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Investigating Design Cognition during Brainstorming Tasks with Freshmen and Senior Engineering Students using Functional Near Infrared Spectroscopy

Dr. Tripp Shealy, Virginia Tech

Tripp Shealy is an Assistant Professor of Civil and Environmental Engineering at Virginia Tech. His research is at the intersection of cognitive psychology and engineering decision making for sustainability.

Dr. Jacob R. Grohs, Virginia Tech

Jacob Grohs is an Assistant Professor in Engineering Education at Virginia Tech with Affiliate Faculty status in Biomedical Engineering and Mechanics and the Learning Sciences and Technologies at Virginia Tech. He holds degrees in Engineering Mechanics (BS, MS) and in Educational Psychology (MAEd, PhD).

Miss Mo Hu, Virginia tech
Darren K. Maczka, Virginia Tech

Darren Maczka is a Ph.D. candidate in Engineering Education at Virginia Tech. His background is in control systems engineering and information systems design and he received his B.S. in Computer Systems Engineering from The University of Massachusetts at Amherst. He has several years of experience teaching and developing curricula in the department of Electrical and Computer Engineering at Virginia Tech.

Dr. Robin Panneton, Virginia Tech

1981-1985 Ph.D. Developmental Psychology; University of North Carolina at Greensboro, Greensboro, NC 1978-1981 M.A. Developmental Psychology ; University of North Carolina at Greensboro, Greensboro, NC 1974-1978 B.S. PsychologyUniversity of Wisconsin at Milwaukee, Milwaukee, WI

My research interests revolve around issues relevant to infants' perception of information that leads to their emerging communicative skills from birth to toddlerhood. These research questions involve probing aspects of infants' learning about objects, about people, and about themselves in relation to objects and people. I am particularly interested in how multiple sources of dynamic sensory information drive infants' attention to and learning about the world in which they live and their ability to communicate about it.

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Abstract

Design cognition 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 to engineering challenges for sustainability using functional near-infrared spectroscopy (fNIRS). fNIRS can be used to study brain activity in more natural environments, while also providing better spatial resolution than EEG and better temporal resolution than 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. By measuring hemodynamic responses during brainstorming tasks with freshmen ($n=14$) and senior ($n=9$) engineering students we find a significant difference ($p<0.001$) in the cognitive activation required to generate solutions. Freshmen engineering students show 5 times greater activation in the dorsolateral prefrontal cortex (known to involve working memory, cognitive flexibility, planning, inhibition, and abstract reasoning) compared to seniors. While seniors show an average of 10 times increase in activation in the premotor cortex (known to be involved in the management of uncertainty, control of behavior, and self-reflection in decision making). The number of solutions generated was also significant ($p=0.032$). Freshmen generated 5.6 solutions on average during the brainstorming activity while seniors developed 4.1. 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, we can begin to explore specific elements of the engineering curriculum that may contribute to student ability to manage complexity inherent in engineering design problems. We hope this interdisciplinary study integrating engineering education and neuroscience generates conversation about other engineering design tasks and settings, in which, fNIRS can be effectively used as a new tool.

Introduction

The ability to take a problem and generate multiple, varied solutions to create a new, creative outcome is a central principle of design cognition. Many strategies exist to generate new design solutions, for example, analogical transfer (Dahl & Moreau, 2002), association (Hernandez, Shah, & Smith, 2010), shifting context (Shah, Smith, Vargas-Hernandez, Gerkens, & Wulan, 2003) and hypothesis testing (Yilmaz, Daly, Seifert, & Gonzalez, 2015). Perhaps the most prominent method is brainstorming, where evaluation is deferred and as many distinct ideas as possible are generated (Osborn, 1993). Often referred to as ideation, this process promotes creativity in design solutions. Pedagogy for enhancing ideation is essential because most engineering design problems demand innovative approaches to the design of products, equipment, and systems. This demand arises from continual changes in the market, technologies, and more recently a focus towards sustainability (Jawahir, et al., 2007; Sherwin, 2004). Research into design education can therefore lead to a more informed understanding of how ideation can be facilitated and build more expertise in design (Jawahir et al., 2007; Sless, 2012; Yilmaz et al., 2015).

