components seem to promote more concept generation. The cognitive data collected with fNIRS was consist with the behavioral results. Greater activation was measured in channels located between Brodmann area (BA) 9 and BA 46 during concept mapping compared to listing. BA 9/46 are known to be involved in executive functions, cognitive flexibility and abstract reasoning (Bembich et al. 2014). Greater activation was measured in channel located between BA 7 and BA 39 during concept listing. BA 7/39 are demonstrated to be involved in sequence and visuospatial processing (Crozier et al. 1999; Köhler et al. 1995). More activation in BA 7/39 when listing concepts might suggest that engineering students spent more cognitive effort holding relationships between concepts in their mind to organize their thoughts and therefore had less available cognitive effort to put towards generating new concepts. In contrast, the concept mapping technique records these relationships as part of the process, potentially, redirecting the effort to hold relationships in their mind to concept generation. Of course, this is only one possible explanation for why students generated more concepts when using concept mapping compared to listing.

The brain network analysis using graph theory demonstrates that concept mapping helps to alleviate brain network costs and complexities. Said another way, participants generated more concepts when using the concept mapping technique but used less network resource and less global coordination in the brain to do so. Future research can begin to explore network costs and complexities before and after educational training with concept maps.

The negative correlation between Systems Thinking Scale Revised (STSR) and concept map scores (CMS) was opposite of the hypothesis. Self-assessment on systems thinking tendency appears to be counter intuitive. The STSR score was a negative predictor of students' tendency to think in systems (Thibodeau et al. 2016). While the STSR does not positively correlate with CMS, the cognitive data captured by fNIRS does positively correlate with CMS. In particular, the correlation between CMS and cognition in the brain occurs in BA 9/46. However, more research is needed to explain why the correlation was found. In addition, the traditional concept map scoring method only counts the number of concepts and links without extensive content analysis included in the scoring. Future research is needed to develop more complete methods for concept map scoring that accurately account for content analysis.

2.7 CONCLUSION

This fNIRS study investigates the difference in concept generation using two techniques, either concept listing or concept mapping. Significantly more concepts were generated when using concept maps than lists. While much previous research suggests concept mapping as an approach to measure student learning. Concept mapping appears to offer benefits not just for assessment but also in the learning process.

Generating concepts using the concept mapping technique also lead to more cognitive activation in BA 9/46, compared to when generating concepts using a list. BA 9 and BA 46 are demonstrated to involve cognitive flexibility and abstract reasoning. While greater activation was measured in BA 7/39 when using concept listing, compared to concept mapping. BA 7 and BA 39 are demonstrated to involve sequence and visuospatial reasoning. Thus, not only are differences in behavioral outcomes (i.e. number of solutions) observed between the two types of tasks but also differences in cognitive function. Using concept mapping led to significantly more activation in the area of the brain associated with abstract reasoning. These results further support the positive benefits of using and teaching concept mapping to students. In addition, collecting the physiological changes in cortical regions with fNIRS provides another level of detail and supporting evidence that otherwise would have been lost to researchers only collecting behavioral outcomes and self-assessment.

The correlation among the self-assessment survey called systems thinking revised score (STSR), concept map scores (CMS), and cognitive activation in the brain reveals the limitation of traditional concept map scoring as a method and questions the accuracy of self-assessment on their systems thinking to predict concept map scores. A significantly negative correlation was observed between STSR and CMS, and it might result from the inaccuracy within both parameters to measure systems thinking production and tendency. The cognitive load, measured as the positive area under the curve in change of HbO, within BA9 and BA46, was significantly positively correlated to CMS.

Connections in brain network were also found to vary between concept generation using a list or mapping technique. Concept listing resulted in denser and more complex networks. In contrast, concept mapping led to sparser and less connected networks. One possible explanation is concept mapping offers participants a tool to record relationships between ideas so this information is not needed to be stored in the brain thus localizing the effort needed to complete the task. This has direct effect on cognitive load theory in education. Cognitive load theory suggests education intrusion should make learning easier to cognitive manage. Concept mapping appears to help. Developing a holistic perspective and giving more consideration to relationships might not necessarily increase difficulties for students to think about the system problem. The results suggest the contrary. Recording the relationships between concepts helps alleviate brain network coordination. Engineering education can take the cognitive advantage of concept mapping to help students think in system to develop better understanding on sustainability and to so while require less cognitive effort.

