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Neuro-cognitive Differences Among Engineering Students when Using Unstructured, Partially Structured, and Structured Design Concept Generation Techniques

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Abstract

This paper presents the results from an experimental study measuring engineering students' neuro-cognition when generating solutions using three concept generation techniques: unstructured (brainstorming), partially structured (morphological analysis), and structured (TRIZ). Twelve engineering students were given the same three design tasks and one of the three concept generation techniques for each task. Students generated concepts while a functional near infrared spectroscopy system captured their physical changes in oxygenated blood to the prefrontal cortex in their brain. While there is literature describing which brain regions support particular cognitive functions, far less is known about how this supports design concept generation and how cognitive processes differ when using various techniques. The results suggest that different concept generation techniques lead to significantly different patterns of activation and coordination among brain regions, which might influence divergent thinking and creativity during design. Increased coordination between the left and right hemisphere was observed when using TRIZ, while an increase in coordination only in the right hemisphere was observed during brainstorming and an increase only in the left hemisphere during morphological analysis. Brainstorming and TRIZ also resulted in an increase in cognitive activation in the region of the brain associated with abstract reasoning and cognitive flexibility. Through better understanding of the neuro-cognitive patterns during design, future research can begin to explore specific elements of the engineering curriculum that may contribute to student ability to generate concepts and solve engineering design problems. This interdisciplinary study is meant to generate conversation about engineering design and offer a new tool through neuroimaging to understand differences in design cognition and the effect of tools, techniques, and education.

Introduction

Engineering design is described by many scholars as a process with several stages: problem exploration, concept generation, solution evaluation and design communication [1]. The concept generation phase is the time to bring problem understanding, social factors and practical knowledge together to develop possible solutions [2]. The quality and quantity of concepts generated in this phase affect and even determine the outcomes of the final design solution [3], [4]. Prior research demonstrates that numerous concept generation techniques can be used to facilitate engineers to increase creativity and generate more design alternatives [3], [5], [6]. Therefore, understanding concept generation and its techniques has importance for engineering education and the design industry.

There are two broad categories to classify concept generation techniques: unstructured design methods and structured design methods [7], [8], [9]. Unstructured concept generation techniques encourage intuitive reasoning and aim to remove the mental block of narrowing boundaries during concept searching. Structured concept generation techniques focus on formalizing concept generation procedures and generating solutions to meet multiple functional requirements. There are some widely applied concept generation techniques used in engineering design industry [10], [11], for example, brainstorming, morphological analysis, and TRIZ.

Brainstorming is a common technique used to generate as many concepts as possible by deferring judgement and criticism during the concept generation process [12]. This technique can be regarded as unstructured since concepts are generated randomly with a wide boundary and with no predefined direction [7]. Morphological analysis is more structured that brainstorming. Gero et al. [7] defines the morphological analysis method as partially structured because of its three steps process of decomposing a problem into several items based on different functional requirements, then providing several solutions to each sub-problem and finally selecting and combining sub-solutions to final designs. Morphological analysis is best used to explore possible solutions to complex problems with multiple dimensions in the concept generation process [13]. TRIZ is another concept generation technique which provides a systematic, structured approach to solve engineering problems based on logic, previous experience, and knowledge [14]. TRIZ is a set of fundamental design principles that are meant to eliminate technical and physical contradictions in solutions [15]. With clearly defined steps and well-elaborated design principles, TRIZ is a highly structured concept generation technique and widely applied in engineering education and design [16]–[18].

Prior research investigated how these methods influenced design cognition by comparing behavioral differences when using these three concept generation techniques [7], [19]. They found that the more structured the technique, the more focused designers are reasoning about problems. While these findings provide evidence that the structured approach improves focus, these results provide little information about how these techniques influence cognitive processing. In other words, prior research about concept generation measures cognition using think-aloud protocols, observation, and measuring variation in design outcomes. The research presented in this paper helps answer how these techniques influence how designers process information and whether difference in patterns of activation are evident neurologically. Assessing behavioral change alone is not sufficient to reveal underlying difference in cognitive function and patterns of activation in the brain. By understanding the demand patterns of cognitive activation in the brain and the functional coordination (e.g. abstract reasoning and evaluation) and how these vary across techniques can lead to assessing where deficiencies occur and how each technique may enhance either the temporal response (how fast solutions are generated) or reduce the cognitive load (the energy required) to develop a design solution.

