Design Science

Cognitive differences among first-year and senior engineering students when generating design solutions with and without additional dimensions of sustainability

Mo Hu [1], Tripp Shealy [1] and Julie Milovanovic [2]

1 *Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, USA*
2 *UMR AAU-CRENAU, Department of Architecture, Graduate School of Architecture Nantes, Nantes, France*

Abstract

The research presented in this paper explores how engineering students cognitively manage concept generation and measures the effects of additional dimensions of sustainability on design cognition. Twelve first-year and eight senior engineering students generated solutions to 10 design problems. Half of the problems included additional dimensions of sustainability. The number of unique design solutions students developed and their neurocognitive activation were measured. Without additional requirements for sustainability, first-year students generated significantly more solutions than senior engineering students. First-year students recruited higher cortical activation in the brain region generally associated with cognitive flexibility, and divergent and convergent thinking. Senior engineering students recruited higher activation in the brain region generally associated with uncertainty processing and self-reflection. When additional dimensions of sustainability were present, first-year students produced fewer solutions. Senior engineering students generated a similar number of solutions. Senior engineering students required less cortical activation to generate a similar number of solutions. The varying patterns of cortical activation and different number of solutions between first-year and senior engineering students begin to highlight cognitive differences in how students manage and retrieve information in their brain during design. Students' ability to manage complex requirements like sustainability may improve with education.

Key words: design cognition, engineering education, sustainability, fNIRS, brainstorming

Received 15 April 2020
Revised 29 December 2021
Accepted 05 January 2021

Corresponding author
Mo Hu
moh6@vt.edu

Des. Sci., vol. 7, e1
journals.cambridge.org/dsj
DOI: 10.1017/dsj.2021.3

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CAMBRIDGE UNIVERSITY PRESS

1. Introduction

Engineering design is a goal-oriented process to solve complex problems that involve technical, economic, social and environmental dimensions (Pahl *et al.* 2007). Engineering designers use a range of techniques to develop solutions to complex problems. For example, framing the design problem in multiple ways (Wright *et al.* 2015), applying structured design principles to generate new ideas (Cross & Cross 1998), allowing time for reflection (Schön 1983) and engaging with stakeholders (Bucciarelli 1988). No matter the technique or process, some form of idea generation or concept generation is involved (Smith 1998; Goldenberg *et al.* 1999;

Jonson 2005; Knoll & Horton 2010). Idea generation is arguably the most critical phase of design because future solutions are dictated by the ideas generated during this phase.

Idea generation also offers an opportunity to consider additional dimensions of sustainability (Ashford 2004; Morris *et al.* 2007; Collado-Ruiz & Ostad-Ahmad-Ghorabi 2010; Cucuzzella 2016). Dimensions of sustainability refer to an integration of economic performance, social inclusiveness and environmental resilience in a balanced manner for the benefits of current and future generations (Chitchyan *et al.* 2016; Pieroni *et al.* 2019). Integrating sustainability into engineering design and adopting sustainable methods, such as passive design, biomimetic design and circular economy, is crucial considering the economic, social and environmental crisis (i.e., climate change, resources constraints and economic inequality) (Curran 2009; Pereira 2009). Design for sustainability sets higher requirements for engineers to satisfy (Collado-Ruiz & Ostad-Ahmad-Ghorabi 2010; Ceschin 2014; Maccioni *et al.* 2017) and might reduce the problem and solution space during engineering design (Hay *et al.* 2017a).

Engineers must not only meet economic constraints, but also find solutions with higher mutual environmental and societal benefits. Knowing when and how to integrate additional dimensions of sustainability into the engineering design process can be a challenge (Collado-Ruiz & Ostad-Ahmad-Ghorabi 2010; Ceschin 2014). For instance, providing engineers with environmental information too early, or having them reflect on these dimensions too soon, can hinder their creative ability due to fixation (Collado-Ruiz & Ostad-Ahmad-Ghorabi 2010). Finding methods that promote sustainability as a driver for creative solutions is essential (Klotz *et al.* 2019).

Developing engineers who can create design solutions to meet sustainability challenges is increasingly part of engineering education (Dym *et al.* 2005; Allenby 2011). Teaching design for sustainability requires students to push past traditional problem-solving approaches (Mills & Treagust 2003; Dym *et al.* 2005; Daly *et al.* 2012, 2014). Students must use new search processes that include empathy (Blizzard 2013), systems thinking (Cardenas *et al.* 2010) and draw on requisite knowledge from the physical and social sciences (Klotz *et al.* 2018).

Engineering design is a complex cognitive process that relies on a set of explicit (knowing that) and tactical skills (knowing how) developed through experience (Schön 1981). Engineering design is not an assembly of a solution from existing components, but instead a search process for appropriate solutions using all cognitive means necessary to gain a new perspective on the problem at hand (Howard *et al.* 2008). Including more dimensions about sustainability inevitably makes this cognitive process more challenging because it requires cognitively managing multiple dimensions during design (Hu *et al.* 2019).

To help refine engineering education so students can efficiently create solutions that enhance outcomes for sustainability will require a better understanding of the cognitive processes involved in design (Cross 2001) and design for sustainability (Hu & Shealy 2018). Investigating cognitive differences of engineers' behaviour between novice and trained engineers can also provide new insight for design education (Newstetter & McCracken 2001; Cross 2004). Trained engineers tend to use more structured approaches to design. This can limit the number of cognitive processes that designers use as a control or inhibitor to cognitive activation (Kavakli & Gero 2003).

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Methods for measuring design cognition for sustainability are generally limited to protocol analysis (Ericsson & Simon 1984; Van Someren *et al.* 1994; Gero & Mc Neill 1998), ethnography, posttask surveys and observation (Coley *et al.* 2007). These methods require extensive resources to obtain reliable results. Recent advances in neuroscience now enable more direct measure of design cognition for sustainability to supplement behavioural analysis (Goucher-Lambert & Cagan 2015; Seitamaa-Hakkarainen *et al.* 2016; Goucher-Lambert *et al.* 2017; Gero & Milovanovic 2020).

In this paper, a combined approach is used to explore students' performance to address engineering design problems and how students cognitively manage additional dimensions of sustainability. Students' neurocognitive activation was measured while generating solutions to brainstorming tasks with or without additional dimensions of sustainability. Functional near-infrared spectroscopy (fNIRS) was used to measure neurocognition. The objective of the research was to identify underlying neurocognitive processes in first-year and senior engineering students when brainstorming and measure the effect of including additional dimensions of sustainability in the design problem. Better understanding the neurocognitive activation associated with this type of cognitive design process is the first step to provide a framework to train engineering students to leverage sustainability, rather than let it inhibit, more creative solutions (Klotz *et al.* 2019).

The paper begins with an overview of different methods to help designers generate ideas. This is followed by an explanation about why sustainability challenges in engineering are important prerequisites for engineering design. The challenge to integrate design, creativity and sustainability into the engineering curriculum is also raised. The background section is followed by the research questions, which explore the neurocognitive activation patterns during concept generation and the effects on neurocognition when additional dimensions of sustainability are included in the design problem. The methodology combines measures of neurophysiology and behaviour to understand differences in idea generation between first-year and senior engineering students, with and without additional dimensions of sustainability. The results include independent *t*-tests and paired *t*-tests performed on behavioural and neurocognitive data to explore differences between the two participant groups (first-year and senior engineering undergraduate students) for two types of tasks (concept generation and concept generation when design problems contain additional dimensions of sustainability).

