Using neuroeducation methods to compare engineering student performance on linear and systems tasks

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***Abstract*— This Research Work-in-Progress paper investigates engineering students' cognitive activities while completing linear and systems thinking tasks related to sustainability, which requires students to simultaneously utilize a large variety of constructs related to environmental, social, economic, and technical systems. To solve such interconnecting problems, systems thinking is necessary during decision-making rather than linear thinking modes that are more typical of solving closed-ended problem sets. This study uses an electroencephalogram (EEG) and self-report data to investigate engineering undergraduate students' cognitive activities when completing different tasks. We hypothesize that concept maps allow individuals to organize their thoughts within a systems thinking framework, and thus result in a more complete and holistic response than a linear thinking equivalent (i.e., listing task). We also hypothesize that creating a concept map is a more complex cognitive process than writing a list of terms and thus students (at least initially) would experience greater cognitive load while completing the concept mapping tasks. EEG and self-report measures of cognitive load will allow comparisons of undergraduate engineering students' performance on a linear or systems thinking task. Data collection is on-going so our paper will focus on methods, preliminary results, and future work.**

Keywords—neuroscience, cognitive load, systems thinking, sustainability

I. Introduction

Linear thinking is an approach based on a logic model, which can be simple or complex, can hold a variety of different elements, and can be presented in a graphical format. The problem with logic models is that they present a linear perspective in which inputs are directly linked to activities and outcomes [1]. Linear thinking struggles to determine the impact of multiple variables on a single result. This is a major limitation for engineering students, especially within the sustainable design paradigm and other multifaceted design structures.

Systems thinking improves upon linear thinking in that it allows for the conceptualization of multiple components that come together to create complex problems. Systems thinking encompasses a wide variety of fields of study including general systems theory (GST), systems dynamics, complexity science, and systemics [1]. Systems thinking is considered a more holistic perspective than linear thinking alternatives, and it can strengthen a linear design strategy by placing the specific concept into a larger context [2]. This holistic approach overcomes the limitations of a linear thinking strategy by allowing more information to be utilized when interpreting the impact of a change, or series of changes, in a complex system [1].

Performing a specific task, whether linear or systems, imposes a load on a learner's cognitive system, that can be represented by a multidimensional construct referred to as cognitive load [3]. Cognitive load includes the concepts of mental load, mental effort, and performance [4]. Mental effort, compared to mental load and performance measures, is considered more directly related to cognitive load [5]. Mental Effort is measured while participants are working on a task, and is the feature of cognitive load that refers to the cognitive capacity allocated to accommodate the demands of the tasks being performed [6]. Using an electroencephalogram (EEG), cognitive load can be measured based on the ratio of theta waves to alpha waves. A greater ratio is indicative of a higher cognitive load [7].

As a secondary measure of cognitive load, researchers employed the NASA-TLX (Task Load Index) self-report assessment tool. The NASA-TLX is a multidimensional

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assessment tool that was developed by NASA in the late 1980s for gathering information about the magnitude and sources of workload related factors [8]. The NASA-TLX carefully and specifically defines six dimensions of workload: mental demand, physical demand, temporal demand, performance, effort, and frustration. The NASA-TLX is a well-established self-report measure that has been used and cited frequently for decades. It is a common metric of self-reported workload in EEG research. [9].

This study compares the performance of engineering undergraduate students of different class years (sophomores, juniors, and seniors) while completing linear thinking (i.e., listing) tasks and systems thinking (i.e., concept mapping) tasks related to complex sustainability problems. It is important to note that while concept mapping is a task that embodies systems thinking, systems thinking is not limited to the creation of concept maps. For purposes of this study, concept mapping is being explored as a method to capture and directly measure systems thinking. Collecting EEG and self-report measures of cognitive load will allow comparisons of undergraduate engineering students' performance on a linear or systems thinking task and potentially compare performance across class years. We predicted that students would experience greater cognitive load while completing systems thinking versus linear thinking tasks due to producing a more complex artifact (concept map versus list of concepts) but that performance on the systems thinking task would be better than the linear thinking task.

II. Methods

Participants are being recruited at a mid-sized public university with engineering and other STEM programs. The participants, all sophomore, junior, or senior students, are recruited from engineering courses and invited to participate in a weekday or weekend session as an extracurricular activity. Engineering majors do not specialize by discipline and thus share a common curriculum. Given a limited engineering department size, students may be recruited from other majors that require and teach systems thinking concepts, such as other STEM departments and psychology. The target sample size is approximately twenty participants, as this would be considered adequate for both NASA-TLX and EEG data analysis. After reviewing informed consent documentation and selecting a session slot (approximately 90 minutes), each participant receives instructions for completing a pre-session activity. The research team requests that participants complete a primer on concept maps, consisting of PowerPoint slides and an embedded video with instructions, prior to the experimental session. Participants are also asked to complete and bring a sample concept map on the topic "how to bake a cake" as verification that they either reviewed the presentation or were already skilled with making concept maps.