The ability to reduce cognitive load is closely related to cognitive load theory, which suggests tasks for learning should be broken down into small objectives [20]. In education, learning happens best under conditions that reduce complexity and are aligned with human cognitive structures [21]. The research presented here contributes to this body of literature by exploring how approaches in design correlate to neuro-cognitive function. Moreover, previous literature in design suggests that the degree of creativity in design outcomes might be related to the neuro-cognitive process or mechanism behind designing [22], [23]. In other words, the regions of brain activated during design contributes to design outcomes. Activities that increase or decrease cognitive activation in regions, for example, that elicit abstract reasoning or uncertainty, will have a resultant impact on the design outcome. Measuring the cognitive activation of different brain regions during design can therefore provide evidence of the physiological differences in cognition during different design approaches.

To explore the cognitive activities during design, a neuroscience approach to image the human brain was used to collect physiological data among engineering students during concept generation. There are several imaging techniques: functional near-infrared spectroscopy (fNIRS), electroencephalogram (EEG), and functional magnetic resonance imaging (fMRI). fNIRS can be worn as a cap and the sources on the cap emit near-infrared light in the spectrum of 700-900nm into the cortex. Hemoglobin absorbs more light than water and other tissue in the brain. Increase in hemoglobin in the brain is associated with an increase in cognitive activity [24]. The light which is not absorbed is reflected back to the detectors on the cap. The different absorption spectra of oxy-hemoglobin and deoxy-hemoglobin make it possible to describe activated brain regions and cognitive activities through the change in hemoglobin concentration, or Blood Oxygenation Level Dependent (BOLD) response.

fMRI similarly measures activity indirectly through changes in hemoglobin in the brain. As a brain region is activated, the body sends more blood to that region and fMRI detects these changes by imaging the blood oxygen level-dependent contrast (BOLD) signal in a special magnetic scanner [25]. The negative of fMRI experiments is that they require participants to lie on their back in a relatively enclosed space. fNIRS, however, allows participants to sit upright allowing to study brain activity in more natural environments and in educational settings. Both fNIRS and fMRI find fault in their low temporal resolution (i.e. order of seconds compared to milliseconds) because of the physiological time required for blood to flow. EEG measures cognitive change much more quickly but is limited in spatial resolution [26].

The low spatial resolution of EEG and the unrealistic setting of fMRI (i.e. participants lying on their back inside of a tube) makes fNIRS the most appropriate technology to measure decision making, design, and problem solving in engineering [27]. Previous research using fNIRS explored cognitive differences between seniors and freshmen engineering students; the findings provide evidence that years of education significantly influence cognitive processes during design [28].

In other research fields, fNIRS is used to study risky decision making and math problem solving [29]–[31]. fNIRS is also used to study brain creativity during divergent thinking [32] and free drawing [33]. In most fNIRS studies, the regions of interest in the human brain is the pre-frontal cortex, which is demonstrated to be responsible for executive functions including abstract reasoning and working memory [34]. Pre-frontal cortex includes several Brodmann areas (BA), which is defined by cytoarchitecture in human brain, such as BA 8, 9, 10, 46 and 47. These sub-regions are demonstrated to associate with varying cognitive functions [35]. For example, BA 46 plays critical roles in problem solving and cognitive flexibility [36], while BA 8 is associated with inhibitory control and processing with uncertainty [35], [37]. In this study, the region of interest is the pre-frontal cortex due to the connection between these regions and design thinking [38].

Research Questions

This paper presents a study using fNIRS to investigate the cognitive differences of concept generation using unstructured, partially structured and structured concept generation techniques (brainstorming, morphological analysis and TRIZ). fNIRS data describes the activated brain regions and functional connectivity among different regions when using these three concept generation techniques. Comparing differences in connectivity among activated regions in the brain can help construct a better understanding about how different concept generation techniques influence design cognition. The specific research questions are as follows:

(1) What are the differences in cognitive activation patters when using unstructured, partially structured and structured concept generation techniques?
(2) Do partially structured and structured techniques require more or less cognitive activation in the pre-frontal cortex compared to unstructured?

