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EXPLORATION OF THE DYNAMICS OF NEURO-COGNITION DURING TRIZ

Julie Milovanovic
Virginia Tech
Blacksburg, VA, USA

Mo Hu
Virginia Tech
Blacksburg, VA, USA

Tripp Shealy
Virginia Tech
Blacksburg, VA, USA

John Gero
University of North Carolina at Charlotte,
Charlotte, NC, USA

ABSTRACT

The Theory of Inventive Problem Solving (TRIZ) method and toolkit provides a well-structured approach to support engineering design with pre-defined steps: interpret and define the problem, search for standard engineering parameters, search for inventive principles to adapt, and generate final solutions. The research presented in this paper explores the neuro-cognitive differences of each of these steps. We measured the neuro-cognitive activation in the prefrontal cortex (PFC) of 30 engineering students. Neuro-cognitive activation was recorded while students completed an engineering design task. The results show a varying activation pattern. When interpreting and defining the problem, higher activation is found in the left PFC, generally associated with goal directed planning and making analytical judgement when interpreting and defining the problem. Neuro-cognitive activation shifts to the right PFC during the search process, a region usually involved in exploring the problem space. During solution generation more activation occurs in the medial PFC, a region generally related to making associations. The findings offer new insights and evidence explaining the dynamic neuro-cognitive activations when using TRIZ in engineering design.

Keywords: design neuro-cognition, TRIZ, prefrontal cortex

1. INTRODUCTION

Designing is a problem solving activity [1] that aims to solve ill-defined problems [2] with context based solutions [3]. Addressing design problems involves generating concepts. This process relies on cognitive activities that mobilize a large range of cognitive functions [4,5]. Engineers sometimes apply techniques to generate concepts and to boost innovation and creativity such as brainstorming, mind mapping, morphological analysis or TRIZ [6]. Recently, the design community has shown a growing interest into exploring how these techniques differ by understanding brain behavior during concept generation [7–9] and creativity tasks [10]. The underlying agenda is to provide a better understanding of neuro-cognitive processes recruited while designing, and the correlation between cognitive design processes and designers' cortical activation. Characteristics such as designers' background [11] or the concept generation technique used by the designer [12] affect brain behavior. Identifying the neural correlates for concept generation when using varying techniques can lead to a better understanding of the underlying framework of techniques and motivate the development of new tools to assist designers based on their brain behavior and design outcomes [8,13]. The research presented in this paper is a step in that direction.

We analyzed designers' neurophysiological activation in their prefrontal cortex when generating ideas using TRIZ, a method to generate innovative solutions [14]. TRIZ is a well-structured idea generation technique organized around distinctive steps (i.e., interpret and define the problem, search for standard engineering parameters, search for inventive principles to adapt, and generate final solutions). Little is known about designers' brain behavior while using TRIZ [9]. This study explores the differences in brain behavior for each step of TRIZ, when used to solve a design task. The results presented here are part of a wider project on analyzing the neuro-cognition of three different types of concept generation techniques. Previous findings from this wider project are presented in [12,15–17]. In previous work, our focus was limited to the concept generation phase of TRIZ. In this article, for the first time, the neuro-cognition of all of the different steps of TRIZ are analyzed and compared. This provides new insight about how the requirements for each step of TRIZ change neuro-cognition.

2. BACKGROUND

2.1 Using TRIZ to generate inventive solutions

The TRIZ (Theory of Inventive Problem Solving) methodology, developed by the Russian scientist G. Altshuller in the 1960's [14], has found its way into diverse industrial sectors, ranging from the energy and electrical industry, the design of home appliances, the automotive industry and mechanical engineering [18,19]. TRIZ's use by professionals is driven by its capability to promote innovation rapidly, to increase the competitiveness of the company using this approach and to adapt to new regulations [20]. The TRIZ toolkit contains a wide range of tools and techniques aiming at defining, formulating and modeling a problem (analytical tools) or providing recommendations for system transformations (knowledge-based tools) [21]. The most popular TRIZ tools include the use of the contradiction table and the inventive principles. The latter stemmed from recurring patterns observed by Altshuller in patented technologies. TRIZ's inventive principles are a set of conceptual solutions for technical problems that drive the process of problem solving and innovation [21]. These conceptual solutions are applied to the design problem reduced beforehand to its essentials, in a conceptual format. At the conceptual level, designers seek a match between the problem and the solution they generate. The last step in TRIZ consists in transforming the conceptual solution into a factual one. Contrary to other techniques like brainstorming that explores matching a defined problem with a defined solution, in TRIZ, the designer seeks a match between problem and solution at a conceptual level (Figure 1). TRIZ requires users to decompose and analyze the problem systematically before generating new concepts.

