

## Measuring Connections: Novel Methods and Findings

### Dr. Elise Barrella P.E., DfX Consulting LLC

Dr. Elise Barrella is the founder and CEO of DfX Consulting LLC which offers engineering education and design research, planning and consulting services. She is a registered Professional Engineer and was a Founding Faculty member of the Department of Engineering at Wake Forest University. She is passionate about curriculum development, scholarship 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). 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. 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. Prior to joining the WFU faculty, she led the junior capstone design sequence at James Madison University, was the inaugural director of the NAE Grand Challenges Program at JMU, and developed first-year coursework and interdisciplinary electives.

### Dr. Mary Katherine Watson, The Citadel

Mary Katherine Watson is currently an Associate Professor of Civil and Environmental Engineering at The Citadel. She holds BS and MS degrees in Biosystems Engineering from Clemson University and a PhD in Environmental Engineering from The Georgia Institute of Technology. She enjoys, and has invested significantly, in the development of her undergraduate students, serving as past faculty advisor for numerous student groups. Dr. Watson is passionate about improving access to engineering education and serves as the faculty director for a scholarship program to recruit and support high-performing, low-income civil engineering students. Dr. Watson is also interested in understanding and assessing students' cognitive processes, especially development of cognitive flexibility and interactions with cognitive load. Dr. Watson is the proud recipient of seven teaching awards and six best paper awards. She was previously named the Young Civil Engineer of the Year by the South Carolina Section of ASCE and currently serves as a Senior Associate Editor for the Journal of Civil Engineering Education.

### Dr. Robin Dawn Anderson, James Madison University

Robin D. Anderson serves as the Academic Unit Head for the Department of Graduate Psychology at James Madison University. She holds a doctorate in Assessment and Measurement. She previously served as the Associate Director of the Center for Assessment and Research Studies at JMU. Her areas of research include assessment practice and engineering education research.

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## Executive Summary for NSF Poster Session

Faculty often observe that difficulty with connecting knowledge from across classes or domains limits students' ability to fully analyze problems and evaluate trade-offs. Knowledge retrieval and transfer can be particularly challenging when students are presented with a new problem context or expected to make connections across disciplines. Problems related to “sustainability” and/or “systems” exemplify the multi-faceted and multi-disciplinary problems that require students (and professionals) to demonstrate cognitive flexibility.

Cognitive Flexibility Theory (CFT) was suggested as a means to understand how students learn in complex and ill-structured domains and thereby improve problem-solving performance [1]. In the CFT literature, there is no clear consensus on a definition of cognitive flexibility or how it is directly measured in a complex problem-solving situation such as engineering design projects. One common definition of cognitive flexibility is the ability to switch between thinking about two different concepts and being able to think about multiple concepts simultaneously (for example, multiple design criteria or constraints in an engineering problem or multiple dimensions of sustainability). Accordingly, some researchers have used time spent on tasks in relation to performance on tasks as indicators of cognitive flexibility. Another definition is the “selective use of knowledge to adaptively fit the needs of understanding and decision-making of a particular situation” [1, p. 548]. The latter definition seems appropriate for describing cognitive flexibility in engineering problem-solving but does not seem to be fully captured by existing measures of time spent on task and performance.

Guided by CFT, the main goals of our NSF EEC project were to improve students' abilities to apply sustainable engineering concepts across different problem contexts or design projects and to develop direct measures for assessing student learning gains. Specifically, we studied (1) appropriate measures of cognitive flexibility and related neurocognitive measures that apply to design and other open-ended engineering tasks; (2) effectiveness of instructional materials and assessments to measure and help students improve their ability to transfer knowledge to/across sustainable design problems; (3) similarities and differences in students' responses to the interventions between different types of engineering programs. Our research was conducted through two types of studies focused on (1) exploring neuroscience theories and measures related to cognitive load, efficiency, and flexibility for complex problem-solving; and (2) developing and validating a Sustainable Design rubric for use with multi-disciplinary engineering capstone design projects. Each study's methods and results are briefly reviewed in this summary and more details can be found in team publications cited in the references section.

### Rubric study

In 2017, a systematic review of ASEE proceedings showed a lack of rigorously-developed assessment tools for measuring student sustainable design skills [2]. In order to address the assessment gap, we developed a new sustainable design rubric, that has been tested by students and faculty at two different institutions. Rubrics are a promising assessment tool because they can be used for students to scaffold application of sustainable design principles and also by

instructors to quantify the impacts of their course innovations [3]. The Sustainable Design Rubric (see Table 1) is appropriate for both formative and summative assessment of student projects and can be completed by students or faculty [4], [5]. Further, we adapted a widely accepted process for investigating the validity of tests and similar instruments in order to rigorously examine the rubric’s performance. Benson lays out a multiple stage process for developing a strong program of construct validation, which includes substantive, structural, and external stages [6]. The rubric consists of 14 criteria across 4 categories (Social, Environmental, Economic, and Trade-offs) and is described in detail in previous publications [4], [5].