Hypothesis

The hypothesis is that unstructured, partially structured, and structured concept generation techniques lead to significant differences in cognitive activation patters along the pre-frontal cortex among engineering students. The expectation is that brainstorming requires greater intra-hemispherical activation along the right hemisphere while partially structured and structured approaches elicit more inter-hemispherical activation. Intra-hemisphere means within one hemisphere and inter-hemisphere means between both hemispherical regions of the brain. This hypothesis is based on prior research in neuroscience that suggests inter-hemisphere and intra-hemispheric connective functions in the brain are correlated with creativity and divergent thinking [39], [40], [32]. The rationale for expecting greater activation in right intra-hemisphere during brainstorming is because Moore et al. [40] found that intra-hemispheric connectivity in the right might play more important roles than the left hemisphere to increase creativity. The null hypothesis is brainstorming does not produce greater connectivity in the right intra-hemisphere.

The expectation to find greater inter-hemisphere connectivity among partially structured and structured approaches to concept generation is because these more structured approaches require divergent ways of thinking (i.e. breaking the problem down into smaller pieces and requiring thinking about core engineering principles). Jaušovec [41] found that creative individuals have more inter-hemisphere and intra-hemispheric connectivity than those who are less creative. Bogen [42] proposed that divergent thinking, which was essential for creative output, would be mediated primarily by inter-hemisphere connectivity not intra-hemisphere connectivity. The structure, either requiring students to break down the problem into smaller pieces (partially structured) or reviewing engineering design principles and the TRIZ matrix (structured), likely requires a balance between cognitively searching for possible design approaches and assessing how these ideas align with the structured approach. The null hypothesis is partially structured or structured approaches to concept generation lead to intra-hemispherical, not inter-hemispherical connections among cognitive activation in the brain.

The second hypothesis is: partially structured and structured techniques require more cognitive activation in pre-frontal cortex compared to unstructured because partially structured and structured concept generation techniques require more judgement and analytical reasoning to review, assess, and iterate over a final design solution. Without this structure, students are able to fixate on an initial solution without any additional consideration for other options, perspectives, or inclusion of engineering principles. The null hypothesis is partially structured and structured techniques do not require more cognitive activation in the pre-frontal cortex compared to the unstructured design process.

Methods

Data

Positive area under the curve (AUC) is the measure used to represent cognitive load. AUC is used in neuro-imaging studies (e.g., [43]–[45]) to represent cognitive activation. Figure 1 illustrates the AUC as the shaded area under the Blood Oxygenation Level Dependent (BOLD) response. The significance level when comparing AUC across design processes was 0.05.

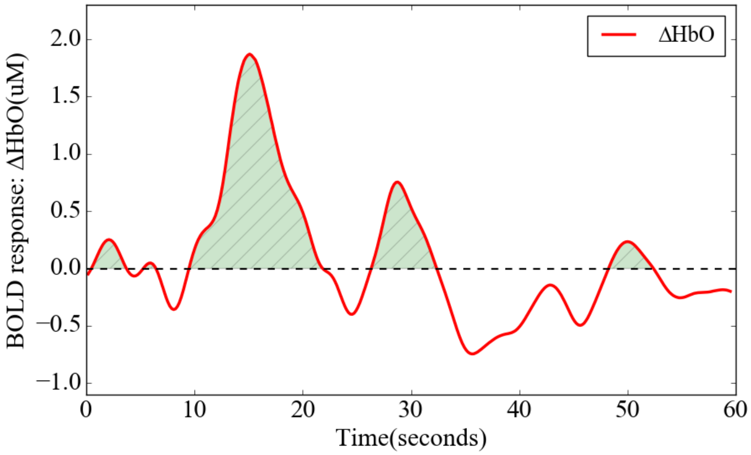

Figure 1: Area Under the ΔHbO Curve (AUC) represents cognitive activation

Data collection

Twelve graduate engineering students from Virginia Tech participated in the study. All of the participants are right-handed. Before each experiment began, the three concept generation techniques were introduced to each participant. After the introduction, participants were instructed to finish three design tasks at their own pace using unstructured (brainstorming), partially structured (morphological analysis) and structured (TRIZ) concept generation techniques. Participants were outfitted with the fNIRS optodes to measure cognitive activation during each task.