To date, many empirical studies have investigated the cognitive processes of individuals during brainstorming or ideation processes (Coley et al., 2007; Cross, 2001; Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Daly, Mosyjowski, & Seifert, 2014). Though, 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 of cognition over subject reported behavior.

To add to engineering education methods when studying design, this paper introduces a new method to measure design cognition. 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). Neuroimaging data can provide engineering education researchers an additional tool to better triangulate behavioral findings. The emergence of 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 thinking. Understanding the regions of activation in the brain required for conceptualizing a system, for example, is important because we can begin 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 such as self-reporting. In essence, that which was once an un-examinable black box can now be examined and in multiple conditions.

Adopting Cognitive Neuroscience Techniques to Study Design Cognition

Making sense of brain-behavior relations is a search to understand the functional architectures of cognitive systems (Coltheart, 2001; Eysenck & Keane, 2015)—for example, how does some function of interest (e.g., risky decision making) occur and in what region? To explore such a question requires a model about how the brain works and is organized. Significant bodies of research are built upon the simplifying assumption of *modularity* to which we might make the analogy of an assembly line in a factory: each worker performs only one task, and any given function necessarily and reliably involves the same subset of workers. In terms of scientific inquiry, this means that we must merely induce a function (e.g., present the image of former teacher to a participant), identify the specific areas of the brain involved, and we will have reliably characterized the architecture of that function (e.g., decision making).

If we see those areas of the brain involved in any future task, then we can reliably assume that the participant is performing the function of interest. Despite evidence that modules are interconnected and do not exhibit the domain specificity of the single-worker single-task model, research anchored in modular brain architecture is still widely accepted. For discussion of a more modern approach to the modularity issue, please see (Karmiloff-Smith, 1995). As imaging techniques and computational power have improved, the modularity assumption can be loosened to instead investigate correlations between modules and identify the networks involved with specific functions (Eysenck & Keane, 2015).

Brain Data Collection Techniques

Two common methods used to explore neural processes of decision-making and problem solving under laboratory conditions are electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). EEG involves a head cover (e.g., cap or net) which places electrodes on the scalp and measures electrical changes in the brain. Temporal resolution is very good (detects quick changes) though spatial resolution (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 & Keane, 2015).

In contrast to EEG, fMRI technology 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 & 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, better able to detect regions of activation. 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, was calculated from the photon path length, based on the Modified Beer-Lambert Law. The BOLD effect is based on the fact that when neuronal activity is increased in one part of the brain, there is also an increased amount of cerebral blood flow to that area which is the basis of hemodynamic response. This increase in blood flow produces an increase in the ratio of oxygenated hemoglobin relative to deoxygenated hemoglobin in that specific area. Shown in figure 1, the deoxygenated blood is inversely related to oxygenated blood. Both are measured with fNIRS, though typically only one is reported.