2. Background

2.1. Design ideation in engineering

Designing is a reflective process (Schön 1983), based on an iteration of problem formulation, idea generation and evaluation of the proposed concepts to formalize design solutions. It relies on a set of cognitive processes that promote an alternation of divergent and convergent thinking (Goldschmidt 2016), and of problem and solution space exploration (Maher & Poon 1996; Dorst & Cross 2001). Idea generation aims to address a given design problem by the proposal of multiple ideas. Divergent thinking serves to explore the solution space by formulating multiple design possibilities. As design problems are considered ill-structured

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(Simon 1973), the proposal and evaluation of multiple concepts is a way to reframe and structure the problem space and begin the design process again.

Concept generation is a crucial part of the design process and supports designers' reflective conversation with the concepts being developed (Schön 1992). The underlying objective of promoting concept generation is to support creativity and innovation in the design solutions generated. Many tools are available to encourage concept generation (Goldenberg *et al.* 1999; Jonson 2005; Knoll & Horton 2010). Each technique relies on diverse strategies (Smith 1998). For instance, morphological analysis depends on an analytical strategy to decompose the problem and systematically associate a partial solution to subproblems to stimulate unconscious thought (Allen 1962). Brainstorming is another approach. It builds upon suspending judgement and criticisms during ideation to increase the flow of ideas (Osborn 1993). The generation of multiple solutions for later evaluation increases the chance for better design and serves to avoid fixation on an initial solution (Ball *et al.* 1998). Indeed, studies support that the number of ideas generated correlate positively with the creativeness of those ideas (Osborn 1993; Paulus *et al.* 2011).

Learning how to design and be creative is part of the engineering education process. Students rely on these skills to address real world engineering problems. A common instructional approach to teaching idea generation in engineering courses is to challenge students with open-ended problems without defined target products. The openness of problems can entice the flow of ideas among students (Daly *et al.* 2014). Idea generation tools such as brainstorming and concept generation can be integrated into engineering courses to improve the type of solutions students develop (going beyond basic principles) and promote creativity (Daly *et al.* 2012).

2.2. Importance of integrating sustainability into engineering design

The proposal of ideas is a way to explore the problem space by reframing it through the evaluation of the concepts generated. Engineering design problems are complex as they aim to resolve both technical, social and economic parameters. Environmental factors should not be disregarded (Goucher-Lambert & Cagan 2015). 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 these needs and call for more participation among engineers.

To explore the impact of considering sustainability in the design of transportation, consider an engineer tasked with alleviating congestion on a highway. Guided by conventional design theory and processes, an engineer may consider the level of service on the existing roadway and decide to add more road lanes to reduce congestion. However, such a design solution could be counterproductive, or further exacerbate the initial problem by induced demand (Lee *et al.* 1999; Hymel *et al.* 2010). Adding a new road lane will bring new automobile drivers, and over time, typically within 5 years, it leads to an increase in traffic (Noland 2001; Cervero 2003).

Adding design constraints for sustainability can entice creative solution generation (Litman & Laube 2002; Fini *et al.* 2018). For example, the development of a subway system was not economically feasible in Curitiba, Brazil and an investment to expand their highway system was not socially acceptable given only 10 per cent of their population owned vehicles. These economic and social constraints encouraged engineers and planners to propose a radically different idea: to repurpose existing road lanes into bus rapid transit lanes. At the time, removing existing road lanes to reduce traffic seemed counterintuitive but it helped alleviate traffic, and today residents enjoy the lowest per capita transportation costs and best air quality in the country (Lindau *et al.* 2010).

Sustainable design solutions, like the example of Curitiba, are more likely to emerge from a design approach that includes multiple dimensions of sustainability. The Mayor of Curitiba explained '…creativity starts when you cut a zero from your budget. If you can cut two zeroes, it's much better' (Lerner 2007). In other words, the presence of economic constraints led to a more sustainable outcome.

Engineers need technical and analytical skills to undertake engineering design but they also need to consider how their design affects broad dimensions of sustainability such as local development, health and downstream pollution (Azapagic *et al.* 2005; Staniškis & Katiliūtė 2016). Engineers should learn how to take advantage of methods such as passive design (Bhikhoo *et al.* 2017), biomimetic design (Linke & Moreno 2015) or circular economy (Pieroni *et al.* 2019) to solve engineering problems. Sustainability requirements are as important as technical ones, and should be integrated early because introducing them later into the design process creates less opportunity for change (Gervásio *et al.* 2014), and often results in 'greenwashing' (Kapalko 2010). Creative design and innovation are necessary to go beyond social and cultural boundaries (Cucuzzella 2016). Cucuzzella (2016) identified four levels of design for sustainable innovations: product improvement, product redesign, function innovation and system innovation. The later tackles sustainable issues at a global scale, challenging existing social and cultural assumptions to exceed beyond a mere artifact redesign.

2.3. Educating engineering students about sustainable design

Teaching sustainability calls for a transdisciplinary approach to foster system innovation (Ashford 2004). Active learning is best suited to teach transdisciplinary skills and systems thinking needed to tackle sustainable development projects (Mulder *et al.* 2012). A lack of consistent integration of active learning and focus on sustainability in courses across engineering programs still persist, even though recent progress has been made in that direction (Siller 2001; Azapagic 2005; Chau 2007; Huntzinger *et al.* 2007). The process of integrating sustainability in engineering curriculums is still an active area of research (Lozano 2010; Bielefeldt 2013).

Students learning to design for sustainability are encouraged to develop complex cognitive skills to resolve both abstract and applied problems (Salganik & Rychen 2003; Barth *et al.* 2007; Lambrechts *et al.* 2013). For example, sustainable thinking is a key element into a paradigmatic shift from *designing things right* to *designing the right things*, meaning that it aligns with current needs without compromising future generations (Cardenas *et al.* 2010). Sustainable design has the potential to integrate both paradigms to *design the right things right.*

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Creative brainstorming is a necessary tool in education to help students frame complex and intertwined concepts and find ideas during design ideation (Kajzer Mitchell & Walinga 2017). Requiring students to practice brainstorming concepts that also meet sustainability requirements is effective in teaching and learning about sustainable design. It can enhance higher-order thinking skills (Fini *et al.* 2018). Adding sustainability as a design requirement in the educational context is also a driver for the development of students' creativity (Bremer *et al.* 2010). Creativity is fostered through design for sustainability, as the aim of this type of design is not only to provide a solution to the design problem but to question the problem itself (Morris *et al.* 2007).

While engineering education is meant to help students cognitively deal with the complexity of sustainability through training and the use of more structured approaches for design, education attainment and prior knowledge can result in design fixation (Genco *et al.* 2012). Designers with expertise are more likely to attach new design concepts to their initial and early solution concepts and fail to consider more radical alternatives (Cross 2011; Genco *et al.* 2012). To address complex and interdisciplinary sustainability problems, engineers need to generate a wide range of alternative solutions, sometimes outside of industry norms (Cross 2004). Education provides both positive and potentially negative effects through fixation and reliance on learned industry norms during design.

2.4. Measuring design neurocognition to reflect on design education in engineering

Including sustainability into the design processes adds more requirements to an already cognitively complex process. The effect of adding sustainable constraints when generating design solutions is not well understood. Including sustainable requirements makes engineering design problems more complex and brings into question ways to teach engineering design.

