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Methods for Measuring Systems Thinking: Differences Between Student Self-assessment, Concept Map Scores, and Cortical Activation During Tasks About Sustainability

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Abstract

Systems thinking is a necessary skill towards solving complex civil engineering problems with interconnected environmental, social, and economic inputs and outputs. The dynamic relationship between systems components can act as a barrier for sustainability if decision makers work to reduce rather than understand complexities. To help advance methods for assessing and measuring students' ability to think in systems, multiple methods were used and compared, including: a previously developed 15-item self-report survey named Systems Thinking Scale Revised (STSR), three scoring approaches to concept mapping and advanced cognitive neuro-imaging methods to measure physical changes in cognition. Engineering students (n=28) completed the STSR survey to report their capacity of systems thinking. They were outfitted to wear a functional near-infrared spectroscopy (fNIRS) system and asked to draw a concept map related to sustainability topics about energy, food, climate, and water. Their concept maps were scored using three approaches: the traditional, holistic, and categorical scoring method. The result shows that students' self-evaluated systems thinking tendency is negatively (Spearman's r = -0.50, p = 0.016) correlated with their concept map performance graded with the traditional scoring method, while positively (r = 0.39, p = 0.038) correlated to the sub-scores on the environment concepts using the categorical scoring method. Efficiency in brain connectivity, which is calculated using fNIRS data, is positively correlated with the complexity index using the categorical scoring approach (r = 0.45, p = 0.016) and the sub-scores of comprehensiveness in holistic scores (r = 0.42, p = 0.025). The results suggest students with higher performance of systems thinking were also more cognitively efficient. This study contributes to engineering education by demonstrating a new measurement tool to understand systems thinking and students' cognitive abilities. The results also demonstrate possible discrepancies in previously developed surveys, concept map scoring techniques and cognition measured through changes in cortical activation. This trans-disciplinary approach bridges engineering education, sustainability, and neuroscience and begins to open new avenues of research helping measure the effectiveness of assessment techniques with physical responses of cognitive activation.

Introduction

Systems thinking is a necessary skill towards solving complex civil engineering problems with interconnected environmental, social, and economic inputs and outputs. For example, tasked with alleviating traffic congestion, a narrowed approach might be to expand the roadway. However, using a systems thinking perspective, such an approach, could be counter-productive, creating a positive feedback loop, and exacerbate the initial problem (a phenomenon called induced demand [1], [2]). Adding a new road lane brings new drivers, and over time (typically within five years) leads to more traffic, more pollution, and contributes to a reduction in community quality of life [3], [4]. Similarly, viewing energy efficient building materials in isolation to how they perform within a system may lead to less than optimal solutions. For instance, windows with a low U-value typically cost more but produce less heat transfer, which can equate to reduction in HVAC loads, leading to a net positive benefit for both financial investors and the environment.

Unfortunately, civil engineering practice still too frequently ignores these dynamic relationships between system components. For example, rating systems like Leadership in Energy and Environmental Design (LEED) guide engineers to think about individual parts using a checklist of options. LEED draws criticism for over simplifying, even neglecting, the potential emergent benefits of a more holistic approach [5]. This type of reductionist approach, is in part, a coping mechanism from bounded rationality [6] and, in part, due to educational training [7]. Bounded rationality suggests that humans have limited capacity or information processing ability, so people tend to construct simplified models of real situations and fail to consider the complexities from a system scale. Many traditional institutions, unwittingly or not, train students as specialists without the broad view of the systems in which they will work [8], [9].

The challenge for educators is not only to overcome the barrier of traditional reductionist or linear thinking in education and develop methods to teach systems thinking [10], but also to assess the effects of such curriculum changes on students' ability to think in systems. This type of assessment requires new forms of assessment methods and instruments to measure students' systems thinking abilities [11]. Recently, many have contributed to the discussion on assessing or measuring the ability of systems thinking [13]–[16]. These methods broadly fit into two types: instructor assessment of thinking outcomes and student self-evaluation of thinking ability. An instructor assessment of thinking requires students to complete predefined systems thinking tasks, which have a rubric or standard to grade participants' performance. Self-evaluation usually involves surveys, interviews or questionnaires, which requires students to reflect on their ability, tendency, or cognition about systems thinking.

