The Effects of Multiple-Intervention Neurofeedback on Engineering Design Ideation

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ABSTRACT

This research explores the application of neuro-cognitive feedback in enhancing the ideation phase of engineering design. Brainstorming is identified as a dominant method for ideation, relying on cognitive processes linked to memory. Neuro-cognitive feedback is introduced as a technique to maintain high cognitive responses during ideation by providing information about brain states, aiding in semantic processing and attention. The study employs functional near-infrared spectroscopy (fNIRS) for neuro-cognitive feedback (NF), showing its advantages in spatial and temporal resolution, mobility, and cost over EEG and fMRI. This feedback method involves placing sensors in a headband on the forehead to measure cortical activity and provide real-time feedback to participants. The technique has been validated in various fields, including medicine, sports, and the arts, for enhancing cognitive and creative performance. A key focus of the research is on the effects of neuro-cognitive feedback on ideation and brain behavior. The research method involved recruiting engineering graduate students, employing various design tasks, and using fNIRS for data collection and analysis. It reveals differences in brain behavior between the baseline and neuro-cognitive feedback sessions, particularly in the right dorsolateral prefrontal cortex (DLPFC), which is associated with generating new ideas. Multiple neurofeedback sessions showed performance improvements in engineering design tasks, with changes in task-related oxygenation in the prefrontal cortex. The study concludes that neuro-cognitive feedback enhances ideation by providing a sustained high cognitive response, aiding in self-regulatory control of brain activity, and improving performance in various cognitive tasks. The results indicate significant improvements in ideation fluency and time spent on tasks with neurofeedback, suggesting its effectiveness in enhancing cognitive functions in engineering design.

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GENERAL AUDIENCE ABSTRACT

This study investigates how neuro-cognitive feedback can improve the brainstorming phase of engineering design. Brainstorming, a method in design ideation, provides concrete quantitative results to compare idea production. The research evaluates neuro-cognitive feedback to boost cognitive activity during brainstorming by monitoring brain states to assist in understanding and attention. It utilizes a technology called functional near-infrared spectroscopy (fNIRS) for this purpose. This technique, which has proven benefits in fields such as athletics and the arts, involves a headband with sensors that measure brain activity and provide immediate feedback.

The research focused on civil engineering graduate students, using various design tasks and fNIRS for data gathering and analysis. It found that neuro-cognitive feedback impacts a brain area that contributes to the creation of new ideas and the cohort saw improved performance in engineering tasks. The results highlight that the multiple interventions help manage brain activity and improve task performance. The findings suggest that this method significantly boosts the efficiency and duration of brainstorming sessions in engineering design, showing its potential to enhance cognitive skills.

Contents

INTRODUCTION

Refining how designers solve problems is an ongoing process. Methods such as framing the design problem in multiple ways [1], applying structured design principles to generate new ideas [2], allowing time for reflection [3], and engaging with stakeholders [4]. A throughline in each one of these approaches is idea generation. It is in the idea generation phase that the fragments of every new solution begin to appear, and it is in studying idea generation that neurofeedback can be particularly useful [5].

Many different kinds of stimuli exist to improve engineering design ideation [6,7]. For example, human interaction [8, 9], chemical stimuli (caffeine) [10], tDCS [11,12], and others [13, 14]. Neuro-cognitive feedback is a unique type of stimulus because it improves performance through self-regulation [15]. It is also customizable to each designer and it does not require additional human resources (e.g., peer interaction). Neuro-cognitive feedback can reduce stress through heightened self-awareness [16], enhanced memory [17], and attention [18-20]. These cognitive functions are requisites for engineering design ideation [21]. Neuro-cognitive feedback also supports social cognition by helping teams synchronize through neuro-coordination [9-15]. This research explores neuro-cognitive feedback for engineering design ideation more directly. The experiment takes advantage of significant prior neuro-cognitive feedback research [22-29] and applies this understanding to engineering design ideation in a new way.

The motivation for the study in this paper is to improve engineering design ideation by providing the foundation for and testing of a neuro-cognitive feedback tool. The innovation of this project is the application of neuro-cognitive feedback over multiple sessions in an engineering population. The study measured the efficacy of real-time neuro-cognitive feedback and the effects on engineering design fluency. The purpose was to distinguish key differences between engineers with and without this type of neuro-cognitive feedback.

Empirically testing the effects of real-time neuro-cognitive feedback with engineering graduate students can open new avenues of research. The contribution of this project is the application of cognitive neuroscience to the engineering design process. While much current research advances computers to replace humans, the vision here is a future where neuro-cognitive feedback aids, rather than replaces, human cognition.