Prior design studies usually measure design cognition (i.e., high-order thinking or creative thinking) through self-report or protocol analysis (Ericsson & Simon 1984). Both self-report and protocol analysis are limited in their ability to explain how the designer cognitively processes and manages dimensions of sustainability. Advances in cognitive neuroscience offer an opportunity for design researchers to explore cognitive activation in the human brain during design. Methods from cognitive neuroscience provide an objective measurement representing changes in design cognition (Borgianni & Maccioni 2020; Gero & Milovanovic 2020).

2.4.1. Role of the prefrontal cortex in design cognition

The prefrontal cortex (PFC) is a critical brain region for problem solving and decision-making (Siddiqui *et al.* 2008). The cognitive functions of the PFC include executive control functions, attention, working memory, planning and inhibition. These functions play important roles during design ideation (Gibson *et al.* 2009; Goel 2014). Prior research highlights how the PFC in the right and left hemispheres perform distinct functions in concept generation. The right PFC is more active in divergent thinking and sustained attention (Cabeza & Nyberg 2000; Moore *et al.*

2009). The left PFC shows more activation in goal-directed planning and making analytic judgments (Aziz-Zadeh *et al.* 2013; Luft *et al.* 2017).

Subregions in the PFC are also involved in varying functions necessary for concept generation. The dorsolateral prefrontal cortex (dlPFC), in both hemispheres, are active during creative thinking and making new associations (Funahashi 2017). Creative tasks tend to activate the right dlPFC more strongly (Shealy *et al.* 2018). Literature about the right dlPFC is also known to contribute to exploration (i.e., without rules) and improvization; for example, electric stimulus to the right dlPFC increases performance among novice jazz musicians (Rosen *et al.* 2016). The right dlPFC is known to be a critical area for creative design tasks (Hay *et al.* 2019). Ventrolateral prefrontal cortex (vlPFC) is associated with self-reflection (left vlPFC) and uncertainty processing (right vlPFC) (Levy & Wagner 2011; Herwig *et al.* 2012). The medial prefrontal cortex (mPFC) is involved in memory retrieval and design empathy (Seitz *et al.* 2006; Euston *et al.* 2012).

Among engineering students, an intervention involving concept mapping reduced cognitive activation in the dlPFC but lead to more concepts generated among students (Hu *et al.* 2019). More structured concept generation techniques, such as TRIZ can also decrease cognitive load broadly across the dlPFC compared to brainstorming (Shealy *et al.* 2018). Brainstorming usually demands bilateral coordination between the left and right PFC (Shealy & Gero 2019).

2.4.2. Effect of design education and expertise on brain activation

A direction of prior design cognition research explores how interventions, expertise, training and education change patterns of brain activation (Berkowitz & Ansari 2010; Huang *et al.* 2013; Benedek *et al.* 2014; Yang 2015; Borgianni & Maccioni 2020). Expert designers elicit significantly higher activation in their PFC compared to novices during creative conceptual imagination tasks (Liang *et al.* 2019). Experts produce higher creative quality products than novice designers and elicit higher activation in their right hemisphere (Sun *et al.* 2013). Sun *et al.* (2013) also found that the use of text as an intervention when sketching is effective to increase the activation in the right hemisphere associated with diverse analytical thinking. Although neurocognition among designers is not that straightforward. Skilled musicians show deactivation or reduced activation compared to novice or nonmusicians during music improvization (Berkowitz & Ansari 2010) and music matching tasks (Petrini *et al.* 2011). Hu and Reid (2018) also found that contextual experience (i.e., prior experience with specific design context) has a negative effect on designers' mental state associated with creativity and also limited the novelty of their proposed solutions.

3. Research questions

The complexity of engineering design cognition and the additional dimensions of sustainability during design motivated the study presented in this paper. Engineering education should help students manage these complexities (Collado-Ruiz & Ostad-Ahmad-Ghorabi 2010; Hu *et al.* 2019). In particular, during the concept generation phase to ensure the right types of solutions are being put forward. The purpose of this study was to explore how first-year and senior

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engineering students develop design solutions and cognitively manage aspects of sustainability. The research questions are:

(i) How does the year of educational training in engineering influence students' ability to generate solutions?
(ii) How do additional dimensions of sustainability influence students' ability to generate solutions?

3.1. Hypotheses

The number of unique solutions generated (the behavioural component) and the cortical activation in the PFC (the neurocognitive component) were the two factors measured. Engineering students are trained and practice concept generation during their undergraduate education, so the first hypothesis is that senior undergraduate engineering students generate more solutions and generate solutions with less cognitive effort (measured from changes in oxygenated blood in the PFC). The expectation is concept generation will require a greater diversity of active brain regions as well as greater intensity of activity (i.e., greater amplitude of oxygenated blood in the PFC) among first-year students compared to senior students.

The senior engineering students who participated in the study were trained in sustainability through their coursework. The second hypothesis is senior undergraduate engineering students manage the additional dimensions of sustainability with more cognitive ease. In other words, they generate more ideas to address sustainable design problems than first-year engineering students with less cognitive effort. When dimensions of sustainability are included, the hypothesis is higher cognitive effort in the dlPFC is recruited from both groups but less among senior engineering students compared to first-year engineering students.

4. Methods

4.1. Experimental design

This study was approved by the Institutional Review Board at Virginia Tech. Engineering undergraduate students ($n = 23$, 12 first-year students and 11 seniors) participated in the study. All senior engineering students reported they have taken courses related to sustainability. Students either took a course titled Sustainable Systems or Sustainable Infrastructure. None of the students took both courses.

Students were given 10 engineering design problems based on Richard Smalley's list of the most pressing issues facing humanity in the next 50 years (Smalley 2003). Any list of design problems like this is inherently limited, but this list was previously used for similar tasks in similar studies with engineering students in college (Blizzard & Klotz 2012). It also provides design problems with which previous engineering students were familiar and tasks that span across environmental, social and economic dimensions of sustainability (Blizzard *et al.* 2015).

The design tasks were also checked for content validity with three experts in engineering education and a group of 15 graduate engineering students. The graduate engineering students were asked to brainstorm solutions to the 10 problems and then rate the level of difficulty of each problem. Students reported in interviews that there was little difference in task difficulty between the problems.

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The problems spanned topics including renewable energy, water quality, poverty and air pollution.

Students who participated in the research received the engineering problems in random order. The 10 problems were randomly divided into two categories: five were not given any additional dimension of sustainability and another five were given additional requirements for sustainability. The topics that received the additional dimension of sustainability were randomly selected out of the 10. The five tasks without additional specific dimensions of sustainability included: 'Prevent accident deaths in a busy intersection', 'Alternative power generation sources other than coal for Haiti', 'Provide water in rural African villages', 'Remove carbon dioxide from the atmosphere' and 'Reduce slum populations in developing countries'.

The other five tasks that included additional dimensions of sustainability were: 'Heat a house in winter. Your solution cannot include mechanical systems' (i.e., passive design), 'Reduce construction waste going to the landfill. Your solution must reuse discarded objects to create new products' (i.e., circular economy), 'Prevent water body contamination in cities. Your solutions must mimic or include processes found in nature' (i.e., biomimicry), 'Reduce traffic congestion in and around Washington, DC. Your solution must minimize demand for cars' (i.e., human-centered solutions) and 'Protect New York City against another Super Storm Sandy. Your solution must also restore nature' (i.e., natural systems and resilience).