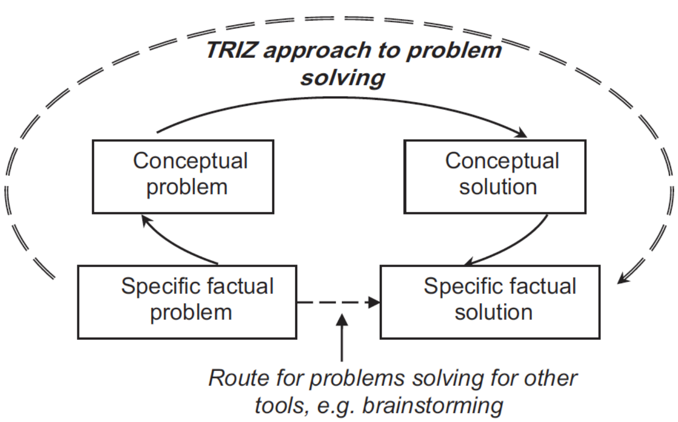

FIGURE 1: TRIZ METHOD TO PROBLEM SOLVING (SOURCE: [21])

Using TRIZ tends to increase focus among designers [22] but can lead to a mental fixation on problem constraints [23]. Design fixation while using TRIZ can occur because of its problem-driven approach following logical steps guided by analysis, situational context, and constraints. Nonetheless, using TRIZ has been beneficial to increase innovation and is widely used in engineering education [24].

2.2 Neuro-cognition of designing, problem solving and creativity

The prefrontal cortex (PFC) is the brain region of interest in this study as it plays an important role in ideation and creativity for design tasks [25,26]. The PFC controls executive functions in the brain, such as planning, decision-making, attention, working memory and is critical for internal representation of goals and means to achieve them [27]. Concept generation relies on dual cognitive processes, such as convergent and divergent thinking [28], which aligns with findings suggesting a bilateral activation of the PFC while performing such tasks [17,25]. The left part of the PFC tends to be associated with control, judgment, and goal directed planning whereas the right part of the PFC tends to activate during creative problem solving [29,30]. The PFC includes several inter-connected sub-regions, especially the ventrolateral PFC (VLPFC), situated in the lower lateral part of the PFC and dorsolateral areas (DLPFC), situated in the upper lateral part of the PFC [27].

Previous studies suggest that creative tasks strongly involve the right DLPFC [31, 32]. For example, Goel & Grafman [32] found the right DLPFC to be critical for ill-structured representation and computations by comparing abilities of a designer with lesions in their right PFC to a designer without brain lesions. However, there is no consensus pointing toward specific brain patterns related to a creative behavior due to a lack of consistency and repeatability of results in neuroimaging studies on creativity [33]. In fact, most studies on creativity focus on divergent thinking tasks such as the Alternative Uses Task (AUT) or Remote Associates Test (RAT) which lacks ecological validity [33]. Although some studies point towards an association of creative thinking with mind-wandering or defocused attention [34], using of a well-structured method like TRIZ has proved to increase engineers' idea novelty [24].

Using TRIZ tends to engage a more problem-focused cognitive effort than other design techniques [22]. Interestingly, distinct neuro-cognitive behaviors are observed when using different concept generation techniques [12,16], which suggest a possible correlation between ideation tools and cortical activation in the PFC. A study measuring brain behavior using an electroencephalogram (EEG) pointed out an increase in gamma wave in the frontal part of the brain when subjects had an insight to solve a problem after learning about the TRIZ method [35]. Findings on the neural correlate of idea generation using TRIZ are scarce and research in this area is still in its infancy. The exploratory research presented below provides first detailed insight into engineers' brain behavior while using the TRIZ method in design.