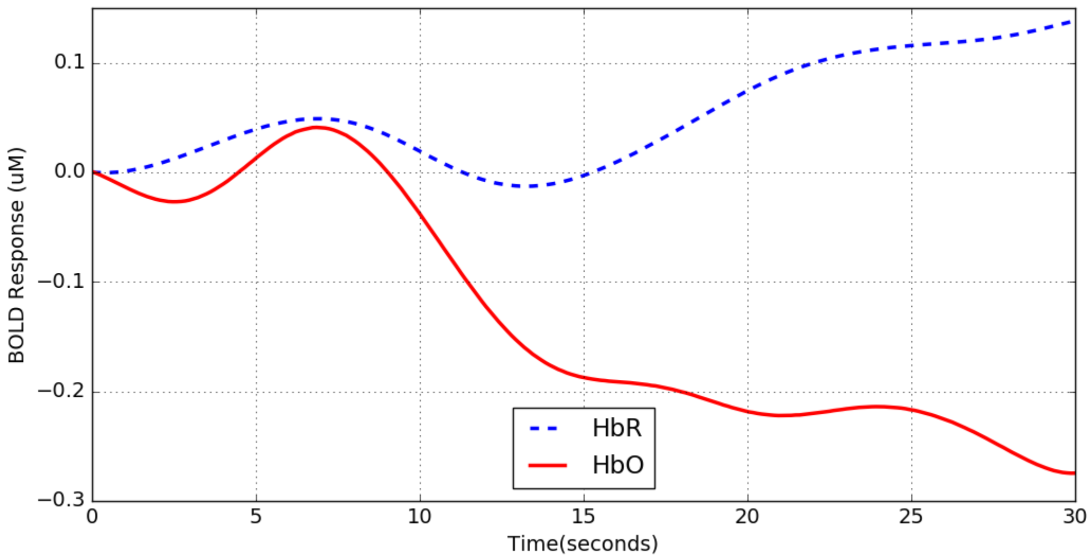

Figure 1: BOLD response, HbO and HbR are inversely related

The drawbacks from fNIRS are its lack of high spatial resolution compared to fMRI and inability to provide information about sub-cortical brains 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 extremely interesting as a resource to understand design cognition in educational settings.

Brain Regions of Interest

The cerebral cortex (cortical regions) is the outer surface of the brain and is divided into two mirrored hemispheres, and four lobes: the frontal lobes: where much of our 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, which 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, which are responsible for interpreting and remembering visual information; and the temporal lobes, which interpret and remember complex auditory information and appear to be important in memory for information over the long run.

Research Question

By measuring the change in oxygenated hemoglobin and location of the change during brainstorming tasks in freshmen and senior engineering students, we can construct a more detailed understanding of the mental processes required for these types of problems and change over time through education. Our specific research question is: do the years of educational training in engineering significantly (using a confidence interval of 99%) influence the cognitive activation in regions of the brain during brainstorming tasks?

We expect to find engineering 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 managing complexity than freshmen students measured by a decrease in cognitive energy loads and more specific brain region activation (specifically the dorsolateral prefrontal cortex) as well as greater number of generated solutions.

Methods

Students were given 5 engineering design problems based on Richard Smalley's list of the most pressing issues facing humanity (Smalley, 2003) in the next 50 years. The problems spanned topics such as renewable energy, water quality, poverty, and air pollution. Students received the engineering problems in random order. 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 preliminary studies to ensure neither too much or too little time for the brainstorming sessions. In total, the experiment lasted 7.5 minutes (5 brainstorming tasks, 60 second for each task with 30 second rest periods in between tasks). This study has been approved by the Institutional Review Board at Virginia Tech.

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. Though, by reviewing pilot study data and video recordings, we recognized that students would frequently reflect on their brainstorming performance during the rest period. And this caused a spike in the cognitive activation in the prefrontal cortex. To correct for participants reflecting on the previous task we included simple arithmetic questions every ten seconds. 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 (Dresler et al., 2009; Meiri et al., 2012). Based on prior research, simple arithmetic problems are often solved from memory not processing.

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. 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. Though, future analysis will also include metrics for novelty.

Freshmen and senior engineering students across disciplines were recruited to participate in the study. In total, 23 engineering students (10 female) participated (14 freshmen and 9 seniors). The freshmen were all general engineering students. All were right handed between the ages of 18-19, and 13 were male. A broad range of senior engineering students were recruited to participate. An investigation into design literature did not suggest to expect a difference in creativity, ideation, or brainstorming ability across engineering discipline. Though, this an area for potential research in the future and discussed more in the conclusions. Seniors were majoring in civil engineering, mechanical engineering, or computer engineering. The senior engineering students were between the ages 21-23, 8 out of 9 were right handed, and 3 were male.

The study began by participants reviewing and signing the consent form,, learning about the fNIRS machine, and practicing a brainstorming example problem in preparation for the experiment to begin. Participants were made aware that the number of solutions generated were being recorded and the purpose was not to evaluate the ideas at this stage rather just generate as many as possible.

Sensors and detectors were placed along the frontal cortex. Figure 1 shows a graduate research assistant wearing the cap and the corresponding regions being measured. In total 18 channels (a channel is 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).