Further understanding why particular feedback methods can enhance cognitive activity can pave the future for performance enhancement. This project evaluates (1) how multiple interventions can coach design engineers to use the feedback to increase brain activity and (2) whether in this case, increased brain activity, subsequently increases the fluency of design ideas.

BACKGROUND

Engineering design is a process of problem exploration, ideation, solution evaluation, and design communication [30]. The ideation phase during engineering design is critical to producing creative solutions to complex systems problems [31]. Ideation is the time to bring together problem understanding, engineering science, social factors, and practical knowledge to develop possible solutions [32]. The quality and quantity of solutions generated inform and even determine the outcome of design [2, 33]. Only after ideation can a solution be chosen for further development.

Brainstorming remains a dominant approach for ideation [34-36]. Designers are instructed to imaginatively generate as many solutions as possible while suspending criticism of the solutions being generated [31, 37, 38]. Previously generated solutions can be combined to form new solutions [38, 39]. The cognitive process needed for brainstorming originates in the mental structures that control memory cognition [40]. Brainstorming works by classifying attributes of solutions identified in primary memories, which serve as probes to seek and retrieve matching traces in secondary memory, and transform these memories into new and modified mental schemas [41]. To continue to brainstorm requires repeated prompts to memory functions that re-initiate the searching process. More mental energy is required for each new search [42, 43].

Neuro-cognitive feedback to enhance engineering design ideation

Brainstorming produces a high cognitive response early during the solution-generation process, but this high cognitive response is not sustained over time. In an effort to bolster a high cognitive response, the purpose here was to look to neuro-cognitive feedback to reduce the decay of cognitive activation during brainstorming over time. Neuro-cognitive feedback improves performance by making information about hidden brain states accessible to our consciousness [20]. It provides a feedback loop to induce learning mechanisms and allows individuals to search for appropriate mental strategies through self-regulatory control of brain activity [24]. Neuro-cognitive feedback can effectively change localized brain activity by tapping into learning processes [18, 22]. People who receive neuro-cognitive feedback learn to increase a specific component of their cognitive activity, and that enhanced activity facilitates semantic processing in working memory [44] and attention [6, 45, 46].

How does neuro-cognitive feedback enhance ideation?

Neuro-cognitive feedback works by placing sensors on the scalp to measure cortical activity, analyzing this data in real-time, and then providing feedback regarding the current brain state to the participant using a video display. The efficacy of this type of feedback has been validated through multiple studies [47], systematic reviews [19, 20, 23, 48], and clinical trials [49, 50]. The same signals that provide neuro-cognitive feedback are also successfully being used to control computers in brain-computer interaction (BCI) [51-53].

For more than two decades, neuro-cognitive feedback has been making an impact in fields like medicine [54] to treat brain injury [55], migraines [56], ADHD [57, 58], substance abuse [59], and pain management [60-62]. Neuro-cognitive feedback is also used to enhance performance among professional athletes[8, 63]. For instance, golfers report improved focus from neuro-cognitive feedback training and demonstrate higher putting accuracy [64, 65]. Marksmanship improves among professional rifle shooters [21]. Neuro-cognitive feedback can also improve musical expression [17], and creative performance through dance [66], and boost cognitive performance [18] in creativity tasks [67, 68] and IQ [69, 70] scores among students.

Neuro-cognitive feedback is successful in the practice of the creative arts [23], clinical application in the treatment of disorders and diseases [61], and brain-computer interface for self-regulation [62]. Neuro-cognitive feedback is also used to train musicians on attention and relaxation to improve their performance [23]. Even professional athletes use it [16, 63]. For instance, golfers report improved focus and demonstrate higher putting accuracy [64, 65].

In athletics and the performing arts, every deft and precise movement is the product of activity originating in the brain. Like creativity, the practices of sport and of art are at their inception, cerebral. Neurocognitive feedback is a method by which high cognitive response can be sustained over time by reducing the decay in cognitive activation. Feedback provides a framework for a feedback loop to facilitate learning, providing touch points for the self-regulation process in learning [24].

Effect of neuro-cognitive feedback on ideation and brain behavior

In a previous study, the brain behavior of engineering students in the neuro-cognitive feedback group was different than the control [5]. Not only did engineering students in the neuro-cognitive feedback group elicit more oxy-Hb but the increased oxy-Hb was observed in different brain regions than the control group. Another phenomenon of interest in this type of study is the hemispherical dominance of oxy-Hb during ideation [71, 72, 73, 74]. Hemispheric dominance (i.e., more oxy-Hb in the right or left hemisphere of the PFC) is a previously observed factor for creativity [73, 75]. Creative tasks tend to recruit more activation from the right hemisphere of the brain compared to the left [73].