The presence of additional sustainability requirements is explicit in some tasks, such as a forced inclusion of environmental benefits in the solution, while in other cases the additional sustainability requirement is derived from imposing a specific sustainable design method, for example, biomimicry or passive design. The randomization of tasks that received the additional dimensions of sustainability and the averaging of the number of outcomes and neurocognitive response over the five tasks, described in more detail in the analysis techniques section, helped limit the possible effect of an individual task on the overall data. In addition to the broad integration of sustainability requirements taken from similar prior experiments (Klotz *et al.* 2014; Blizzard *et al.* 2015; Hu & Shealy 2018), the use of multiple tasks offers a more comprehensive understanding about the broad effects of adding dimensions of sustainability and enabled a more broad contribution to the understanding of design cognition for sustainability.

Students were given 60 seconds to develop as many solutions as possible to each problem. Following each 60-second concept generation session, students were given a 30-second rest period before the next design problem. In total, the experiment lasted around 16.5 minutes. The timing of 60 seconds for each task was based on pilot studies (Grohs *et al.* 2017; Shealy *et al.* 2017). The time frame for the resting period was chosen considering the pattern of human cortical activation. The 30-second time frame is double the length of the typical hemodynamic response for a cognitive task (Pinti *et al.* 2015). The purpose of the 30-second rest period was to bring the activated brain regions back to a resting state before the next task. In a pilot study, data and video recordings captured a spike in the cognitive activation in the PFC during the rest period. In discussion with participants during the pilot study, students described reflecting on their performance during this rest period. To reduce this reflection, basic arithmetic questions were included every 10 seconds during the 30 second rest period. These arithmetical

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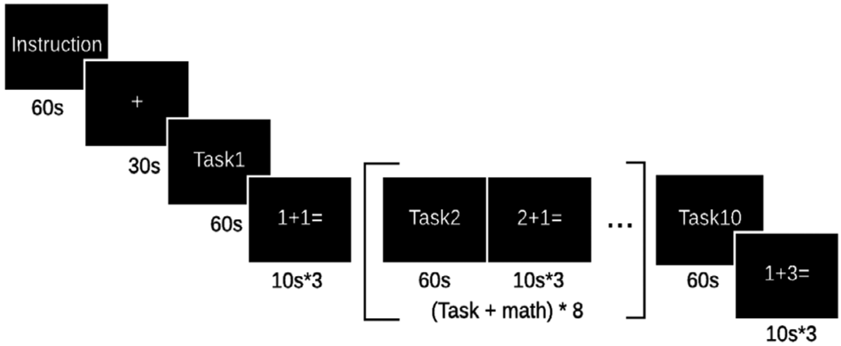

Figure 1. Block design process.

problems do require cognitive activation in memory but less processing and effort than concept generation or reflection, and the region of activation is not the same (Dresler *et al.* 2009). The experimental design is outlined in Figure 1.

During the concept generation task, students verbally described their design solutions and a researcher tallied the number of unique 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 task was recorded only once. Metrics for measuring design ideation usually includes quantity, quality, novelty and variety (Shah *et al.* 2003). Experiments about concept generation, generally requires suspended evaluation, and are typically evaluated based on the number or novelty of solutions generated (Kudrowitz & Wallace 2013). In this study, the quantity (i.e., number of unique responses) was the main measurement because of its objectivity and prior literature demonstrating that the higher the fluency, the higher the novelty of solutions (Hocevar 1979; Paulus *et al.* 2011; Kudrowitz & Wallace 2013; Shiu 2014). Novelty is related to fluency (Hocevar 1979; Paulus *et al.* 2011; Kudrowitz & Wallace 2013; Shiu 2014). The quality of solutions is also important for design but generally in phased concept generation sessions, assessment of the quality of solutions is reserved for after the concept generation phase is over.

4.2. fNIRS data acquisition

fNIRS was used to measure change in cognitive activation. fNIRS is unique compared to functional magnetic resonance imaging (fMRI) because fNIRS allows participants to operate a computer or perform a task in an upright sitting position (Eysenck & Keane 2015). A drawback of fNIRS compared to fMRI is that fNIRS is unable to capture subcortical activation in the brain due to limited power of the light emitted into the cortex. Although, brain regions critical for design cognition, such as the PFC, are adequately accessible with fNIRS (Strait & Scheutz 2014). Another instrument used frequently in neurocognition research is Electroencephalogram (EEG). Compared to EEG, fNIRS has higher spatial resolution and allows for better detection of change in cortical regions of the brain (Eysenck & Keane 2015). A limitation of fNIRS is that it fails to capture the activation on the order of milliseconds like EEG.

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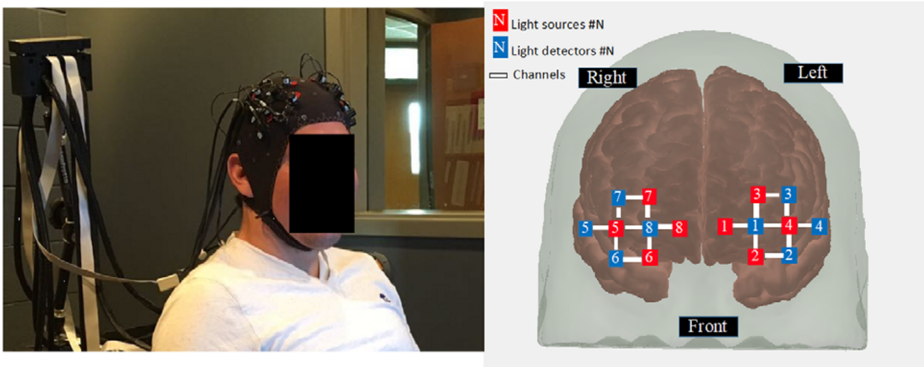

Figure 2. fNIRS placement along the frontal cortex.

fNIRS is safe, portable and noninvasive. It is worn as a cap, similar to EEG, and emits 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 (deoxy-Hb) and oxy-hemoglobin (oxy-Hb) absorb more light than water and tissue in the brain. The relative concentration of oxy-Hb is calculated from the photon path length, based on the Modified Beer–Lambert Law. The assumption with measuring oxy-Hb is when neuronal activity is increased in one part of the brain, there is also an increased amount of cerebral blood flow to that area (Glimcher & Fehr 2013). This increase in blood flow produces an increase in the ratio of oxy-Hb relative to deoxy-Hb in that specific area. Both are measured with fNIRS, though typically only the oxy-Hb is reported in fNRIS studies (Hu & Shealy 2019).

fNIRS sensors, including light sources emitting the near-infrared light and detectors measuring the reflected light, were placed along the prefrontal frontal cortex so that fNIRS instrument will capture the change in hemoglobin in this region of interest. Figure 2 shows a participate wearing the cap and the brain regions covered by the sensors. In total eight sources and eight detectors were placed along the left and right hemisphere (four sources and four detectors on each hemisphere) of the scalp. These sensors and detectors composed 18 channels. A channel is the connection between one light source and one neighbouring detector.

4.3. Analysis techniques

The data collected in the study included the behavioural data (number of solutions generated in brainstorming tasks) and neurocognitive data (change in Oxy-Hb using fNIRS in the PFC). Statistical methods, including two-way ANOVA, two sample *t*-tests and paired *t*-tests, were used to compare the difference between first-year and senior engineering students and the effects of added dimension of sustainability on engineering design cognition.

For each subject, the number of solutions in each task was counted and averaged respectively to obtain the number of solutions when additional dimensions of sustainability were and were not present. This averaging technique reduced the possible effects from different design problems. The statistical method used to compare the number of solutions was a two-way mixed-design ANOVA with repeated measure on one factor between first-year and senior engineering students when dimensions of sustainability were and were not present.