Upon arrival at the laboratory, participants review a physical copy of the informed consent document and sign it if they would like to continue. If the participant satisfactorily completed the sample concept map on "how to bake a cake" prior to the experiment, the participant proceeds to a brief demographic survey that records their age, class year, gender, dominant hand, and how experienced they thought they were (on a scale of 1-10) with making concept maps. The participant also completes Davis and Stoink's (2016) Revised Systems Thinking Scale, a self-report measure of an individual's tendency towards systems thinking [10]. Next, the researcher fits the participant with a B-Alert X10 EEG system. If the researcher deems that the participant needs to review the concept mapping process, or if the participant requests a review, the researcher walks the participant through the concept map presentation and a practice concept map prior to the demographic survey and fitting the B-Alert X10 EEG headset.

Once the EEG headset is fitted on the participant, an impedance test is run to ensure a good connection between the participant's scalp and the EEG's sensors. Adjustments are made to individual sensor sites on the EEG if the impedance test does not show good conductivity across all sensor sites. After passing the impedance test, the participant completes three individual metric benchmarking tasks, each lasting five minutes. The three tasks provide a baseline for the B-Alert Live software to use as a control for each participant to in order to assess cognitive load, wakefulness, and distraction during the experimental procedure.

After the benchmarking tasks, the experimental procedure begins. Each participant is assigned one of four task sequences. Each sequence contains four issues in the field of engineering: including "climate change", "food sustainability", "renewable energy", and "water availability". Each participant is presented with four tasks shown in sequence on a computer screen, two linear thinking tasks and two systems thinking tasks. The four sequences (A,B,C,D) are varied by the order in which tasks appeared (e.g., systems, linear, linear, systems or linear, systems, linear, systems). The linear thinking tasks are presented as "write a list of concepts related to <one of the four problems>". The systems thinking tasks are presented as "draw a concept map related to <one of the four problems>". Every participant experiences all four topics once in combination with one of task types. For example, if a participant had to make a concept map about "water availability", they would not be instructed to make a list of concepts related to "water availability". Participants are given six minutes for each of the linear thinking tasks and ten minutes for each of the systems thinking tasks. When the time period ends, a sound is played on the computer to inform the participant that the task was complete. The participant then has a thirty second rest period before starting the next thinking task.

At the conclusion of all four tasks, the researcher removes the EEG headset and ask the participant to complete a pair of NASA TLX self-report surveys using the lab computer; one report for the two systems thinking tasks and one report for the two linear thinking tasks. The session concludes with a final post session survey, which asks if participants felt they had enough time to perform each task, experienced any points during the study in which they felt distracted, if they felt the testing environment was suitable to perform work in, and if participants have any comments or general feedback about the experience. Participants are then allowed to ask any questions about the study and are provided with a university dining voucher as compensation.

To date, each session has lasted between 80 and 100 minutes. Several key factors influence total session time: how long the initial EEG headset setup takes, how long a participant takes to complete the NASA-TLX post session questions, how long a participant takes to complete the Revised Systems Thinking Scale, and whether the participant completed their concept map training prior to the experimental session.

During each session the researchers complete an observation form which documents the EEG data collection start time, the variant of the four presentations that the participant completed, what questions the participant asked, if the setup time took longer than anticipated, if there were any times during which the researcher noticed that the participant was visibly distracted from an assigned task, and a small open-ended section for notes or additional comments. All participant generated data is labeled with a unique identifier and stored for analysis in accordance with approved Human Subjects Research procedures.

III. Preliminary Results & Analysis Plans

Data collection is on-going, so this paper presents results from the first four participants in order to illustrate the type of data being collected and to discuss analysis plans. For each participant, the research team is recording over forty pieces of data, including:

- **Demographic Data**
  - Participated in a previous study in our lab? *(Yes/No/Not Sure)*
  - Class Year, Gender, Age *(in years)*
  - Dominant Hand *(Left/Right/Ambidextrous)*
  - Self-Reported Experience with making Concept Maps *(1-10)*
  - Engineering Major? *(Yes/No)*
  - Major, if not engineering
- **Revised Systems Thinking Scale**
  - 15 Questions on 1-7 Likert Scale, with 7 reverse-coded items
  - Final average scores ranging from 1-7 (a higher number indicates a greater tendency towards systems thinking)
- **B-Alert Live Data**
  - Cognitive Load LDF Variable *(Average Load, Peak Load, Top 10% Load, Cumulative Load)*
  - Distraction, Engagement, Sleep variables
- **Scores on Concept Maps**
  - Number of Concepts
  - Highest Hierarchy
  - Cross Links
  - Total Score
  - Time *(number of seconds spent on task)*
- **Order Effects**
  - Which order did the participant perform the tasks in? *(A/B/C/D)*
  - Did the participant experience a linear task or a systems task first? *(Linear Task First / Systems Task First)*
- **NASA Task Load Index**
  - Two complete scores (Linear and Systems)
  - Overall weighted score for workload
  - Individual dimension scores for: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration.

Four participants have completed the entire study thus the process of recruiting participants and running additional studies is ongoing. Table 1 presents an excerpt of preliminary data, illustrating both EEG results and self-report data. Once we approach our target of at least twenty participants, data analysis will be completed in a variety of ways to explore individual variables and combinations of variables, and to triangulate results from different types of data.