3. MATERIALS AND METHODS

The study presented in this paper is part of a wider project that aims to characterize the neuro-cognition of multiple idea generation techniques, namely brainstorming, morphological analysis and TRIZ. Previous published results from our study focused on comparing temporal neurophysiological activation across techniques [12,15,16] or exploring brain region co-activation during brainstorming by measuring change in brain networks [17]. In all previous studies, only the generation of final solutions was considered for the analysis. In this article, we used the same set of tools to explore neuro-cognitive activation in all four steps of TRIZ: 1) read the design brief and identify the problem, 2) search for standard engineering parameters, 3) search for inventive principles to adapt and 4) generate final solutions.

3.1 Design tasks

Thirty graduate engineering students (all right-handed, 22-26 years old) were recruited to participate in the study. All participants had taken courses in engineering design. They were not familiar with TRIZ but were given a lecture and workshop on the TRIZ method. Out of the several TRIZ processes commonly exploited, in our study we used TRIZ as a series of steps based on knowledge-based tools to provide recommendations for system transformations [21]. It included handing students 39 engineering parameters as a design reference, a contradiction matrix, and 40 innovative principles based on an analysis of patented solutions.

Participants received a brief inviting them to design a kitchen measuring tool for the blind. Participants were instructed to use TRIZ to develop a conceptual solution to the proposed problem. The design brief also stated the TRIZ steps (see Appendix).

First, students were asked to read the brief and to define the problem. Then, they used Altshuller's 39 engineering parameters to search for a physical contradiction and well-solved problems that correspond to their specific problem. Defining parameters serves to describe the problem, for instance through "the weight of the object", its "shape", "strength" or its "convenience of use". A physical contradiction appears when requirements are inconsistent to the physicality of the same system. For example, when designing an umbrella, a bigger size would protect the user better but also make it cumbersome to carry around [21]. Therefore, the size of the object becomes a physical contradiction.

The third step consisted of adapting some of the 40 inventive principles to solve the current problem. The contradiction matrix provides a list of relevant inventive principles to resolve the contradictions formulated in the previous step, based on the specific parameters selected. These inventive principles provide conceptual solutions. For example, principle 23 about feedback refers to introducing feedback to improve a process or adapt the feedback according to operating conditions. This principle is found at the intersection of the parameter "productivity" (improving feature) and "loss of information" (worsening feature) in the contradiction matrix. This principle suits the current problem as one could imagine an audio or tactile feedback indicating weight for a blind user.

The last step of the task was to generate as many solutions as possible. Participants did not iterate and went through each phase only once. No time limit was given to participants.

3.2 Measuring design neuro-cognition

Current neuroimaging techniques available to quantify neuro-cognitive activation fall into several categories: electroencephalogram (EEG), functional magnetic resonance imaging (fMRI), and function near-infrared spectroscopy (fNIRS). EEG and fMRI are widely used to study creativity [10] and design [11,36,37]. fNIRS is a more recent neuroimaging technique and is now used in different domains, for instance language processing or clinical studies [38]. It has gained popularity due to its usability in naturalistic environment and resilience to motion artefacts [39,40]. fNIRS does not measure cognitive activity directly rather it measures metabolic demands (oxygen consumption) of active neurons [41], with a penetration depth of about 3 cm. In the fNIRS cap, light is emitted from sources at specific wavelengths (between 700-900 nm) into the scalp. The light scatters, before reflecting back to the light receivers. The oxy-hemoglobin (oxy-Hb) and deoxy-hemoglobin (deoxy-Hb) absorb more light than water and other tissue in the brain. The change in the difference between the emitted light and reflected light is used to calculate the change in oxygenated blood using a Modified Beer-Lambert Law. The oxy-Hb and deoxy-Hb are inversely related.