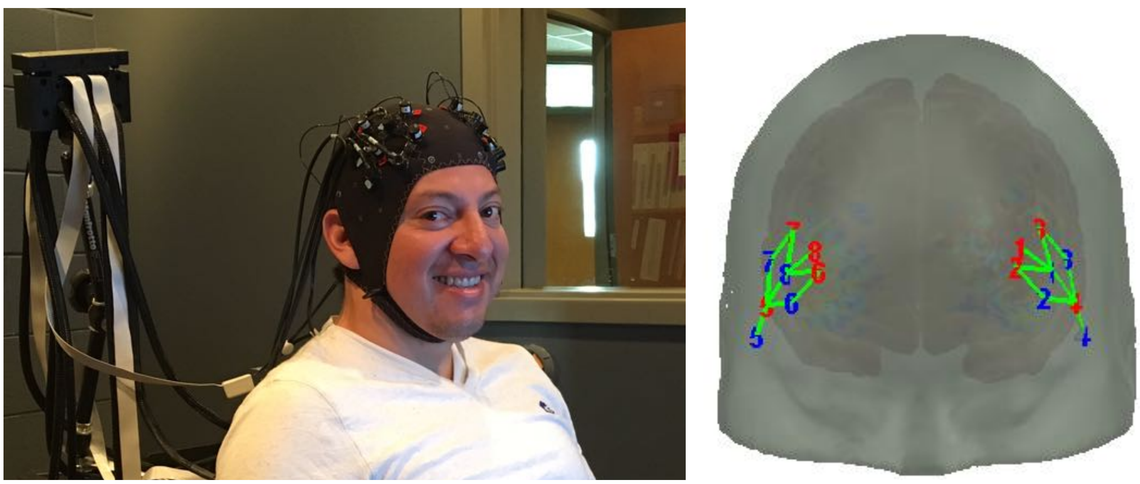

Figure 1: fNIRS placement along the frontal cortex

The fNIRS data was converted from raw data files and filtered by applying a high and low band pass filter using HomER (Huppert et al., 2009). The high and low band pass filter removed instrumental and physiological noise. The fNIRS data for the 5 trials were then averaged together for each participant. The averaged data provided 18 individual channel readings for each subject 60 seconds in length. The 30 second baseline data for individual participant was subtracted from each channel so that the resulting processed data were representative of the increase in cognitive function due to the task.

Channels were averaged across the whole prefrontal cortex, split between left and right hemisphere prefrontal cortex, and also analyzed by individual. Participant data (averaged over all 18 channels) was averaged across the sample of freshmen and averaged for the sample of seniors. Our data averaging approach follows similar previous fNIRS studies (Bunce et al., 2011; Ferrari & Quaresima, 2012; Glotzbach et al., 2011). The result is two series of data that represents the average BOLD responses in the prefrontal cortex region among freshmen and seniors. Similarly, this was done for left and right hemisphere between freshmen and seniors for each individual channel. When multiple t-tests were run a Bonferroni correction was applied, increasing the confidence interval from 99% ($p<0.01$) to 99.998% ($p<0.002$).

Results

The cognitive activation during brainstorming tasks are significantly different between freshmen and seniors. The average BOLD response for freshmen engineering students is significantly ($p<0.001$) greater than senior engineering students. The BOLD response correlates to the cognitive activation required to perform the task. To further understand where the significant difference is occurring within brain regions of interest, the analysis was separated between the left and right hemispheres. The results also indicate both hemispheres are significantly different ($p<0.001$) during brainstorming tasks between freshmen and senior engineering students. The BOLD response among the average freshman is approximately 25 times greater than seniors in the left hemisphere and approximately 1.6 times less in the right hemisphere. Figure 2 depicts the BOLD response between freshmen and seniors in both the left and right hemisphere using HomER's image reconstruction tool (Huppert et al., 2009). The red indicates more cognitive activation (larger increase in BOLD response). The average cognitive activation for freshmen is the image on the left and seniors are on the right. The images corroborate the statically tests showing a noticeable difference in activation between left and right hemisphere between freshmen and seniors.