The emergence of neuroimaging techniques provides researchers with another tool to assess systems thinking. From a neuro-cognitive perspective, collecting and analyzing objective physiological data in the human brain provides an opportunity to advance engineering education using cognitive load theory [17]. In essence, cognitive load theory states that better understanding the cognitive process of systems thinking enables educators to explore better practice to reduce unnecessary cognitive burden and learn more efficiently. This paper presents a study using assessment of thinking outcomes (concept mapping and scoring), self-evaluation (Systems Thinking Scale Revised survey) and measuring cognition through neuroimaging (functional Near-Infrared Spectroscopy) to study the relationship between different methods of assessing systems thinking. The next section of the paper introduce the tools used for assessment.

Assessment of thinking outcomes: concept mapping and its scoring

Illustrative diagrams are a better language for systems thinking than words [7]. Concept mapping is an approach to using illustrative diagrams to conceptualize systems thinking. Concept mapping begins with a main idea and then branches out to show how that main idea can be broken down into specific topics and drawing links between concepts at various hierarchical levels within the map. Illustrating both elements and interconnections is a key principle of concept mapping [18].

To quantitatively analyze a concept map, numerous scoring methods have been developed by previous scholars, including the traditional, holistic, and categorical scoring methods [14]. The traditional scoring method captures the overall concept map quality by counting the number of concepts (NC), the highest level of hierarchy (HH) and number of cross links (NCL) to determine the sub-scores for breadth, depth and connectedness of knowledge related to the systems problem [19]. The holistic scoring method uses a three-point scale to rate the comprehensiveness, organization, and correctness of a concept map [20]. The categorical scoring method is unique because it was developed specifically for concept maps related to sustainability. The categorical scoring uses a cohort-specific metrics to analyze overall quality and connectedness between different categories of sustainability including environmental, social and economic elements [21]. All three methods are used to analyze students' systems thinking ability [15], [22].

Self-evaluation: Systems Thinking Scale Revised

Scoring concept maps is done by instructors or evaluators while the Systems Thinking Scale Revised is a self-evaluation survey developed by Davis and Stroink [23] to measure an individual's capacity or tendency to perceive the social-ecology-economic world as an assemblage of interconnected complex systems. STSR survey contains 15 items stating the relationship in social-ecological systems and it provides a seven-level choice from strongly agree to strongly disagree for each item. STSR is validated using psychometric properties with Cronbach α of 0.78, which shows its internal consistency [23]. Thibodeau et al. [13] demonstrated the positive relationship between STSR and other well-studied constructs to measure people's tendency to engage in holistic thinking and relational reasoning, which are critical in systems thinking.

Neuroimaging technique: functional near-infrared spectroscopy (fNIRS)

The third assessment tool to measure systems thinking ability among students was functional near-infrared spectroscopy (fNIRS). fNIRS monitors brain activity by measuring the change of hemoglobin in human cortex, which is associated with cognitive activities [24]. fNIRS sensors (including sources and detectors) placed on a wearable cap or band emit near infrared lights (wavelength 700-900nm) into the cortex and the detectors receive the light which is not absorbed and reflected back. Oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) absorb more light than other tissues in the brain and they have different absorption spectra, therefore, the relative change of hemoglobin, or Blood Oxygenation Level Dependent (BOLD) response can be captured by the use of light attenuation at multiple wavelengths.

As a non-invasive, safe and portable technique, fNIRS can be used to study brain activity when participants need to complete tasks related to problem solving, design, decision making in engineering in more natural environments and in educational settings [25]. For example, fNIRS was used in prior research to study cognitive efficiency of engineering undergraduates to generate creative solutions to engineering design problems [26]. In engineering, there is a growing number of fNIRS-based brain-computer interfaces (BCI, or also called human-computer interfaces) developed to facilitate effective interaction between people and computer systems [27], [28].

fNIRS is an appropriate technique to measure the cognitive activities when participants do systems thinking tasks. The cognitive process during systems thinking might involve accessing memories, reasoning and planning to organize concepts and connections. Brain functional connectivity, which is defined as the temporal dependency of cognitive activation patterns of different brain regions [29] also support reasoning process during systems thinking. Thus, brain regions of interests in this paper to study cognition of systems thinking include pre-frontal cortex, which is associated with reasoning and working memory [30] and posterior parietal cortex, which is associated with planning and sequence processing [31].

