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Methods and Preliminary Findings for Developing and Assessing Engineering Students' Cognitive Flexibility in the Domain of Sustainable Design

Dr. Elise Barrella, James Madison University

Dr. Elise Barrella is an Assistant Professor of Engineering at James Madison University, who focuses teaching, scholarship, service, and student mentoring on transportation systems, sustainability, and engineering design. Dr. Barrella completed her Ph.D. in Civil Engineering at Georgia Tech where she conducted research in transportation and sustainability as part of the Infrastructure Research Group (IRG). Dr. Barrella has investigated best practices in engineering education since 2003 (at Bucknell University) and began collaborating on sustainable engineering design research while at Georgia Tech. She is currently engaged in course development and instruction for the junior design sequence (ENGR 331 and 332) and the freshman design experience, along with coordinating junior capstone at JMU. In addition to the Ph.D. in Civil Engineering, Dr. Barrella holds a Master of City and Regional Planning (Transportation) from Georgia Institute of Technology and a B.S. in Civil Engineering from Bucknell University.

Dr. Mary Katherine Watson, The Citadel

Dr. Mary Katherine Watson is currently an Assistant Professor of Civil and Environmental Engineering at The Citadel. Prior to joining the faculty at The Citadel, Dr. Watson earned her PhD in Civil and Environmental Engineering from The Georgia Institute of Technology. She also has BS and MS degrees in Biosystems Engineering from Clemson University. Dr. Watson's research interests are in the areas of engineering education and biological waste treatment.

Dr. Olga Pierrakos, James Madison University

Olga Pierrakos is a Founding Faculty and Associate Professor in the Department of Engineering at James Madison University. She is currently a Program Director at the National Science Foundation in the Division of Undergraduate Education. Her expertise and interests focus on diversity and inclusion, engineer identity, PBL, innovative learning-centered pedagogies, assessment of student learning, engineering design, capstone design, etc. She also conducts research in cardiovascular fluid mechanics and sustainable energy technologies. She holds a BS and MS in Engineering Mechanics and a PhD in Biomedical Engineering from Virginia Tech.

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Executive Summary

Engineering problem-solving requires knowledge from multiple domains (i.e., technical, environmental, economic, and social) in order to address real-world sustainability problems. Engineering students should be educated about sustainability and be trained to apply sustainability concepts in design in order to produce better products, processes, infrastructure, and services. During their undergraduate education, students gain knowledge in relevant domains from a variety of courses (both engineering and non-engineering), yet they have difficulty connecting knowledge from across classes or domains to fully analyze problems and evaluate sustainability trade-offs. Operating under this premise, the first goal of our research is to help students apply (or supplement) their knowledge relating to sustainable design dimensions to complex, engineering problems, such as the ones they encounter during capstone design and will encounter in the real-world. The second goal is to improve assessment of students' abilities to apply sustainable engineering design concepts across different problems or design challenges. We hypothesize that with guided practice and feedback, engineering undergraduate students will become better at drawing upon and integrating diverse knowledge domains when they are faced with new, complex problems during professional practice. Project work began in September 2015 through the NSF Research in Engineering Education program.

Cognitive flexibility theory (CFT)[1] provides a basis for assessing and improving students' knowledge transfer and the connection-building required to adequately address sustainability problems. The primary objective of this work is to use CFT and related adaptive expertise constructs to guide both learning and assessment of sustainable design. Our poster will present progress and preliminary findings in two areas: (1) Identifying appropriate measures of knowledge transfer/cognitive flexibility/adaptive expertise that apply to engineering design tasks and (2) Developing assessments to measure and help students improve ability to transfer knowledge to/across sustainable design problems. Specifically, we will describe our efforts to refine measures of cognitive flexibility and adaptive expertise by measuring cognitive functions using an electroencephalogram (EEG), an approach which is underdeveloped in engineering education research, particularly for complex problem-solving like sustainable design. We will also present progress on new or adapted assessment tools that focus on direct measures of student domain knowledge in different contexts (e.g., automated scoring of concept maps) and correct application of knowledge (e.g., cross-disciplinary sustainable design rubrics).

The first part of the project is updating a Sustainable Design Rubric (SD Rubric) for cross-disciplinary applications. Prior to the start of this project, members of the research team developed and tested a sustainable design rubric for evaluating capstone design projects, specifically for civil and environmental engineering.[2] For purposes of this project, non-discipline specific (or adaptable) measurement instruments are necessary for assessing educational outcomes across engineering problem contexts. We are in the process of updating and refining the rubric's content and structure to reflect current practices and ensure its applicability across disciplines. A systematic literature review of sustainability and sustainable design in engineering

curricula and practice confirmed most criteria in the rubric but also indicated several gaps. Some gaps were expected because the original rubric was directed towards civil and environmental engineering projects, but most of the themes were confirmed in other disciplines. Examples of potential gap areas included ethics, affordability and equity, and innovation. While these areas are reflected in the SD Rubric 1.0, the themes were not addressed explicitly or fully captured by the criteria and thus represented areas for improvement. Using a revised set of criteria, we are gathering expert input via a web form and in-person workshops to validate the rubric's content and also collecting examples of how student projects may address/fulfill those criteria.[3] Additionally, the new draft criteria have been compared to well-established sustainability frameworks, including the United Nations Sustainable Development Goals, STAUNCH©, and Envision™ Rating System. By combining expert feedback and gap analysis, we are able to identify and prioritize core (for all engineering disciplines) versus ancillary sustainable design criteria for specific disciplines or applications. By essentially crowdsourcing content and priorities from many disciplinary experts, we intend to make the rubric as adaptable as possible and have common metrics that we can use to assess and compare student populations at different institutions and over time.