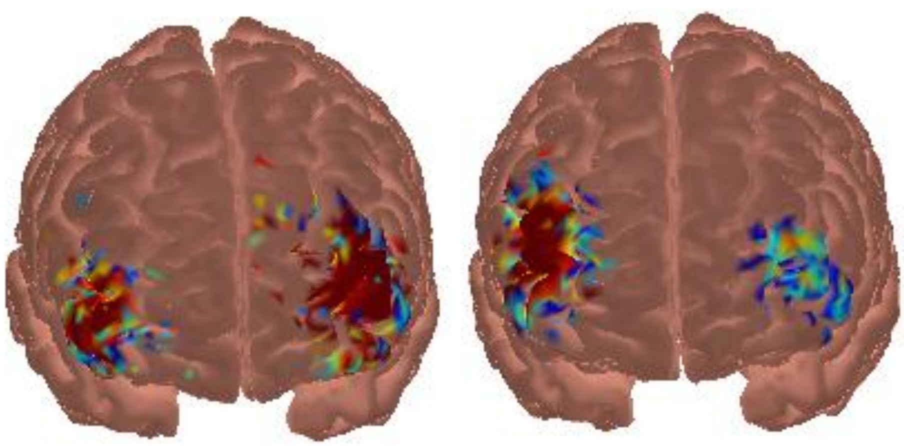

Figure 2: Average cognitive activation among freshmen engineering students (left) compared to average cognitive activation among seniors (right) during brainstorming task. Higher cognitive activation is indicated by red and lower activation by blue.

Investigating further, a channel analysis shows 14 out of 18 channels are significantly different ($p<0.002$, corrected using Bonferroni) between freshmen and senior engineering students. Though the average senior engineering student showed greater activation on the right hemisphere than the left and vice versa for freshmen, the results are not necessarily that straightforward.

These channels map to three known regions in the brain, defined by Brodmann's areas, the three regions (BA8/9, BA46, BA6) are the middle frontal gyrus (MFG), dorsolateral prefrontal cortex (dlPFC), and premotor cortex (PC). BA8 is known to be involved in management of uncertainty (Volz et al., 2004, 2005; Rämä et al., 2001), and executive control of behavior and planning (Burton et al., 2001; Kübler et al., 2006; Sarazin et al., 1998). BA9 is known to involve in working memory (Pochon et al., 2002; Zhang et al., 2003), memory encoding and recognition and error processing/detection (Chevrier et al., 2007). The BA46 is known to involve in working memory, cognitive flexibility, planning, inhibition, and abstract reasoning (Bembich et al., 2014). The BA6 may play a role in in planning/solving novel problems (Fincham et al, 2002; Crozier et al., 1999) and processing self-reflections in decision-making (Deppe et al., 2005). The most significant difference between freshmen and senior engineering students occurred on the right hemisphere. Freshmen showed 5 times more activation in the BA46 than senior engineering students. While senior engineering students showed 10 times more activation in the right hemisphere along the BA6 and 3 times more activation in the right hemisphere along BA8. The BOLD responses for both the BA46 and BA6/8 (average) are provided in Figures 3 and 4.

Conceptually, these results provide insight into the neural mechanisms that support and facilitate task completion. The findings show significant variance in the neural mechanisms between freshmen and seniors to complete the same task. An analogous description is the increased cognitive activation indicates the cognitive "tools" participants favored to complete the task. Freshmen showed a greater activation in the region of the brain associated with working memory, cognitive flexibility, and abstract reasoning where as seniors showed greater activation in the region of the brain associated with management of uncertainty and self-reflection in decision making.