Research Questions

Using the three different assessment tools (concept map scoring, self-evaluation, and cognition measured by fNIRS) to measure systems thinking, this study investigates both behavior and cognition of systems thinking among engineering undergraduates. Through the comparisons of these assessing methods, better understanding on the difference and relationships among these measures is constructed, and can be used in future research to help design systems thinking or sustainability courses in engineering education. The specific research question is:

> *What relationships exist between concept map scoring, self-evaluated systems thinking tendency, and cognitive activation during systems thinking tasks?*

The traditional, holistic and categorical scoring methods were used in concept map scoring. The STSR survey was used to measure engineering students' self-evaluation of systems thinking tendency to perceive the socio-ecology-economic world. Cognitive activation during tasks was measured using fNIRS. The change of oxygenated hemoglobin (ΔHbO) and functional connectivity among regions in the brain were the two assessment methods for fNIRS.

The null hypothesis for the research question is that there is no relationship between these measures. Correspondingly, the alternative hypothesis is that the STSR is positively correlated with concept map scores, especially with the categorical score, since both the STSR scores and the categorical scores have a focus on the connectedness among environmental, economic and social aspect of the system. Another hypothesis is cognitive activation is a positive predictor of systems thinking performance, i.e. positive relationship should be found between the cognitive activation and the concept map scores. The last hypothesis is that there is positive correlation between the STSR scores and the cognitive activation.

Methods

Data Collection

Twenty-eight engineering undergraduates participated in the study. Participants were a mix of freshmen and seniors. Between classes, difference in their ability of systems thinking or concept mapping might exist, but it is outside the scope of this research. To avoid impact on students' choice in the STSR survey, the survey was completed by students one to two days prior to participating in the systems thinking tasks. For each student participant, there were two systems thinking tasks requiring them to draw a concept map related to sustainability topics on paper, and the topics were randomly chosen from renewable energy, food sustainability, water availability and climate change, which are in the list of the 14 grand challenges for engineering in 21^{st} century [32]. A pilot study was conducted in which engineering undergraduates finished four concept maps for these topics, and the average time for a map is 8.6 minutes, thus, the time for each task was set as 10 minutes in the experiment.

Participants were required to finish the concept mapping task wearing the fNIRS cap, which recorded their cognitive activation in regions of interest. The sensor configuration is shown in Figure 1. Ten sources and sixteen detectors, forming 26 channels (connection between one source and one detector), were placed along the pre-frontal cortex (PFC) and posterior parietal cortex (PPC), covering Brodmann area (BA) 8, 11, 39 and 46. Generally, Brodmann areas are associated with varying cognitive function and divided by the cytoarchitecture within the brain.