Broadly, the study contributes to engineering education by demonstrating a new measurement tool to understand student cognitive abilities. The results demonstrate discrepancies in previously developed surveys, concept map scoring techniques, and cognition. The research also adds to the growing discipline of sustainability science. Sustainability requires a systems thinking approach. Concept mapping is a technique to illustrate the connection and relationship between concepts. The results from this study demonstrates that concept mapping reduces the complexity and cognitive effort to generate concepts. This study also contributes to neuroscience by demonstrating applications for novel methods in neuroimaging to measure and assess real world problems. This trans-disciplinary approach, bridging engineering education, sustainability, and neuroscience is meant to open new avenues of research. This study provides an example, and hopefully offers a way forward for other researchers in the future.

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LESSONS LEARNED

Through this research with knowledge from different backgrounds, numerous experiments and data analyses, I acquired many experiences and lessons learned.

Literature review process can be tough sometimes, especially when I had little understanding on cognitive neuroscience, but it is also a great way to learn fast. The summary of experiment design and statistical analysis methods I made in the first semester helped me a lot for my following research. Besides, online resources are quite helpful for novice. For example, the website http://www.fmriconsulting.com/brodmann/Interact.html offers a comprehensive summary on brain regions functions and related research. I believe this website is a good tool for researchers interested in cognitive neuroscience.

Another difficulty in interdisciplinary research is a balance among different research fields. Over the past one year, more efforts were made to understand fNIRS and cognitive psychology and sometimes I even felt obsessed with these research and forgot my purpose for engineering sustainability. I will try to spend more time understanding decision making and engineering sustainability to prepare for my PhD research.

Before collecting data, designing fNIRS experiment and tasks properly is important and pilot studies are usually needed to decide the tasks. During collecting data, being prepared and making sure all software and hardware work well is critical and could eliminate the waste of data and time. Besides, a good communication with participants is also important to collect data rightly. Moreover, it will be better to enroll a few more participants than sample size designed because we might not be able to use data from individual due to bad signal or other issues in experiment.

Having a powerful tool for fNIRS data processing and analysis can help increase efficiency greatly. From my point of view, processing data with scripts will be easy and more efficient than using interface operation since there are tremendous data points for each participant and we usually need to do the same or similar processing for data of each participant. I recommend using either Python or R, and they are also quite useful to visualize results with nice figures.

All these challenging but interesting process in research confirmed my desire to continue doing research as a PhD student and a researcher in the future. I believe all the lessons learned and tools acquired in Master's thesis will help me in the future.

CONCLUSION

This research using fNIRS quantitatively measures the cognition of designing and thinking for sustainability provides researchers and educators with insights into how sustainability requirements impacts design cognition and how different ways of thinking influence cognition of concept generation for sustainability.

In first study, the data indicate a consistent mapping between events at the neural level (greater activation) and events at the behavioral level (more solutions generated). From behavioral level, the result indicates that sustainability requirements in design significantly ($p<0.05$) limited the number of solutions generated to solve the engineering design problems. From the cognitive level, these parameters decreased the cognitive efficiency to generate solutions. Moreover, sustainability requirements led to activation shift from right hemisphere (associate with creativity) to left hemisphere, which might indicate that sustainability requirements impede creative thinking in design. Future analysis on the novelty of solutions students generated could help examine this hypothesis.

The years of engineering education also influence the cognition of solution generation. In this study, freshmen had more activation in brain regions associated with cognitive flexibility and abstract reasoning, while seniors had more activation in regions associated management of uncertainty. Besides, with more years of training in engineering, seniors have higher cognitive efficiency to generate solutions.

The second study investigates cognitive difference between concept listing and mapping for sustainability indicate that concept mapping leads to more concepts related to sustainability. The cognitive activation recorded by fNIRS indicates that more concepts generated in maps correlate with more cognitive activation in brain regions associated with cognitive flexibility and abstract reasoning. Moreover, concept mapping helps reduce the brain network cost and complexity to complete the concept generation tasks.

The correlation among self-assessment survey measuring individual's ability of systems thinking (STSR), the concept maps scores (CMS) and BOLD response during concept mapping suggests that self-assessment might not be accurate or sufficient to reveal systems thinking since the self-assessment ability of participants was negatively related to their behavioral results. However, the positive correlation between CMS and BOLD response represents a consist mapping between behavioral result and cognitive result.

This research provides a better understanding of the role of certain brain regions, cognitive change and brain network during engineering students thinking for sustainability. The results demonstrate the cognitive challenge that sustainability brings to engineering design, and systems thinking can help engineering students generate more concepts related to sustainability. This trans-disciplinary approach, bridging engineering education, sustainability science, and neuroscience is meant to open new avenues of research. This research provides an example, and hopefully offers a way forward for other researchers in the future.