Another learning and assessment approach that we are working with is concept maps, which are grounded in neuroscience research, specifically semantic memory theory. The size and connectedness of neuronal networks is related to cognitive flexibility and can be represented by concept maps. Deployment of concept maps in different courses, at our study institutions and at other institutions who are already using our methods and materials, indicate that they are viable measurement tools at different educational levels and in different course contexts.[4] Further, evaluations of student concept maps from three universities suggest the effectiveness of integrating sustainability instruction across course contexts versus isolating in a single course.[5]

Despite early successes with concept maps, using and evaluating the tool in large classes or with multiple concept map assignments could deter faculty from using them outside of a research project due to time commitment for scoring the maps. Thus, we prioritized the creation of an automated scoring tool using the Traditional Method, a component-based scoring approach, to allow for rapidly evaluating a large number of concept maps and extracting concepts for content analysis. The program automates counting the number of concepts, highest hierarchy, and number of cross-links as indicators of knowledge breadth, depth, and connectedness, respectively. First, the program extracts information from concept maps created using CmapTools, a free concept mapping software. Each concept map is quickly imported, recreated, and analyzed for traditional sub-scores using Python language data structures and the NetworkX software package. In a preliminary study, two trained judges and the computer program scored a sample of concept maps ($n = 78$). High agreement (Krippendorff's alpha ≥ 0.80) between manual and automated scores was observed for number of concepts and number of cross-links. Although less than acceptable agreement between manual and automated scores was observed for highest hierarchy, the two measures of knowledge depth (highest hierarchy and longest path) were highly correlated (Spearman's rho ≥ 0.5). The program is operational and freely available online[6] but currently uses longest path as a surrogate for highest hierarchy to measure knowledge depth. Overall, the computer program can be used to rapidly, precisely, and reliably score concept maps to aid in assessment of conceptual knowledge.

In addition to rubrics and concept maps, we are investigating other ways to directly measure cognitive flexibility (and related mental functions like cognitive load and cognitive efficiency), such as using an EEG to measure brain waves. Cognitive load is defined as the total amount of mental effort that is being used by the working memory at a given time.[7] While cognitive load varies across all individuals, the general principle is that too much cognitive load can be detrimental to task completion. However, experiencing high amounts of cognitive load is not always detrimental to learning. In fact, high and healthy amounts of cognitive load can allow us to improve our problem solving ability and increase our cognitive efficiency. Cognitive efficiency is our ability to use the mental resources that we have in order to solve problems.[8] Being able to determine what is a healthy amount of cognitive load for ourselves, and developing a high level of cognitive efficiency, is what allows us to solve highly-difficult problems and better develop cognitive flexibility. Cognitive flexibility is our mental ability to quickly switch between different concepts and to even think about multiple concepts simultaneously. This is a crucial part of solving complex problems because frequently there are multiple facets to each problem which need to be considered and evaluated before the problem can be solved.[1]

There are few studies in undergraduate education, let alone engineering education, that use EEG (or brain imaging techniques) to evaluate students' cognitive flexibility; no studies that we are aware of focus specifically on sustainable design. The most common way of "measuring" cognitive load or cognitive flexibility in the education literature is student self-report surveys, which are an indirect measure, or scoring problems for correctness and completion time. With the EEG, researchers look for specific brain waves that indicate higher cognitive load or effort while participants complete tasks.[9]

Using sustainable design themed tasks/problems, we will be able to evaluate "correctness" of students' conceptual knowledge and completion time for iterations of tasks while monitoring brain activity using the EEG. A hypothesis is that with regular practice of tasks, like generating concept maps of sustainable design considerations for different cases, students will demonstrate improved cognitive flexibility. To further our understanding of the relationships between cognitive load, efficiency, and flexibility and how they vary during engineering problem-solving, we have designed a two-phase study on cognitive functions using EEG. The first phase of the study, which began in Fall 2016, is using an EEG to directly measure cognitive load experienced while solving engineering problems of varying degrees of complexity. Participants in the first phase are six sophomore and six senior engineering students. During the problem-solving sessions, the participants wear the EEG cap to measure their brain waves as they solve each type of problem and are asked to self-assess workload on each problem using the NASA Task Load Index (TLX) survey[10]. Analysis of the collected brain waves and self-report data from NASA TLX allows testing of the hypothesis that as problems increase in complexity, cognitive load (or mental effort) also increases. The goal of the second phase is to look deeper into how students experience cognitive load as they are solving more open-ended design problems. We hope to establish a mapping of cognitive functions throughout the design process so that we may better define cognitive flexibility in this context.

Over the next year, we will be assessing student work products from design projects using new tools (like the rubric) and assigning new learning activities to students that vary the context in which they are applying sustainable design. This project focuses on practical, evidence-based, direct assessment tools that are transferable to other institutions and across engineering departments. With the rubrics, concept map scoring, and EEG equipment, we will be able to monitor students over time to determine what effects classroom interventions related to sustainable design have on students' cognitive load and development of cognitive flexibility – do they perform better over time when presented with new (but related) design challenges? We plan to triangulate results from the EEG study with other direct measures of students' conceptual knowledge and design skills to better understand the impact of our approach and identify areas for further work.

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