Table 1. Sustainable Design Rubric

<b>Criterion</b>	<b>Earned Points (_/3)</b>	<b>Evidence supporting your rating</b>
1. Minimizes the use of non-replenishable raw materials; requires minimal energy input or uses renewable energy sources		
2. Minimizes quantity of consumable waste (e.g., water, materials) output; manages quantity and quality (benign, usefulness) of waste		
3. Protects or enhances natural ecosystems (water, air, soils, flora, fauna, etc.)		
4. Identifies and engages stakeholders (external to project team) in the design process		
5. Addresses needs of diverse stakeholders, acknowledging culture and other differences among individuals and groups		
6. Protects human health and physical safety of users and society		
7. Promotes human well-being and enhances quality of life for users and society		
8. Evaluates economic impacts of environmental design criterion		
9. Evaluates economic impacts of a social design criterion		
10. Considers affordability for users and/or demonstrates cost competitiveness or cost reduction for client/sponsor		
11. Evaluates economic costs and benefits to inform decisions		
12. Final design impacted by trade-offs among environmental, social, and economic criteria and reflects balance of dimensions		
13. Uses and/or creates innovation(s) in its specific field to achieve sustainability		

14. Worked with experts from other disciplines (i.e., outside engineering) to enhance process or final design		
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Substantive and structural stages of construct validation for the Sustainable Design Rubric were based on a study of capstone design at James Madison University. Our goal was to determine the extent to which our theoretically and empirically defined rubric criteria were accessible to student audiences. We collected data during Spring 2018 from 51 junior engineering students from two course sections of capstone design. Students were given a homework assignment that included evaluating their capstone projects with our draft rubric. Each student belonged to one of fifteen capstone teams and was assigned to evaluate their projects against a subset of rubric criteria (approximately two-thirds of the rubric’s 14 criteria). Students scored individually and then discussed their individual responses with team members to arrive at a set of consensus scores, with written justifications, for all 14 criteria [4].

Based on the students’ scoring results and the reflection questions, students had the most difficulty rating and justifying the economic criteria, usually because they had not yet considered economic costs and benefits of their project. In some cases, students had difficulty understanding a criterion and how it applied to their project. The social criteria were deemed easiest to apply because students saw direct connections to project work they had already completed. However, high ratings for social criteria were often not strongly justified, indicating room for continued improvement in engaging stakeholders and considering their needs. Environmental criteria earned mixed results, with most students finding the criteria relevant to their project but with little direct evidence at the mid-point in their projects. Most students identified areas for additional learning or project improvement as a result of completing the individual scoring and consensus process, which supports using the rubric for formative assessment [4].

During Fall 2019, we implemented the Sustainable Design Rubric as a formative assessment in a civil engineering capstone design course at The Citadel. The assignment was given to 35 students across 7 teams. All teams were assigned an intersection design project that required knowledge from multiple engineering sub-disciplines and involved challenges and trade-offs that could be addressed by different design alternatives. Similar to the JMU study, students first individually scored their projects for a subset of the criteria and then discussed team consensus scores for all 14 criteria. We reviewed students’ responses for appropriateness of scores and quality of written justifications as part of the structural and external phases of SD Rubric validation. We found few intercorrelations between criteria within categories (environmental, social, economic), which would traditionally raise questions about structural validity. However, that finding supports that the 14 criteria are distinct and that the Rubric does not contain unnecessary criteria, which further supports substantive validity. We found correlations between criteria from the economic category and each the environmental and social categories. This provides early evidence of external validity, as we expected these correlations across categories since economic criteria specifically ask students to reflect on the economic impacts of addressing environmental and social criteria. Overall, the Rubric seems to help students grasp what sustainable design “is” or “should look like” for different types of projects [5].

**Neuroeducation study**

The second study used an electroencephalograph (EEG) and self-report data to investigate students' cognitive load and performance when completing concept mapping and listing tasks related to complex issues like food security and water availability. The study was designed to test two hypotheses: first, concept maps allow individuals to organize their thoughts using a networked or systems thinking framework, and thus will result in a more complete and holistic response than listing tasks; and second, creating a concept map is a more complex cognitive process and thus students will experience greater cognitive load during concept mapping tasks than listing tasks [7].