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fNIRS raw data were processed using the package of HomER 2 NIRS in Matrix laboratory (MATLAB) (Huppert *et al.* 2009) and only oxy-Hb response was analysed and reported since it has relatively higher amplitudes and sensitivity than deoxy-Hb (Cazzell *et al.* 2012). The algorithm of hmrMotionArtifactByChannel, hmrMotionCorrectSpline and Band-pass filter (0.03–0.2 Hz in 3rd order) in HomER 2 was used to remove and correct motion artefacts and other noises (e.g., instrumental noise and psychological noise) (Yücel *et al.* 2014; Naseer & Hong 2015). Due to a bad signal, data from three subjects were removed from the analysis. Among the remaining 20 participants (average 19.5 ± 1.64 years old, 10 females, right-handed), 12 were first-year engineering students and eight were senior engineering students.

A block averaging technique was applied for additional noise removal (Kirilina *et al.* 2013). The change of oxy-Hb in the five nonparameter tasks were averaged for each subject. The 30-second baseline data for each individual participant was subtracted from each channel when additional sustainability dimensions were or were not included in the brainstorming task. The resulting processed data are representative of the increase in neurocognitive activation due to the task.

To analyse cognitive difference between first-year and senior students, fNIRS data were averaged channel by channel across the sample of first-year and senior engineering students. This averaging approach follows similar previous fNIRS studies (Bunce *et al.* 2011; Glotzbach *et al.* 2011; Ferrari & Quaresima 2012). The result is two series of data that represents the average oxy-Hb responses in the PFC.

To analyse neurocognitive difference among engineering students when additional dimensions of sustainability were present in the task, fNIRS data were averaged across all samples in the tasks without additional dimensions of sustainability and in the tasks when additional dimensions of sustainability were present. A Bonferroni correction was applied to increase the confidence interval from 95% ($p < 0.05$) to 99.998% ($p < 0.002$). The Bonferroni correction was to control the familywise error rate when using multiple t-tests. Two sample t-tests and paired t-tests were performed to compare the difference in cortical activation between first-year and senior students.

5. Results

The results are presented in the order of the research questions. First, the number of unique solutions generated and differences in neurocognition between first-year and senior students. The subsequent subsections describe the influence of the additional dimension of sustainability on the number of solutions engineering students were able to generate and the effect on their neurocognition.

5.1. First-year students produced significantly more solutions than seniors when brainstorming

A two-way Analysis of Variance (ANOVA) with repeated measure was performed to compare the number of solutions generated by first-year and senior students, with and without dimensions of sustainability. First-year and senior engineering students generated a significantly different ($F(1,39) = 9.12$, $p = 0.007$) number of solutions when additional dimensions of sustainability were not included.

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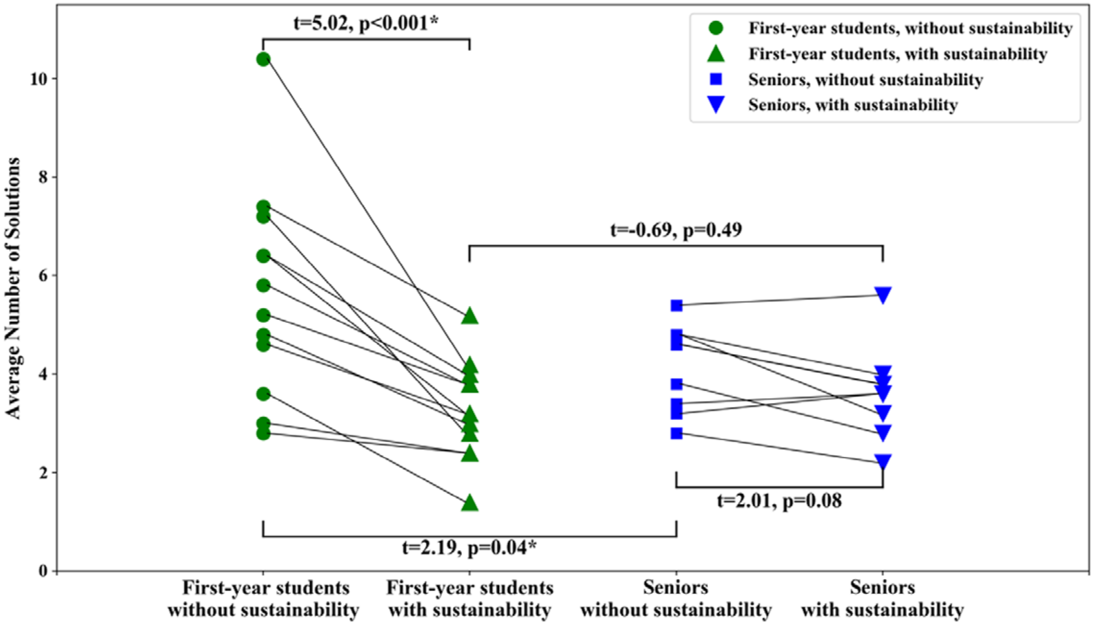

Figure 3. Average number of solutions generated by first-year students and seniors in the brainstorming tasks.

A *posthoc* Tukey test suggests significant difference within subjects ($t = 25.92$, $p < 0.001$) but not between subjects. An independent t-test identified the difference is between subjects when additional dimensions of sustainability were not included ($t = 2.19$, $p = 0.04$). The first-year engineering students generated significantly more solutions (5.63 ± 2.14) than the senior engineering students (4.10 ± 0.92) with a large effect size (Cohen's $d = 0.92$). Figure 3 illustrates the number of solutions generated by first-year and senior engineering students in the two types of engineering design problems.

5.2. Neurocognitive differences are observed between first-year and senior engineering students during the brainstorming tasks

Cortical activation (i.e., the level of oxy-Hb) in 14 out of 18 channels is significantly ($p < 0.002$) different between first-year and senior engineering students when generating concepts. First-year students recruited significantly more cognitive activation in 11 out of the 14 channels. The most significant difference between first-year and senior engineering students occurred in the left and right dlPFC. First-year students recruited and sustained higher cognitive activation for a longer period of time in the dlPFC compared to senior students. This increased cognitive activation suggests more cognitive resources allocated to this region of the brain when generating design solutions by first-year students. The dlPFC plays a critical role in working memory (Zhang *et al.* 2003), cognitive flexibility (Grattan *et al.* 1994) and abstract reasoning (Kroger *et al.* 2002). Figure 4 shows the significant differences in activation between first-year and senior engineering students in four of the channels located in the dlPFC. The shaded areas in the figure represent the