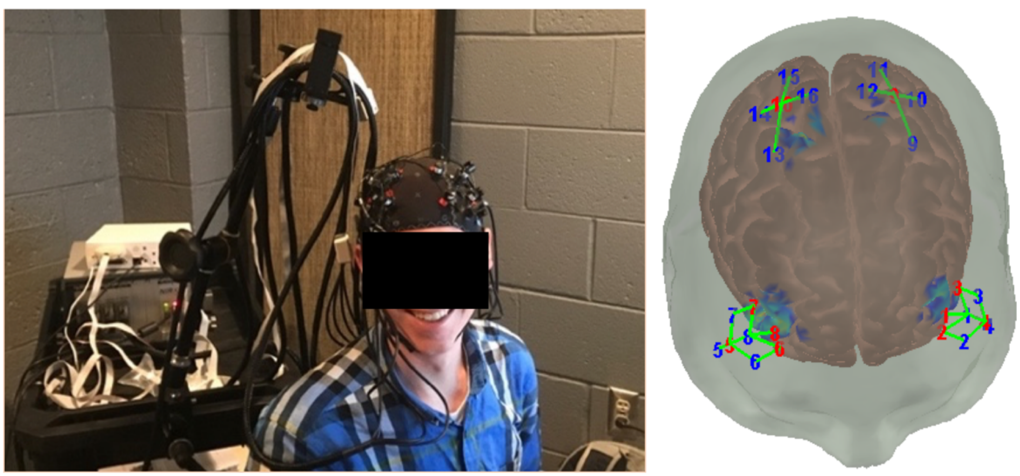

Figure 1: Placement of fNIRS sensors along PFC and PPC

Data Analysis

The data collected from the experiment include the STSR survey, the concept maps and the cognitive activation during the tasks. For STSR, based on participants' choices, a mean score of 15 items in the survey, each ranging from 1-7, was calculated to represent each student's self-evaluation of systems thinking tendency. For the concept maps, the scores including traditional (CMST), holistic (CMSH) and categorical (CMSC) scores, were calculated using the methods reported by Watson et al. [14]. In CMST, the number of concepts (NC), the highest level of hierarchies (HH) and the number of cross-links (NCL) were counted and the total score is calculated using the equation $CMST = (NC-NCL) + 5*HH + 10*NCL$ [19]. In CMSH, the comprehensiveness, organization, and correctness were rated from 1-3 using the rubric developed by Besterfield-Sacre et al. [20] and the total score of CMSH is the sum of the three sub-scores. In CMSC, the percentage of number of concepts in social, economic, environmental categories was calculated, and complexity index was determined using the number of interlinks between different categories divided by the number of categories. CMSC is specifically used to assess concept maps that deal with sustainability and is therefore an appropriate measure in this study developing concept maps about renewable energy, food sustainability, water availability and climate change. The possible score using the CMSH approach ranges from 3 to 9. CMST and CMSC are greater than 0 but have no upper limit.

For cognitive activation, functional connectivity was calculated based on the change of oxygenated hemoglobin from different regions in the brain. Brain functional connectivity is defined as dependency of synchronized cognitive activation of different brain regions [33]. Global efficiency (E) of connectivity was measured, which describes the cognitive effort to transfer information between brain regions. More details on global efficiency in brain connectivity can be found in [34]. Spearman's rank correlation was used to describe the relationship among measures and the significance level is defined as 0.05 in the study. Spearman's rank correlation was used instead of Pearson's correlation because STSR and concept map scores include ordinal and interval data.

Results and Discussion

The average STSR score of all participants is M=5.28, SD=0.45, which is close to the score M=5.30, SD=0.69 in previous studies [23]. The average concept map scores are displayed in Table 1. Significantly moderate or strong positive relationships were found between CMST, CMSH and CMSC as Figure 2 illustrates, which suggests consistency among these methods to grade a concept map.

Traditional scores			Holistic scores			Categorical scores		
	M	SD		M	SD		M	SD
NC	22.55	6.72	Comprehensiveness	2.03	0.71	Social (%)	39	9
HH	4.55	0.82	Organization	1.96	0.52	Economic (%)	18	9
NCL	2.43	0.90	Correctness	2.32	0.43	Environmental (%)	43	13
CMST	67.18	12.41	CMSH	6.32	1.49	CMSC (Complexity index)	1.61	0.67

Table 1 Concept map scores

(M=mean, SD=standard deviation, NC=the number of concepts, HH=the highest hierarchies, NCL=the number of cross links)

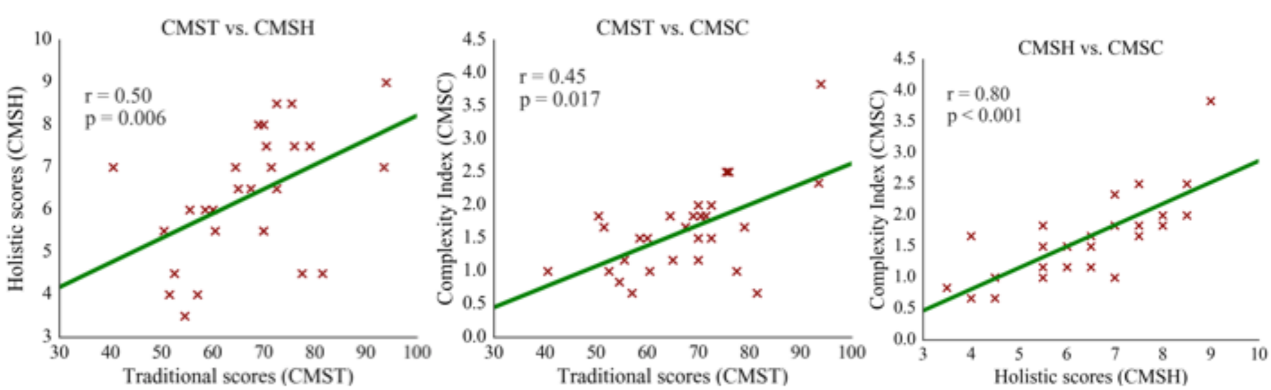

Figure 2 Positive relationship between CMST, CMSH and CMSC
(r in the figure is the Spearman's rank correlation)