In this study, participants were equipped with a fNIRS cap from the LIGHTNIRS system (Shimadzu Co., Japan Kyoto) with a sampling frequency of 4.44 Hz. (Figure 2). Since fNIRS is suited for naturalistic environment, participants could perform the design task in an upright sitting position. Three wavelengths of near-infrared light (780 nm, 805 nm, and 830 nm respectively) were used by this fNIRS system to record a change in participants' oxy-Hb. We only report oxy-Hb due to its relatively higher amplitudes and sensitivity to cognitive activities than deoxy-Hb.

FIGURE 2: PARTICIPANT SETUP AND FNIRS SYSTEM

The sensor placement on the fNIRS cap is illustrated in Figure 3. We used 16 sensors (eight emitters and eight detectors) located using the 10/20 international systems. The eight emitters and eight detectors formed a total of 22 channels. A channel (black lines in Figure 3) is the combination of a light source (red squares in Figure 3) and a nearby light receiver (blue squares in Figure 3). The 22 channels capture the change in oxygenated cortical blood in the PFC. Multiple sub-regions in the PFC are covered: the dorsolateral prefrontal cortex (DLPFC: channels 1, 2, 3, 9, 10 in the right hemisphere, and channels 5, 6, 7, 13, and 14 in the left hemisphere), the ventrolateral prefrontal cortex

(VLPFC: channels 16 and 17 in the right hemisphere, and channels 21 and 22 in the left hemisphere), the orbitofrontal cortex (OFC: channel 18 in the right hemisphere, and channel 20 in the left hemisphere), and medial prefrontal cortex (mPFC: channels 4, 11, 12 and 19) in both hemispheres.

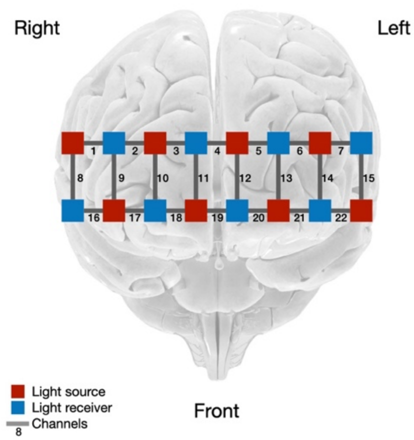

FIGURE 3: SENSOR CONFIGURATION

3.3 Data analysis

Out of the 30 participants, three were removed from the analysis because of a weak signal during the experiment. fNIRS raw data was processed using a bandpass filter (frequency ranging between 0.01 to 0.1 Hz, third-order Butterworth filter) to remove high-frequency instrumental and low-frequency psychological noise [42]. To reduce motion artifacts, participants were instructed to keep their head motion to a minimum. Additionally, an independent component analysis (ICA) with a coefficient of spatial uniformity (CSU) of 0.5 was applied to remove motion artifacts. The parameters in data processing are based on prior research [43]. The filtering process was conducted using Shimadzu fNIRS software and the following analysis was conducted using Python. A baseline correction was applied in which the mean Oxy-Hb during the baseline rest period was subtracted from the Oxy-Hb during the tasks for each channel. Oxy-Hb for each participant was standardized into z-scores.

To measure differences between the four phases of TRIZ, a one-way ANOVA with repeated measures was carried out for each of the 22 channels. Subsequently, t-tests were used to explore differences in activation between each step.

4. RESULTS AND DISCUSSION

On average, students spent 57 sec. (SD=26 sec.) on reading the task and defining the problem, 3 min. and 12 sec. (SD=111 sec.) on searching for engineering parameters, 5 min. and 42 sec. (SD=222 sec.) to search for inventive principles to adapt to their design problem and 3 min. and 9 sec. (SD=120 sec.) to generate solutions. For each phase, the averaged channel activation across participants is represented in Figure 4. A qualitative difference in neuro-cognitive activation is apparent for each of phase as seen in Figure 4. Statistically, the repeated one-way ANOVA shows a significant difference in Channel 14, situated in the left DLPFC ($F(3,78)=3.54$, $p=0.018$).