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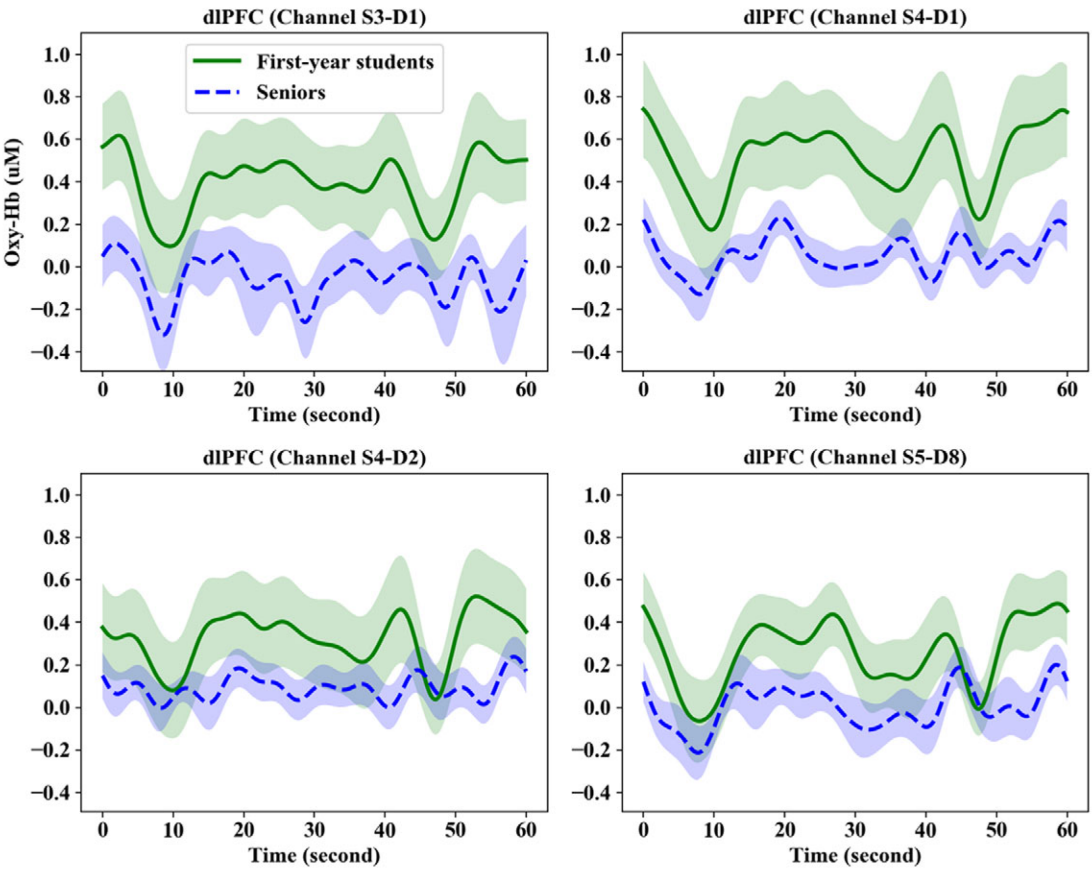

Figure 4. Higher cognitive activation in the dlPFC among first-year students engineering students when generating concepts.

standard error among participants. The effect size in all 11 channels was large (Cohen's $d > 0.8$).

Senior engineering students produced significantly higher levels of activation in three channels, located in left and right vlPFC, shown in Figure 5. Previous research suggests that the left vlPFC is recruited for self-reflection during decision-making (Herwig *et al.* 2012). While the right vlPFC is recruited to handle uncertainty processing (Levy & Wagner 2011). This result might suggest senior engineering students allocated more cognitive resources for self-reflection of their solutions and processing uncertainty, and less cognitive resources might have been available for the dlPFC, associated with divergent and convergent thinking.

5.3. Including dimensions of sustainability reduces the number of solutions generated by first-year engineering students but not senior engineering students

A paired t-test indicated that additional dimensions of sustainability significantly reduced the number of solutions generated by first-year students ($t = 5.02$,

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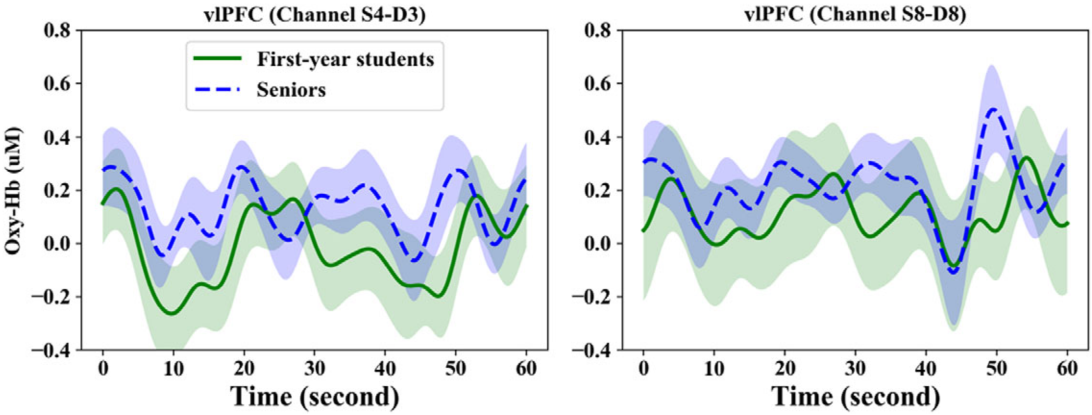

Figure 5. Higher cognitive activation in the vlPFC among senior engineering students when generating concepts.

$p < 0.001$, with a large effect size) but not for seniors ($t = 2.01$, $p = 0.08$), illustrated in Figure 3. The number of solutions senior engineering students generated remained consistent with and without additional dimensions of sustainability. Three out of eight seniors generated more solutions when dimensions of sustainability were required. There was no significant ($p = 0.49$) difference in the number of solutions generated by first-year and senior engineering students when additional dimensions of sustainability were required. In other words, the additional dimension of sustainability only had an effect on first-year engineering students' ability to generate solutions. However, more years of training in engineering did not facilitate senior engineering students to generate more sustainable solutions to engineering problems than first-year students.

5.4. Both first-year and senior engineering students use more cognitive resources when generating solutions to meet additional dimensions of sustainability

The repeated ANOVA indicates that the cortical activation of all the engineering students was significantly higher in the left vlPFC and dlPFC when the additional dimensions of sustainability were added. Figure 6 illustrates the cognitive difference in two channels located in the dlPFC and vlPFC when generating solutions for both types of tasks. As mentioned before, the left vlPFC is associated with self-reflection. The left dlPFC is generally associated with playing an active role during convergent thinking and making analytic judgements (Luft *et al.* 2017). Higher activation in these two regions in the left hemisphere means more cognitive resources are recruited when additional dimensions of sustainability are added to the concept generation task.

Further analysis of students' neurocognition when focusing on tasks with additional dimensions of sustainable between the two groups of students shows the underlying mechanism that differs between them. When generating solutions for the problems with the additional dimension of sustainability, first-year engineering students recruited significantly ($p < 0.002$) higher levels of activation in 10 channels located in the left and right dlPFC with large effect sizes. This increase