Three pre-designed tasks from previous research were used in the study [7]. The tasks were not discipline specific and previously demonstrated to require similar effort and thinking to generate a solution [7]. The first task required participants to assist the elderly with raising and lowering windows. The second task was to design an alarm clock for the hearing impaired. The third task asked participants to design a kitchen measuring tool for the blind. When using the Morphological design approach, participants needed to decompose the problem into several items for different functional requirements of the design and provide options for each sub-problem, and then they needed to judge, select, and combine among these options to finish their design. During TRIZ, participants were asked to use 39 Engineering Parameters and 40 TRIZ

Principle as a reference. In this task, participants needed to identify engineering parameters for the design, and then select the principles. Finally, they needed to decide and summarize their design with the principles they chose. Participants could use figures or words to describe their design for each task on paper. Between tasks, participants had 30 seconds to relax and make the cognitive activity back to general baseline level of cognitive function. The process of including a baseline cognitive measurement and rest period between each design is based on prior defined methods in neuroscience [46].

During the design tasks, fNIRS captured and recorded participants' cognitive activation in the pre-frontal cortex. Figure 2 below illustrates the sensor placement on the cap and the channels (formed by the combination of a source and a detector) covered several Brodmann areas (BA) in the pre-frontal cortex, including BA 8, BA 9, and BA 46. Bordmann areas are regions in brain cortex which is divided by its cytoarchitecture. Neuroscience literature provides insight about cognitive function associated with each. For example, BA 8 is activated when subjects are required to predict future events with internal or external uncertainties [37]. BA 9 is demonstrated to be more activated during judgement tasks [47]. BA 46 and a lateral part of BA 9, also called dorsolateral pre-frontal cortex, are known to be associate with cognitive flexibility, working memory and abstract reasoning [48]–[50].

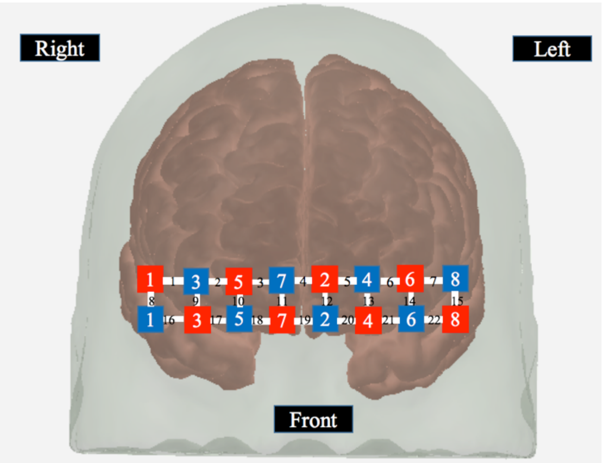

Figure 2: The placement of sources (red) and detectors (blue) along pre-frontal cortex (Connections between sources and detectors are channels from 1 to 22)

Data analysis

Both design outcomes and fNIRS data during concept generation were collected. In this phase, only oxygenated hemoglobin (HbO) in fNIRS data was analyzed and reported. Two participants' data were removed from analysis due to bad signals during the experiment. fNIRS raw data was filtered by a bandpass filter between frequency of 0.1 and 0.01 to remove instrumental and psychological noise [51]. Each concept generation task, included a series of phases. During the brainstorming process, there was only one phase: to come up with a solution to the design challenge. During the morphological analysis task, there were two phases: a decomposition phase and design phase. During the TRIZ task, there were three phases: to review the 39 engineering parameters, to identify TRIZ principles that apply to the design challenge, and finally to develop a solution. The fNIRS data was collected and divided by each phase.

To investigate connectivity of brain functions, correlation matrixes were developed using the change of HbO (ΔHbO) in all channels during each design phase. Only high correlation (greater than 0.8) was considered as connective function in this study. Positive area under the ΔHbO curve (AUC) during design phase in each task were calculated by each channel to represent the cognitive activation in different regions of the brain. ANOVA with repeated measure was used to compare these measures to show the cognitive difference when using these three concept generation techniques. The significance level was defined as 0.05 and effect size is described using Cohen's d value. Cohen's d represents the difference in effect size between AUCs.