For the brief reading and definition of the problem phase, the highest activation appears clearly on the left PFC, specifically in the VLPFC and the lateral DLPFC (Figure 4(a)). Channel 14, situated in the left DLPFC activates significantly higher in this phase than in the other ones. During this first phase, Channel 14 is significantly higher than in the search for engineering parameters ($t(52)=2.29$, $p=0.030$) and the search for inventive principle ($t(52)=1.71$, $p=0.005$). The left part of the PFC tends to be associated with cognitive processes engaged during rule-based design, goal directed planning and making analytical judgement [25,44]. Recruitment of the left PFC while defining the problem aligns with this phase in the design process as students are framing the problem.

During the second phase of the task, students were invited to search for engineering parameters from the given list. The aim of this step is to help students search for existing solutions that would fit the current problem. The idea is to reflect on parameters such as “shape”, “strength” or “convenience of use”. In this phase, high activation switched hemisphere from the reading phase. The strongest activation appears in the right PFC, specifically the lateral VLPFC and DLPFC (Figure 4(b)). No significant differences was found for channel activation, although Channel 16 is close to be significantly higher in this phase than in the first ($t(52)=2.01$, $p=0.05$). This region is generally associated with exploration of alternative hypotheses to explore the problem space [45] and to creative problem solving [46]. The change of hemisphere activation for “searching for parameters” compared to “understanding the design problem” corresponds to previous findings about the association of PFC region activation and design cognition processes. In the first phase, students rely more on planning and understanding (activation in the left PFC [47]), whereas the second phase integrates a prospective dimension of exploring the problem space (activation in the right PFC [47]).

The third phase of the task initiates the definition of inventive principles that can apply to the current problem. This phase was the longest of all the sub-tasks students experienced using TRIZ. Students used a list of 40 inventive principles that were previously presented in a lecture, to define inventive ways to solve their design problems. During this phase, the right PFC was recruited more than the left, specifically the right orbitofrontal cortex (OFC), the right part of the medial prefrontal cortex (mPFC), as well as the right medial DLPFC (Figure 4(c)). The highest activation appears in the lateral part of the right VLPFC (channel 16). According to Aziz-Zadeh and colleagues [48], activation in the right VLPFC correlates with cognitive processes mobilized to evaluate problems rather than solving problems. The cortical activation found in our study corresponds to this previous finding. When students search for inventive principles to apply to their design problem, they need to evaluate the current state of the problem to select relevant inventive principles.