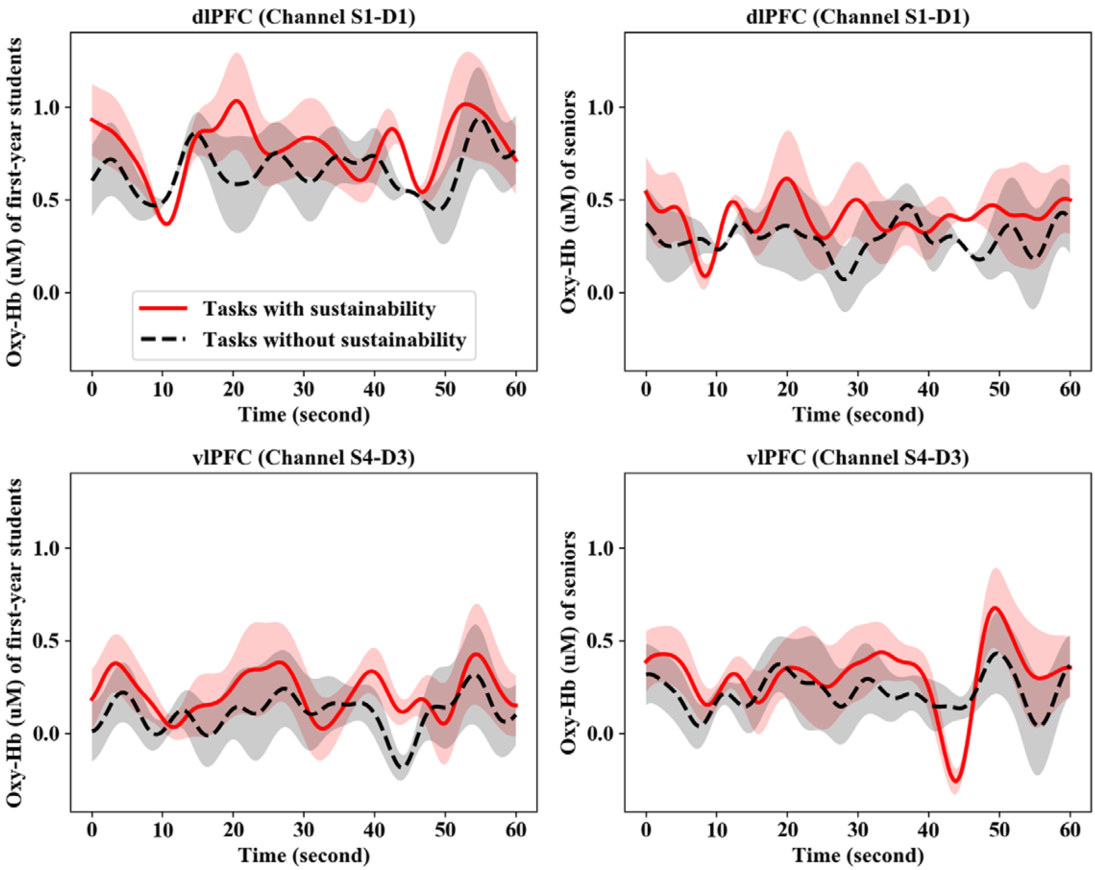

Figure 6. Higher cortical activation in the vlPFC and dlPFC among first-year and senior engineering students when including additional dimensions of sustainability.

in activation occurs without first-year students generating an equal number of solutions as the tasks without the added dimension of sustainability.

Averaged over all channels in the PFC, first-year engineering students recruited more cognitive resources than senior engineering students. The first-year and senior engineering students produced a similar number of solutions when the additional dimension of sustainability was present. The senior engineering students were more cognitively efficient in their ability to generate sustainable solutions compared to the first-year engineering students. Meaning, senior engineering students required less cognitive resources to generate each solution compared to the first-year engineering students. Within the subregions of the PFC, first-year engineering students recruited more cognitive activation specifically in the dlPFC, but this group required significantly ($p < 0.002$) less cognitive resources in two channels located in the left vlPFC compared to the senior engineering students. An increase in activation in the left vlPFC among senior engineering students might suggest seniors recruited more cognition for self-reflection than first-year students (Fiez *et al.* 1996; Ranganath *et al.* 2003; Deppe *et al.* 2005).

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6. Discussion

Quantity is one of the critical metrics measuring the effectiveness of design ideation (Shah *et al.* 2003). Ball *et al.* (1998) point out that during the ideation phase of engineering design, generating more design alternatives is beneficial to increase the chances of a better final design. Theorists and educational professionals teach ideation during engineering design by generating a wide range of alternative solutions (Osborn 1993; Cross 2004; Paulus *et al.* 2011). Ideally, engineering education is supposed to enhance the ability of students to generate more solutions to engineering design problems (Yilmaz *et al.* 2014). However, the results presented in this paper seem to suggest the opposite. In the design tasks without added dimensions of sustainability, senior engineering students, with more years of engineering education, failed to generate a larger range of solutions compared with first-year engineering students.

The fewer solutions produced by senior engineering students might be explained by concept fixation. Usually, designers with more expertise have the tendency to fixate on their early solutions and are reluctant to generate more alternatives (Genco *et al.* 2012). On the other hand, generating a wide range of alternative concepts may not always benefit design quality, therefore generating a limited number of alternatives can be an appropriate strategy (Cross 2004).

The cortical activation captured by fNIRS offers neurocognitive explanations about the difference in the number of solutions generated by first-year and senior engineering students. First-year students recruited more activation in the brain region associated with working memory, cognitive flexibility and abstract reasoning (dlPFC). Senior engineering students recruited more activation in the brain regions associated with uncertainty processing and self-reflection in decision-making (vlPFC).

A possible explanation for the higher activation among senior engineering students in the vlPFC is that the senior engineering students felt uncertain about their ideas and applied a filter to evaluate and reflect if their answer was acceptable prior to verbally providing the solution. This result seems consistent with the findings in previous research, which found that undergraduate engineering students spend more cognitive effort analyzing their solutions (Lammi & Gero 2011) while high-school students generate more ideas without further evaluation about their ideas (Kavakli & Gero 2002). The increased activation among first-year students in the right and left dlPFC provides supporting neurocognitive evidence for why they generated significantly more solutions. First-year students increased involvement of their right dlPFC. This region is usually associated with divergent thinking in creative tasks (Moore *et al.* 2009; Zmigrod *et al.* 2015). First-year students also recruited more activation in their left dlPFC. This region is generally associated with convergent thinking in creative tasks (Luft *et al.* 2017).

6.1. The effects of adding dimensions of sustainability during ideation

Sustainability is generally regarded as a design constraint limiting the engineering design processes (Collado-Ruiz & Ostad-Ahmad-Ghorabi 2010). Concerns about the ability of engineering students to contribute to sustainable design continue to persist (Carew & Mitchell 2008; Davidson *et al.* 2010; Khalili *et al.* 2015).

The results presented in this paper find that requiring students to meet additional dimensions of sustainability increased the difficulty of design concept generation. Students had to recruit more cognitive resources to complete the tasks when additional sustainability requirements were presented.

First-year engineering students were unable to generate as many solutions to the problems with additional dimension of sustainability as they generated when sustainability was not a requirement. These first-year engineering students may not have adequate knowledge about sustainability or design methods to manage this added complexity. Senior engineering students were less affected by the additional dimensions of sustainability. They recruited more cognitive resources but were able to generate a similar number of solutions compared to the tasks without the added dimensions of sustainability. The difference in outcomes between first-year and senior engineering students offers new evidence that engineering education may support the objective of enhancing student capabilities to cognitively manage the added complexities required for sustainable design.

The neurocognitive evidence suggests that both first-year and senior engineering students recruited significantly more cognitive resources to complete the ideation tasks when sustainability was a requirement. This result is consistent with prior studies that find increasingly difficult tasks produce increasingly higher activation in the PFC (Petkar *et al.* 2010; Nguyen & Zeng 2017). However, first-year and senior engineering students appear to use different neurocognitive strategies to handle the design constrains associated with sustainable design. The differences in neurocognitive activation between first-year and senior engineering students were observed when sustainability was not a requirement but becomes more pronounced when sustainability was added to the concept generation tasks.

Adding dimensions of sustainability triggered more neurocognitive activation in the dlPFC for first-year students. Senior engineering students recruited more neurocognitive resources to the vlPFC, the brain region generally associated with self-reflection. A possible explanation for the contradiction between first-year students' higher neurocognitive activation and fewer solutions is that they continue to cognitively search for solutions but do not have the knowledge basis or experience to meet that added design constraints (She & MacDonald 2018; Maccioni *et al.* 2019). A related explanation is first-year students may have become overwhelmed with the added complexity and cognitive overload led to the decrease in productivity (Collado-Ruiz & Ostad-Ahmad-Ghorabi 2010). Another possible explanation is first-year students allocated more cognitive resources to processing the problem, and the problem space, as a result, less cognitive resources remained to generate a large number of solutions.