TABLE I. Preliminary Data Collected for Four Participants

Identifier	Task Type	Task Topic	NASA TLX Total	Total Concepts	Cognitive Load Mean (SD)	Time on Task
P0401 Task 1	Linear	Food	37.67	13	.788 (.096)	565s
P0401 Task 2	Systems	Climate	20.67	24	.801 (.094)	622s
P0401 Task 3	Systems	Water	20.67	23	.709 (.132)	497s
P0401 Task 4	Linear	Energy	37.67	11	.802 (.097)	300s
P0302 Task 1	Linear	Food	57.67	33	.762 (.116)	370s
P0302 Task 2	Systems	Climate	72.34	55	.776 (.110)	707s
P0302 Task 3	Systems	Water	72.34	51	.779 (.103)	610s
P0302 Task 4	Linear	Energy	57.67	26	.790 (.104)	364s
P0403 Task 1	Systems	Food	83.83	6	.800 (.092)	455s
P0403 Task 2	Linear	Climate	36.67	8	.777 (.122)	250s
P0403 Task 3	Linear	Water	36.67	7	.797 (.094)	250s
P0403 Task 4	Systems	Energy	83.83	14	.716 (.134)	575s
P0304 Task 1	Linear	Food	37.34	27	.815 (.088)	360s
P0304 Task 2	Systems	Climate	59.34	24	.836 (.088)	600s
P0304 Task 3	Systems	Water	59.34	20	.823 (.102)	593s
P0304 Task 4	Linear	Energy	37.34	30	.793 (.128)	370s

In addition to calculating descriptive statistics, we will also conduct ANOVA and regression analysis as appropriate to explore relationships among different variables. The EEG data (as illustrated above) is B-Alert's metric for cognitive load, which is reported as a continuous variable between 0 and 1. This variable is based on a linear discriminant function. In other words, this variable uses information from various sensor sites in a proprietary algorithm to determine a probability value for whether an individual was experiencing cognitive load at a specific second. Looking solely at the EEG data, we plan to perform a 3x2 mixed-methods ANOVA with the number of distinct groups (class year) as the between-groups measure and the type of thinking task (linear or systems) as the within-group measure. This framework will allow us to look for differences between class years in terms of cognitive load experienced and it will allow us to look for differences between the types of thinking tasks in terms of cognitive load experienced. For this statistical significance test, our effect size would be r^2, which can be interpreted as how much variance in our dependent variable (cognitive load) is explained by one of our factors (class year or thinking task type).In addition to the EEG load data, we will also explore variables like performance on concept mapping versus linear thinking tasks (in time, total concepts, or other measures) and scores from the self-report measures (NASA TLX, Systems Thinking Scale, concept mapping confidence). Concept map scores will be calculated using the number of concepts listed, the highest hierarchy, and the number of cross links. The scoring approach is called the "traditional method" and was selected from available scoring approaches because of the ability to objectively quantify the depth, breadth, and connectedness of knowledge [11]. Scoring of each concept map will be completed independently by two trained raters and evaluated for acceptable interrater reliability. Initial performance comparison between concept maps and lists of concepts will be based on the quantity of concepts present. To explore the relationship between the concept map/linear thinking task score and participants' cognitive load, we will use a multiple regression framework and identify interactions between continuous (e.g., cognitive load, concept map score, linear thinking score) and categorical (e.g., class year, major, task type, topic) variables. Given the relatively small number of final participants (which is consistent with other EEG cognitive load studies), we can conduct regression analysis at the participant level (n=20) and at the task level (n=80).

IV. FUTURE WORK & SIGNIFICANCE

By measuring the cognitive activation levels during tasks we are able to construct a more detailed understanding of the processes and differences in cognitive load experienced between the utilization of linear thinking compared to systems thinking. Understanding the patterns of activation in the brain required for conceptualizing a system is important because we can begin to assess how learning enhances the temporal response (how fast we think), and how learning reduces the cognitive load (the effort required). We also expect to better understand the cognitive demands of systems thinking so that we can improve educational approaches for systems thinking and sustainability accordingly. The results of this study may allow us to better understand the neurological differences between using linear and systems thinking, through the use of both physiological and self-report assessment. With a better understanding of cognitive load measures for complex learning tasks, we can then start to investigate other cognitive measures that are related to load, such as cognitive efficiency and cognitive flexibility.

Exploration of neuroscience methods yielding characterization of engineering education practices that ultimately assist with validating new learning tools and methods is central to our research. In parallel to our study, researchers at a large public research university are investigating the use of a different brain imaging technology to measure differences between linear and systems thinking tasks. Both studies are working with undergraduate engineering students. Future work will compare findings from both studies in order to inform other researchers; however, this paper focused only on the methods and preliminary results from our EEG study at a mid-sized public university. The ultimate goal of our research is to create and validate teaching methods that enhance students' cognitive resources to meet and exceed the requirements of working within the sustainable design paradigm.

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