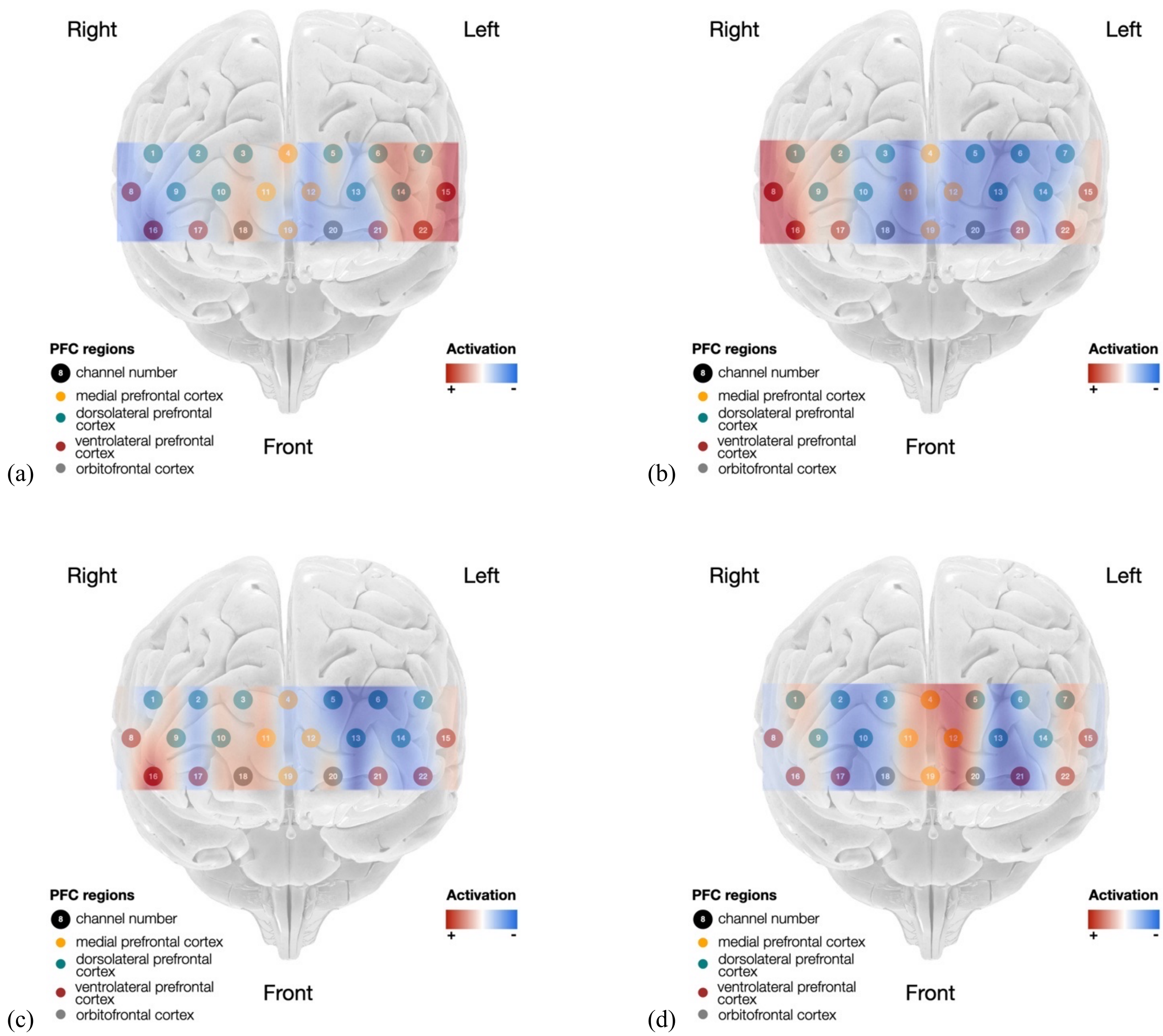

FIGURE 4: HEAT MAP OF PFC ACTIVATION AVERAGE ACROSS PARTICIPANTS FOR EACH STEPS OF THE TASK: (a) READING AND DEFINING PROBLEM, (b) SEARCH FOR ENGINEERING PARAMETERS, (c) SEARCH FOR INVENTIVE PRINCIPLES TO ADAPT TO DESIGN PROBLEM, (d) GENERATE SOLUTIONS

The ultimate phase in this TRIZ method is the generation of solutions. During this phase, all channels from the mPFC were highly recruited (Figure 4(d)), which was not the case in any of the three previous phases. Channel 12 in the mPFC is almost significantly higher in the solution generation phase than in the search for engineering parameters phase ($t(52)=1.94$, $p=0.06$) and the search for inventive principles phase ($t(52)=2.07$, $p=0.05$). Previous studies suggest that the mPFC is associated with adaptive decision making and memory retrieval that connects to learning situated associations (a link between context, locations, events and adaptive responses) [49], and the ability to simulate future imaginative events [50]. In this last phase, students rely on their analysis of the design problem and first insights using the inventive principles at the conceptual level to propose ideas for a kitchen measuring tool for the blind. The high recruitment of the mPFC aligns with the task at hand as students engage in adaptive decision making, informed by their previous reflections.