Results and Discussion

Connectivity difference

A correlation matrix of each participant during each task was developed and high correlation (greater than 0.8) between channels was recorded as high functional connectivity. Great variabilities exist in brain connectivity among all participants, so that the common channels of all participants showing high connectivity were selected for analysis and comparison. For unstructured concept generation tasks (brainstorming), eight pairs of channels located in the right hemisphere were found to have high connectivity for all participants, but no common pair located in the left hemisphere was found. Thus, the null hypothesis is rejected. The heat map of average correlation matrix in Figure 3 (left) indicates stronger intra-hemisphere connectivity in the right than the left hemisphere during brainstorming.

For partially structured concept generation task (morphological analysis), two pairs of channels located in the left hemisphere had high functional connectivity among all participants. As the heat map in Figure 2 (middle) illustrates, left hemisphere had higher functional connectivity during morphological analysis task. Thus, the null hypothesis cannot be rejected because intra-hemispherical connectivity is observed in the left hemisphere.

For the structured concept generation task (TRIZ), six pairs of channels in the left and four pairs in the right showed connectivity among all participants. The heat map in Figure 3 (right) illustrates there are more inter-hemisphere connections between regions in the brain than either brainstorming or morphological analysis. Thus, the null hypothesis can be rejected. Greater functional inter-hemispherical connectivity may suggest coordination between brain regions. This pattern of activation only occurred during the structured approach where both the unstructured and partially structured resulted in intra-hemispherical connectivity among regions in the brain.

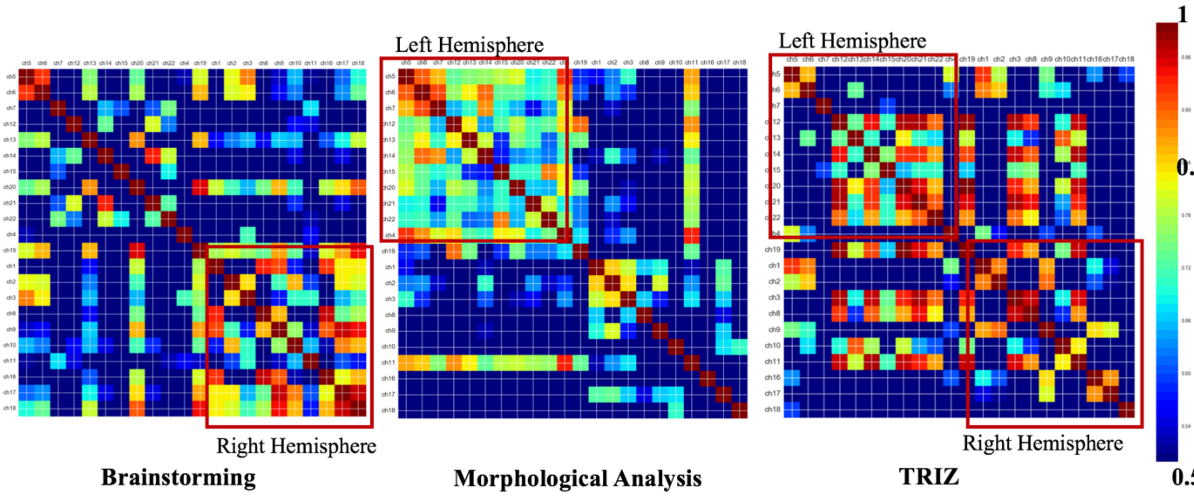

Figure 3: Heat map of average correlation matrix during concept generation tasks shows varying coordination in regions of the brain when using unstructured, partially structured, and structured concept generation techniques
(Note: Red represents that correlation coefficient is 1 and blue is no greater than 0.5; left upper part in each heat map is the intra-hemisphere connectivity in left brain and right lower part is intra-hemisphere connectivity in right brain, the rest parts are inter-hemisphere connectivity)

The connectivity differences among tasks indicates that with more inter-hemisphere and intra-hemisphere connectivity during concept generation using TRIZ, engineering students were possibly most capable of using divergent ways of thinking to enhance creativity during design. Brainstorming, which led to intra-hemisphere connectivity in the right might enable students to be more creative than morphological analysis with greater connectivity in the left. Although, these assertions are merely assumptions and further analysis between the cognitive processes and design outcomes is needed to determine correlations between novelty and quality of design concepts generated and patterns of cognitive activation. These explanations do seem to coincide with the goals of brainstorming to encourage creativity and TRIZ to make the process of creativity more predictable using universal and experience-based principles. Future analysis on the design outcomes or surveys after the experiment might be able to contribute these possible explanations.