Twenty-seven JMU students participated in the study, which is an adequate size for EEG data analysis. Following a brief demographic survey, systems thinking survey, and benchmarking tests with the EEG, each participant completed two listing and two concept mapping tasks in one of four randomly assigned sequences. Each task was related to a sustainability issue: climate change, food systems, renewable energy, or water availability. After finishing all of the tasks, participants completed the NASA-Task Load Index (TLX) instrument (a validated self-report measure of cognitive load) [8] and a brief post-survey on the experience. For each participant, over forty pieces of data were recorded, including the following: demographic data, responses to the Revised Systems Thinking Scale, order effects, EEG performance variables, NASA-TLX scores, listing task metrics, and concept map scores. Quantitative and qualitative analysis examined three questions: (1) do students perform better on listing or concept mapping tasks? (2) do students exert more mental effort (cognitive load) for listing or concept mapping? (3) how did performance compare across different direct and self-report measures? [7]

Analysis showed that overall students' concept mapping tasks resulted in more complex representations of sustainable design than listing tasks without increasing their EEG-measured cognitive load. From a comparison of mean number of concepts, participants overall did not demonstrate a performance difference between concept maps and lists, although there were performance differences when examining certain topics. Of course, the number of concepts is not the only important metric and comparing individual differences rather than overall performance can provide more insights. In addition, qualitative coding of student-generated concepts helps to better understand complexity of responses to different topics and to concept map vs. listing tasks. In terms of the second hypothesis, creating a concept map seemed to require greater cognitive load than listing overall (based on mean cognitive load and NASA TLX scores), but when considering the different topics, this result only held for two topics (climate change and water availability). Related to the third question, it was difficult to identify relationships between different measures due to a large number of variables. For example, while participants overall self-reported higher mental load for concept mapping via NASA-TLX, EEG load measures seemed to vary by topic and by individual, making it difficult to identify a pattern using averages [7].

### **Findings across studies**

While examining how students perform and develop cognitive flexibility on sustainability-related tasks, we made interesting and at times unexpected observations of how students conceptualize and apply the sustainability construct to engineering problems. In particular, in studies involving both concept mapping [9] and application of a design rubric [4], [5], we saw

evidence that students tended to focus on one or two aspects of sustainability. At the group level, engineering students seemed to undervalue economic aspects of engineering problems and, depending on the specific student population, over-represented either social aspects or environmental aspects. This observation has been well documented by numerous studies and assumes that students ideally should develop a balanced understanding of the sustainability pillars [10]. When we looked at individual students, profiles or preferences emerge that indicate socially-minded, environmentally-minded, economically-minded, or technically-minded individuals. Based on our concept mapping/EEG and rubric studies at JMU and The Citadel, we explored two questions: (1) Could a team with different individual student sustainability profiles promote cognitive flexibility of individual team members? (2) Does a diverse, balanced team enhance project performance? [11]

For the concept mapping/EEG study, two scorers independently reviewed participants' listing and concept mapping tasks and assigned each concept to one of four categories: Ecological, Social, Economic, or Technical. Student preferences emerged through scores demonstrating depth in one or two sustainability categories but not much breadth across categories. For example, as a group, participants' concepts represented 41% Ecological, 21% Social, 7% Economic, and 31% Technical. Individual student responses revealed that one participant's breakdown may be 72% Ecological, 16% Social, 0% Economic, and 12% Technical whereas another's may be 7% Ecological, 19% Social, 15% Economic, and 59% Technical [11].

For the rubric study, comparing the individual and team consensus scores showed a shift in scores indicating that the consensus process introduced team members to new considerations. The quantitative observation is supported by students' qualitative comments - most students identified areas for additional learning or project improvement as a result of completing these two processes. Together, our studies (and prior work) suggest that team composition that prioritizes a mix of individual preferences could be a valuable strategy for sustainable design, and help team members appreciate the value of different sustainability aspects [11]. As part of a team, students influence each other's design decisions, often by bringing new knowledge or a different perspective into a discussion. This work could have implications for both student and professional design teams, particularly if combined with activities to help team members identify their cognitive biases with respect to sustainability and to utilize the team's diversity of thought.

## **Conclusion**

The poster will conclude with key take-aways and impact from this research project. Future work, beyond the scope of this project, could include further investigations into cognitive load measurement for complex tasks and exploration of how individual students' cognitive biases (e.g., a preference for environmental over social sustainability dimension) may be leveraged to enhance design team performance.

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