5. PERSPECTIVES: BRIDGING COGNITION AND NEURO-COGNITION OF TRIZ

Engineering professionals rely on TRIZ techniques to support innovation in engineering [18,19], while design researchers explore to what extent TRIZ benefits design thinking [21] and what underlying cognitive processes characterize TRIZ [22,51]. Previous work sets the framework for our empirical study on the neurocognition of TRIZ. Table 1 provides a summary of the theoretical and empirical findings on TRIZ that highlights the contribution of our study. As indicated in Table 1, these findings show a correlation between the tasks provided, the expected cognitive effort it requires, and the cognitive functions related to the activated sub-regions in the PFC. Results show a correlation between cognition and neuro-activation. For example, cognitive studies found a higher focus on the problem space in the first part of a design session while using TRIZ [22,51]. In this study, we found higher activation in the right part of the PFC during the second step (conceptual problem). It corresponds to cognitive processes of creative problem solving [46] and exploration of the problem space through hypotheses [45]. Interestingly, findings on design processes while using TRIZ from cognitive studies in design science and neuroscience aligns as illustrated in Table 1.

The implication of such findings at a methodological level are important. As we start bridging cognition and neuro-cognition of designing, a new generation of methodological tools to measure design thinking are now available. If through the measurement of neuro-cognitive activation, we obtain reliable information on design cognition, tools from neuroscience like fNIRS, may provide a future alternative to resource intensive techniques like protocol analysis [8]. This study provides support in that direction, but more work is needed to confirm the reliability of using neuro-cognitive activation to infer design behavior at a cognitive level. In future work, design experiments can begin to capture design cognition through think aloud while monitoring brain activation, to gain a better understanding of the relevance of using neuro-activation as a primary source to study design cognition.

TABLE 1: SUMMARY OF THEORETICAL BASED ON [21] AND EMPIRICAL FINDINGS ON THE DESIGN COGNITION OF TRIZ

	Specific problem	**Conceptual problem**	**Conceptual solution**	**Specific solution**
Steps from experiment	Reading and defining the problem	Search for engineering parameters	Search for inventive principles	Generate solutions
Findings from previous cognitive studies [22,51]	Higher focus on design problem during the first half of the design session. Design activity focus on evaluation.			
Neuro-activation in PFC (findings from this study)	Higher activation left DLPFC and VLPFC	Higher activation right DLPFC and VLPFC	Higher activation right VLPFC (channel 16)	Higher activation in mPFC
Cognitive function associated to activation based on previous neuro-cognitive studies	Rule based design, goal directed planning and making analytical judgement [25,44]	Exploration of alternative hypotheses to explore the problem space [45], creative problem solving [46]	Evaluate problems rather than solving problems [48]	Adaptive decision making and memory retrieval [49], ability to simulate future imaginative events [50]

7. CONCLUSION

This study provides an initial exploration of the neuro-cognitive activation in different steps of using TRIZ for engineering design. We found that engineers showed varying activation patterns in their prefrontal cortex (PFC) and its sub-regions while using TRIZ, which suggests an evolving neuro-cognitive effort while interpreting a design problem, searching conceptual problems and solutions, and generating concepts. Students utilized their left DLPFC and VLPFC more during reading the description of the design problem. In contrast, the right part of the PFC is more involved when searching for the conceptual problems and solutions. During the final solution generation phase, the mPFC showed higher activation. This sub-region is generally associated with adaptive decision-making and learning situated associations. The results offer new insights and evidence explaining the dynamic neuro-cognitive activations when using TRIZ in engineering design.

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APPENDIX

Design task and TRIZ procedure

Task: Measuring Tools for the Blind

According to a 2008 CDC study, more than 3.4 million Americans are either legally blind or visually impaired. Of those, approximately 1.3 million Americans are legally blind. As such, there is a tremendous need to design products to assist those with this condition. Your employer has been contracted to design and develop a line of kitchen products for blind customers. As part of this larger project, your team has been hired to design measuring tools to aid the blind in the kitchen (i.e., assist in the measurement of liquid and dry substances).

TRIZ procedure

1) Identify the Problem,

2) Search for well-solved problems with Altshuller's 39 engineering parameters. The attached sheet can be used to identify parameters of physical contradictions: one parameter is the improving feature and one parameter is the worsening feature.

3) Look for analogous solutions and adapt inventive principles. Use the attached handout ("TRIZ 40 Design Principles") for further information on the principles that result from the table of contradictions.

4) Generate solutions