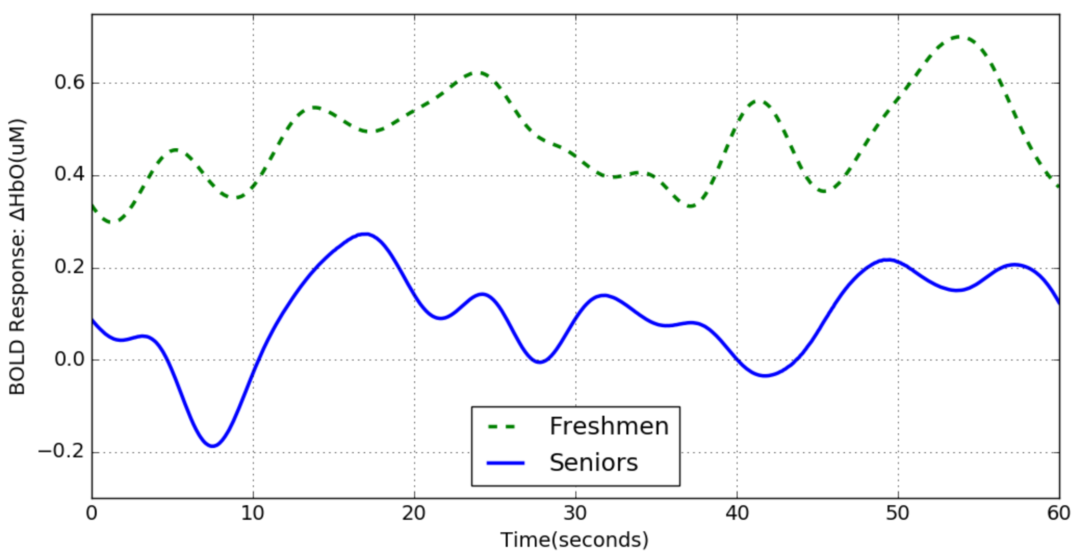

Figure 3: BOLD response dlPFC, right hemisphere (BA46) averaged among participants during brainstorming task

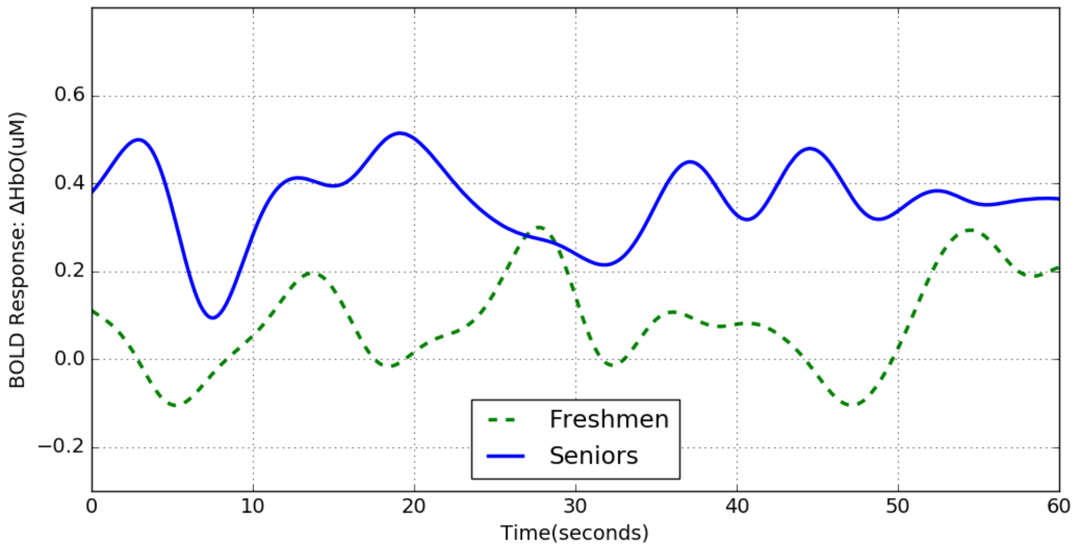

Figure 4: BOLD response MFG, right hemisphere (BA6/8) averaged among participants during brainstorming task

The freshmen engineering students sustained greater activation in the BA46 throughout the averaged brainstorming task, as shown in Figure 3. While seniors show an increase in activation in the BA6/8 early from the task beginning, shown in Figure 4. The BOLD response in the BA6/8 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 4, 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).

The BA6/8 is typically associated with management of uncertainty, control of behavior and self-reflections in decision making. Thus, greater activation in these areas by seniors may suggest second guessing and self-reflection in solutions with uncertainty before verbally initiating them, though this was not tested in the study. However, a t-test between number of ideas generated was significantly ($p=0.032$) less for seniors compared to freshmen. This is illustrated in Figure 5. Freshmen on average developed 5.6 solutions and seniors 4.1 solutions. Hence, freshmen developed more solutions and had greater cognitive activation along the right BA46 whereas seniors developed less solutions and showed greater activation among the right BA6/8. Clearly, the variance of activation among freshmen and seniors indicate a distinction in mechanistic function in the brain when generating solutions to engineering problems.