STSR vs Concept map scores
The relationship between STSR and concept map scores is described using the Spearman rank correlation. Between CMST and STSR, null hypothesis is rejected with a p-value equal to 0.006. However, opposite to the hypothesis, CMST is negatively correlated with STSR. The relationship is moderate with an r value equals to -0.5. Students who evaluate themselves as systems thinkers performed worse on the concept mapping tasks. Figure 3 (left) shows the negative relationship. Between CMSH and STSR, as well as between the complexity index in CMSC and STSR, negative relationships were also found but not significant. Follow-up analysis indicated that STSR is correlated with some sub-scores within the CMSC approach. Significantly positive correlation was found between STSR and percentages of the number of concepts related to environmental topics to the total number of concepts as Figure 3 (right) illustrates but not for concepts related to social or financial elements of sustainability.

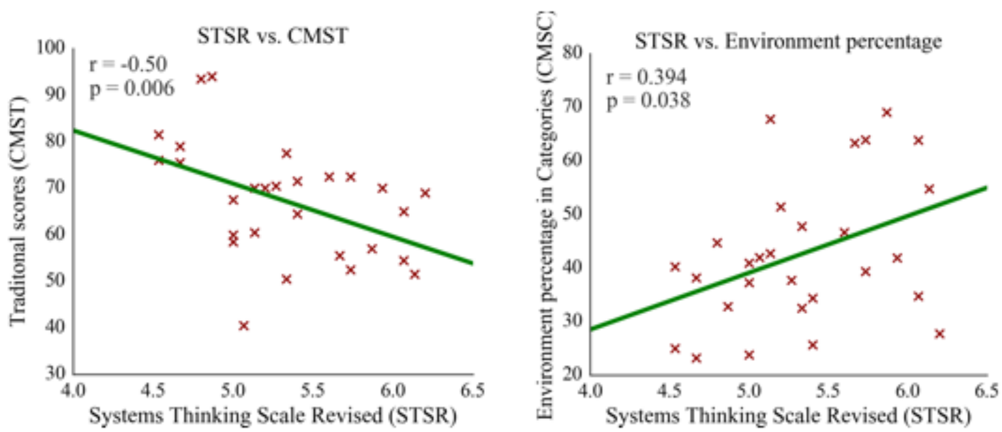

Figure 3 Relationship between STSR and concept map scoring

The negative correlation between STSR and CMST means that students who evaluated themselves having high tendency of systems thinking were more likely to have a poor performance in systems thinking tasks. To some degree, the result suggests that self-evaluation using Systems Thinking Scale Revised survey might not be accurate to reveal students' overall ability of concept mapping, which is another approach to measure systems thinking. Of course, the CMST method only counts for the number of concepts and links, and might not adequately measure content of systems thinking like the holistic (CMSH) or categorical (CMSC) approach. A combination of the traditional, holistic and categorical scoring methods might provide a better alternative to measure systems thinking.

There are some limitations in this study. The influence of the fNIRS cap on the performance of participants (e.g. stress, attention, etc.) was not captured, however, one assumption based on nearly two decades of research in cognitive psychology using fNIRS is that the cap has minimal impacts on performance ability. The design of the study also helped reduce the effect of the cap because all participants wore the equally during the task and therefore should be representative across tasks.

While the STSR self-assessment survey is a negative predictor of performance in systems thinking tasks using the traditional scoring approach (CMST), the STSR is a positive predictor for students' consideration on environmental issues using the categorical scoring approach (CMCC). The result coincides with the conclusion from prior research [13] that STSR is more likely to predict people's behavior or judgement on environmental rather than other systems in systems thinking. It might also suggest that when thinking about sustainability, students tend to have more considerations on environmental problems while neglecting other factors such as human quality of life and economic feasibility within the problem. This tendency to neglect factors about social and economic sustainability can also be found from the concepts allocated among the three categories in Table 1. Only considering environmental issues is not representative of a holistic, systems thinking approach to sustainability.

Concept map scores vs Cognitive activation

Global efficiency (E) is a measure used to describe brain connectivity, which represents the information transfer among different brain regions. The correlation analysis was conducted between the global efficiency (E) and the concept map scores. The result indicates that global efficiency is positively correlated with complexity index in categorical scores approach and also with the sub-scores of comprehensiveness in holistic scores. Positive correlations were also found between E with traditional concept map scoring (CMST) and the holistic approach (CMSH) but not significant. Figure 4 illustrates the positive relationships between the concept map scores and the global efficiency.