Activation difference in design phases

ANOVA with repeated measure was used to compare area under the curve (AUC) (i.e. the increase in blood flow in regions of interest in the brain) during different concept generation tasks. Great variabilities in AUC exist between subjects, however, ANOVA with matched pairs shows concept generation techniques have significant effects on cognitive activation in the pre-frontal cortex. Significantly ($F(2,18) = 6.04$, p-value=0.010) different cognitive load among different techniques was found in channel 1 (located in the right BA 46, associated with abstract reasoning and cognitive flexibility). The follow-up post-hoc analysis (Tukey HSD) indicated that unstructured ($\bar{x} = 5.12$, SD = 3.4) and structured ($\bar{x} = 4.92$, SD = 2.26) tasks exhibited significantly higher cognitive load in right BA 46 than partially structured ($\bar{x} = 2.86$, SD = 2.67) task with a large effect size (Cohen's d = 0.74 for unstructured vs partially structured and 0.84 for structured vs partially structured), however, there is no significant difference between unstructured and structured. Figure 4 shows the different AUC in design phase using three techniques for each subject. The null hypothesis is partially rejected. The expectation was partially structured and structured design processes would lead to significantly higher cognitive activation but the results find partially structured design processes led to the least cognitive activation. The increased cognitive activation among unstructured and structured design processes appear similar but the results about connectivity among regions illustrated in Figure 3 suggests these regions correlate with different areas in the brain during each of the design processes.

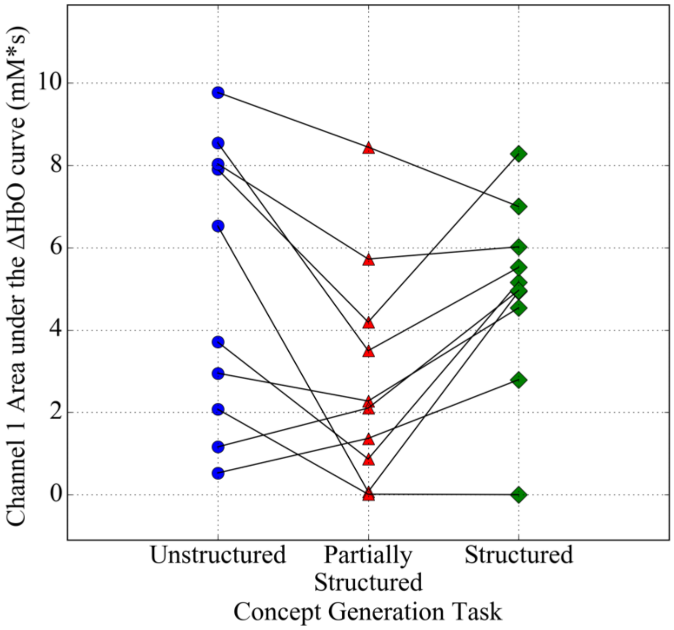

Figure 4: Area under the ΔHbO curve for channel 1 (right BA 46), associated with abstract reasoning and cognitive flexibility, is greater during unstructured and structured concept generation

One possible explanation for the difference between unstructured, structured, and partially structured is that when generating concepts using the partially structured technique, students did not have any design principles as reference and they need to make selections among sub-solutions, hence they might ignore some functional requirements or not be willing to generate extra design alternatives. In other words, design might become a selection process when using morphological analysis and this is represented with deactivation in the region of the brain associated with abstract reasoning and cognitive flexibility.