The increased neurocognitive activation in brains of the senior engineering students occurred in the vlPFC, the region associated with self-reflection. Prior research finds this region critical for performance in sustainable design and design participants elicited higher activation in the vlPFC when they showed more preference for sustainable products (Goucher-Lambert *et al.* 2017).

6.2. Implications for sustainable design teaching in engineering education

The senior engineering students who participated in the experiment had taken sustainability-related courses. These senior engineering students likely had more

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knowledge about sustainable design. Unsurprisingly, they appear more prepared to cognitively manage additional requirements for sustainable design compared to the first-year students. Prior research suggests students who learn about broad dimensions of sustainability were subsequently better prepared to produce novel engineering design solutions (McWhirter & Shealy 2020). The results presented here provide new supporting evidence for the potential benefit of education for sustainability to enhance engineering design.

In addition to courses about sustainability, senior engineering students had more experience with the engineering design process. They had practice with managing design requirements like sustainability and this likely had an effect on the outcome. Experience is a significant factor in design cognition (Kavakli & Gero 2002, 2003). Cognitive differences from experience are observable in the brain. For example, air traffic controllers with decades of experience required significantly less cognitive resources to manage a higher number of airplanes than novice air traffic controllers (Harrison *et al.* 2014).

Teaching design ideation techniques like Theory of Inventive Problem Solving (TRIZ) or the use of concept mapping may help improve students' ability to cognitively manage the complexity of sustainability (Shealy *et al.* 2017; Shealy *et al.* 2018). For example, students that use concept maps during design ideation produce significantly more concepts and also require less cognitive resources (Hu *et al.* 2019). Future research could explore the effects of teaching first-year students design techniques like concept mapping prior to design ideation tasks and measure the effect on design cognition.

The use of concept maps may also help senior engineering students. Concept mapping was previously demonstrated to direct more cognitive resources to the dlPFC (Hu *et al.* 2019). This is the region of the brain associated with divergent thinking and was less recruited among senior engineering students compared to first-year engineering students during the concept generation tasks. Senior engineering students produced fewer design solutions than first-year students when sustainability was not a requirement.

The observed neurocognitive changes from the study presented in this paper offers potential opportunities for interventions to help improve sustainable design outcomes. For example, future research could explore whether priming the recruitment of activation in the dlPFC, or through transcranial direct current stimulation (tDCS) to the dlPFC, can improve senior engineering students' ability to generate more novel design solutions (Sahar *et al.* 2020). Designers who first completed the Stroop test (requiring participants to quickly and accurately name font color that is mismatched with word text) subsequently produced more creative solutions than designers who did not complete the Stroop test. The increased level of creativity was equal to designers that received a transcranial shock (Sahar *et al.* 2020). This type of intervention, through priming or tDCS, may also help overcome design fixation. For example, tDCS can help enhance cognitive control (Feeser *et al.* 2014) and reduce attention bias (Heeren *et al.* 2015).

In addition to future research exploring the effects of interventions to improve sustainable design, future research should also begin to explore if added dimensions of sustainability produce unique mental activities or if the observed mental activities are similar to concept generation process with other types of design constraints or requirements. For instance, a future study could compare the

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activation patterns between sustainable design and empathic design. Empathetic design may elicit higher activation in the mPFC (Shealy *et al.* 2020) and may lead to a shift of cognitive functions between divergent and convergent thinking in the right and left PFC (Milovanovic *et al.* 2020).

7. Limitations

There are several limitations to this study that are worth mentioning. fNIRS data from this study only include the change of oxygenated hemoglobin in the PFC. Other brain regions (e.g., parietal cortex) likely contribute to concept generation. This is a limitation common to all neuroimaging studies that do not capture whole-brain activation (Ayaz *et al.* 2012; Cazzell *et al.* 2012). The time constraint for each design task is another limitation. It may have contributed to the number of solutions students generated. A consistent amount of time for each concept generation task was necessary so the neurocognition within and between subjects could be averaged and compared. Future research can begin to explore not just the initial patterns of neurocognition among designers (in the first 60 seconds) but longer periods of time and with more subjects (Shealy *et al.* 2018). Another limitation is that this study focused on neurocognitive differences and the number of unique solutions engineering students generated. Future research can begin to explore the uniqueness of solutions rather than just the fluency of solutions.

The quality of each solution was not included as an evaluation metric because this is beyond the initial phase of concept generation, which focuses primarily on the quantity of solutions. Future studies can use more metrics, such as quality, novelty and variety, to measure the effectiveness of ideation to address sustainable design tasks. The 20-person sample size is another limitation (Schönbrodt & Perugini 2013). Although, the number of participants is above the average of seven subjects in a systematic review of conceptual design cognition (Hay *et al.* 2017b) and similar to the average sample size of 27 in other fNIRS studies for problem solving and decision-making (Hu & Shealy 2019). Future research should replicate the results with a larger sample size (Shrout & Rodgers 2018).

Another limitation was the design problems. The use of 10 previously developed engineering design problems was intentional to control for potential experimental error between each individual problem. Future research could begin by replicating the experiment with the two sets of problems in counterbalance to achieve better parity. The list was also inherently limited. Future research could also replicate the study with an additional new set of design tasks.

Another future study could ask students to narrate how they developed solutions or if they felt uncertain, and to reflect about their solutions before verbally saying them out loud. More descriptions about how and why students generated concepts would give additional insights into the cognitive processes observed in the brain. Another line of research stemming from this study is how the use of mnemonics, specific training or design methods and tools related to sustainability may influence where and how engineers access information in their brain. For instance, prompting students with design heuristics (Daly *et al.* 2012) or priming exercises (She *et al.* 2018) may lead to more targeted ideas or refocus their solutions to options previously not considered.

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8. Conclusion

The interdisciplinary study reported in this paper explores how engineering students cognitively produce solutions to engineering design problems and cognitively manage added dimensions of sustainability. The results indicate that first-year students generate more solutions and elicit higher cortical activation associated with cognitive flexibility than seniors when additional dimensions of sustainability are not included. Seniors recruited higher activation in the region of their brain primarily associated with uncertainty processing and self-reflection, suggesting a possible tendency of evaluation and design fixation. The inclusion of additional sustainability dimensions in the brainstorming task required higher cognitive activation associated with cognitive flexibility for both first-year students and seniors, however, only first-year students, showed a decrease in the number of solutions when dimensions of sustainability were included.

Many empirical studies have investigated the cognitive processes during brainstorming or ideation for sustainability by observation or self-report (Cross 2001; Coley *et al.* 2007; Daly *et al.* 2012). A key limitation is the subjectivity and lack of reliability that comes with observation and self-report. The study presented in this paper provides a novel objective measure of design cognition through neuroimaging and demonstrates the potential of using fNIRS to triangulate design cognition and outcomes.

This interdisciplinary study, combining sustainable design and neurocognition, contributes to the science of sustainable engineering by demonstrating the effects of sustainability requirements on design behaviour and design cognition. Better understanding the activated brain regions required for sustainable design and how additional dimensions of sustainability affect students' ability to produce outcomes begins to shed light on the current gap and potential need of engineering education for sustainability. Future studies can begin to test the effectiveness of novel design methods and tools, for example, concept mapping or priming, to overcome fixation and enhance engineering students' ability to develop engineering design solutions.

Acknowledgments

This material is based in part on work supported by The National Science Foundation, through Grant EEC-1929892. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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