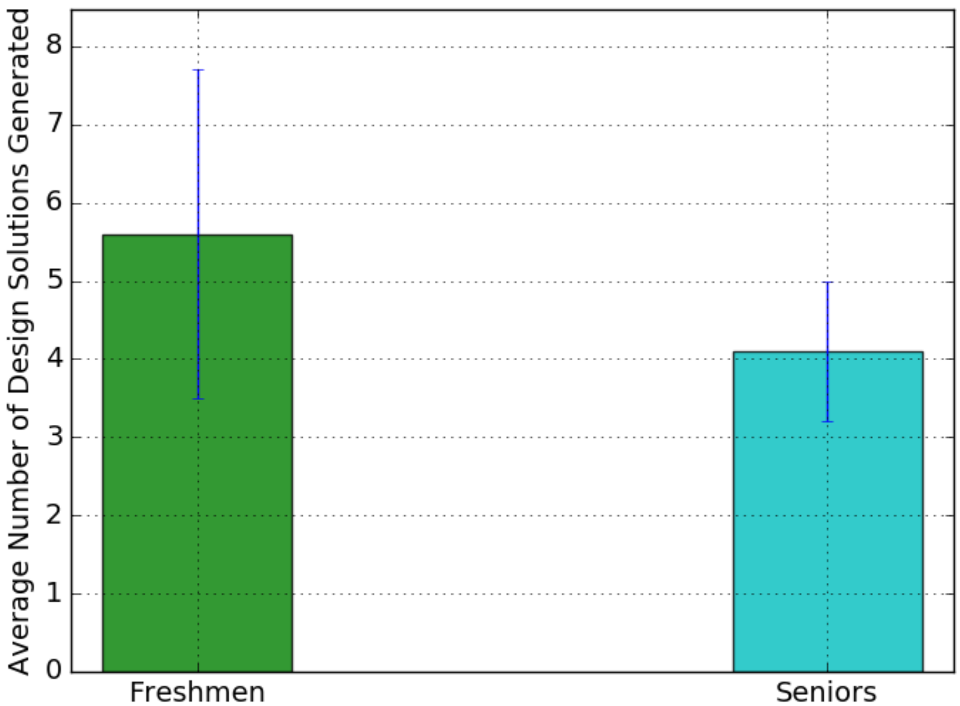

Figure 5: Average number of solutions generated during brainstorming tasks

Conclusion

The results indicate a consistent mapping between events at the neural level (greater activation) and events at the behavioral level (more solutions generated). Further, the physiological data collected with fNIRS indicates significant difference in cognitive activation between freshmen and senior engineering students during brainstorming tasks. Freshmen have a significantly higher level of cognitive activation, though performed better based on the number of solutions developed. The region of activation between freshmen and seniors most statistically different was the dorsolateral prefrontal cortex (PFC), premotor cortex (PC) and middle frontal gyrus (MFG). Freshmen demonstrated a sustained and significantly greater activation in the right dlPFC while less in the right MFG and PC.

While not tested, one hypothesis for the significant difference in activation, is seniors applied a filter or evaluation to their answer prior to verbally suggesting a solution and were less cognitive efficient to generate novel solutions to the problems. In fact, the shift in activation may suggest this is the case. The MFG (BA8) is known to involve in management of uncertainty, control of behavior and PC involve in solving novel problems and self-reflection in decision making. And seniors generated significantly fewer solutions. 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. Another line of research stemming from this preliminary study is how the use of mnemonics or training related to sustainability influences 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 we could not find evidence to expect one type of engineer to be more creative, or capable in brainstorming, future research could investigate the cognitive differences across engineering disciplines.

Better understanding the role of certain brain regions during educational experiments like design across a range of subject groups appears to hold promises to advance teaching and education theory. The purpose here is to demonstrate the potential to use fNIRS as a method for design education and as a potential tool to triangulate other data sources engineering education researchers are already collecting. Ultimately, bridging neuroscience techniques to engineering education is an area that requires the integrated understanding of both disciplines. But the effort seems to hold promise for future endeavors merging these disciplines and at the same time design education research offer 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.

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