Another region with significantly ($F(2,18) = 4.53$, p-value=0.026) different cognitive load when using unstructured, partially structured, and structured concept generation tasks was channel 19 (located at middle BA 8, associated with uncertainty processing) as Figure 5 indicates. Between partially structured ($\overline{x} = 6.18$, SD = 6.19) and structured tasks ($\overline{x} = 10.15$, SD = 6.95, significant difference was found by the post hoc test (using Tukey HSD), and the effect size is medium (Cohen's d = 0.60). This could suggest that when using TRIZ, students allocated more cognitive effort to process uncertainty than morphological analysis. In part, this might be due to more divergent thinking and higher creativity during design using TRIZ. Another possible explanation is students were less familiar or confident with TRIZ and the design principles it provided. During morphological analysis students broke down the problem into smaller pieces and then combined them to develop a solution. Whereas, the structured approach, students had to make decisions about which of the 39 principles and 40 TRIZ elements were relevant and which to discard. The higher number of choices when using the principles and TRIZ could lead to greater feeling of uncertainty and this was evident in the results. Future analysis on the design outcomes and post-task interviews can provide additional evidence and support for these assumptions and explanations.

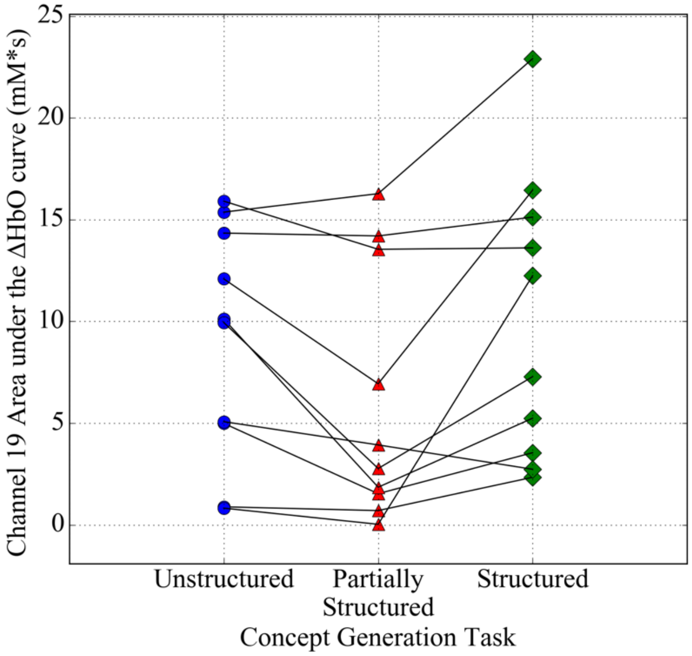

Figure 5: Area under the ΔHbO curve of channel 19 (middle BA 8), associated with uncertainty processing, is greater during unstructured and structured concept generation

BA 9, which is associated with judgement, did not show significant difference in cognitive load. This result might suggest that even though there were more constraints using morphological analysis and TRIZ, students did not take more cognitive effort to make judgements about their concepts and solutions compared to brainstorming.

Conclusion

Generating solutions using unstructured, partially structured and structured concept generation techniques lead to differences in brain connectivity, which is believed to influence creativity and divergent thinking [52]. The unstructured technique leads to intra-hemisphere connectivity in the left for all participants, and the partially structured technique leads to intra-hemisphere connectivity in the right hemisphere, while the structured technique leads to intra-hemisphere connectivity both in the left and right hemisphere and also inter-hemisphere connectivity between both the left and right hemisphere.

Different concept generation techniques exhibit varying cognitive load in parts of pre-frontal cortex. In right BA 46, which is associated with abstract reasoning and cognitive flexibility, significantly higher activation (measured by positive area under the ΔHbO curve) was found when using structured compared to the partially structured technique. In the middle BA 8, which is associated with processing uncertainty, the structured technique leads to significantly higher activation compared to the partially structured technique, while no significant difference was found between the structured and the unstructured techniques. A more detailed analysis of the temporal data collected will provide a more nuanced understanding of the relationships between design behavior, cognitive behavior and neurophysiological behavior.

The next step is to measure the difference in students based on design training. Through a better understanding of these processes, the goal is to explore specific elements of the engineering curriculum that may contribute to student ability to generate concepts to engineering design problems. This interdisciplinary study, integrating engineering design education and methods from neuroscience, aims to generate conversation about other engineering design tasks and settings, in which, neuroimaging techniques can be effectively used as a new tool to generate a new class of data to assist in understand differences in design cognition. These differences in turn can be correlated with differences in design cognition and can be used as the basis of testing the effect of education interventions. They can provide empirical support for models of designing and lay the foundation for methods to test the effects of changes in the design environment such as the use of new tools, the use of homogeneous teams and the use of heterogeneous teams.

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