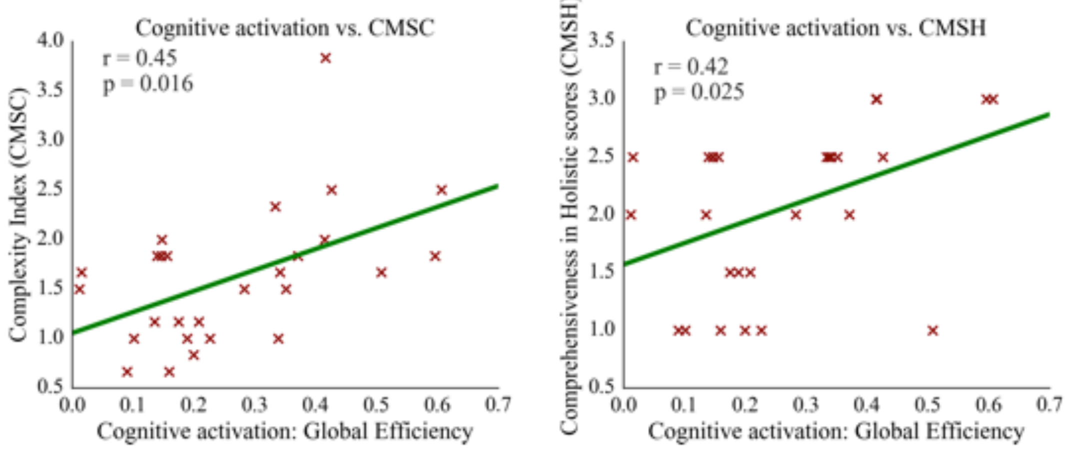

Figure 4 Positive relationship between Global Efficiency and CMS

The positive relationship between the global efficiency, the complexity index and the comprehensiveness score suggests that higher efficiency of information transfer in the brain is correlated with higher complexities and comprehensiveness of systems thinking in students' concept maps. The results indicate that systems thinking performance is positive predictor of cognitive efficiency. The positive correlation suggests that increasing systems thinking ability using concept mapping can help students improve cognitive efficiency. More research is needed to explore how to improve these cognitive abilities when teaching systems thinking to engineering students.

STSR vs Cognitive activation

No significant correlations were found between STSR and global efficiency of cognitive activation. Future research should use more detailed systems thinking tasks instead of concept mapping to investigate the relationship. More specifically, systems thinking tasks can be divided into holistic thinking tasks, relational thinking tasks and complex thinking tasks, which might be more related to the psychometric aspects measured by the STSR survey.

Conclusion

This study measured engineering students' systems thinking for sustainability problems using assessment of thinking outcomes, self-evaluation and cognitive activities. The results demonstrate relationships between these measures. Students' self-evaluated systems thinking tendency using the Systems Thinking Scale Revised (STSR) survey were found to negatively correlate with concept map performance when using the traditional scoring method, while positive relationship was found between the STSR scores and the proportion of the number of environment concepts to the total number of concepts in all categories (social, economic and environmental), which indicated that STSR might not be able to predict overall systems thinking ability accurately but could reveal students' consideration for environmental issues in engineering.

Between cognitive activation and concept map scoring, significant correlations were found between global efficiency in the brain and the complexity index when using the categorical scoring methods and also the sub-scores of comprehensiveness in holistic scores. Participants that score high using the categorical and holistic concept mapping techniques were more likely to demonstrate high global efficiency. These results indicate subject physiological data measured by fNIRS might be a better alternative than self-evaluation to reveal the ability of systems thinking for sustainability problems using concept mapping. The results also suggest that fNIRS is a plausible technique to evaluate the effects of teaching systems thinking on cognitive efficiency. Even though no significant correlation was found between STSR and cognitive activation, more specific systems thinking tasks should be used in the future to explore the relationship between psychometric measures with neuroimaging measures.

Broadly, this study contributes to engineering education by demonstrating a new measurement tool to understand systems thinking and students' cognitive abilities. The results demonstrate consistency and also possible discrepancies in previously developed surveys, concept map scoring techniques and cognition. The research also adds to the growing discipline of sustainability science, which requires systems thinking. This trans-disciplinary approach, bridging engineering education, sustainability, and neuroscience is meant to open new avenues of research.

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