Effect of Multiple Neurofeedback Sessions on Cognitive Performance and Changes in Oxy-Hb

Multiple intervention sessions create opportunities for participants to adapt to the feedback and learn how to apply it to the design task [76]. In a study with airplane pilots providing training exercises mimicking job-specific decision scenarios, participants returned to the same three tasks at the same difficulty level over four sessions [77]. For two of the three tasks, the results showed an increasing trend in behavior performance and a decreasing trend in task-related oxygenated hemoglobin changes in the prefrontal cortex over the four sessions. The results of the third task, which did not yield any performance changes across sessions and instead saw an increasing trend in task-related oxygenation changes, can be explained by the ceiling effect that participants reached and by the simplistic nature of the task, answering multiple choice questions.

Participants also completed a fourth different task at dynamic adapted difficulty levels, referring to difficulty adjustment based on the individual's performance metrics. The difficulty of the assigned task was then modified based on regular performance. The results of these tests showed increased oxygenation with increased task difficulty which suggested that neurofeedback could be used to help team members address deficiencies. This type of adaptive training has been shown to improve outcomes and minimize the cognitive workload required for a task [78, 79].

What is being fed back to designers?

The feedback is derived by placing sensors on the scalp that measure the change in oxy-Hb and analyze this data in real time. Obelab's functional near-infrared spectroscopy (fNIRS) system and its NIRSIT software are used to provide feedback to the participants. The software supports raw hemoglobin data and it provides advanced neuro-cognitive feedback options. The feedback used in this study was in the form of a heat map on an animated three-dimensional (3D) brain where the warmer colors indicate a positive change in oxy-Hb.

The warmer colors are explained to the participants as activation in the corresponding brain region. Further analysis or interpretation is withheld. Elevated levels of oxy-Hb increase the amount of red on their display. Participants in the study received feedback about the change in oxy-Hb in their PFC and were told to sustain high levels of activation (red).

The display shows the change in oxy-hemoglobin and not deoxy-hemoglobin or total-hemoglobin because retest reliability is higher for oxy than for deoxy-hemoglobin, indicating that oxy-hemoglobin studies are more reliable [50] and is the most sensitive signal to changes in cerebral blood flow [51].

Why functional near-infrared spectroscopy?

For this study, fNIRS was used to produce both the neuro-cognitive feedback and for the data collection. fNIRS was preferred for this application, over electroencephalography (EEG), because it provides better spatial resolution with fewer channels. The mobility of fNIRS allows us to collect data with engineers in more realistic settings compared to functional magnetic resonance imaging (fMRI) [80]. A summary of the benefits of fNIRS is provided in Table 1.

Table 1. Comparison of instruments

Criteria	EEG	fMRI	fNIRS
Spatial resolution	Mediocre	High	Moderate
Temporal resolution	High	Mediocre	Moderate
Mobility	Participant sits upright	Participant lays down	Participant sits upright
Data processing	Moderate	Intensive	Low
Cost to operate	$0 (after purchasing)	~$500 per hour	$0 (after purchasing)
Ease of use	Time intensive placing electrodes	Requires technician	Less time intensive than EEG

fNIRS emits near-infrared light into the human cortex, and the refracted light that is not absorbed is detected by sensors [43]. The change in light absorption indicates a change in oxy and deoxyhemoglobin.

RESEARCH QUESTIONS AND HYPOTHESES

While it is clear that neurofeedback (NF) is an effective tool in improving cognitive function and endurance, what remains unclear is how this feedback is best used by an engineering cohort. In a previous, unpublished pilot study, comparing a feedback group, a placebo group, and a control group, it became obvious that there was no way to measure to what degree the population was benefiting from the feedback or leveraging it as a tool. Multiple intervention sessions provide an opportunity for participants to develop a working relationship with the device, to better figure it out. With a five-session study, we have the opportunity to evaluate the participant's baseline, assess their performance across multiple sessions of feedback, and measure their retention of any skill or performance boost in a conclusion session without feedback. Here the objective was to answer the following questions in service of this knowledge gap.

1. How do multiple NF sessions modify neuro-cognition in the PFC? Is there increased, or sustained elevation in oxy-Hb, after the intervention is removed?
2. How do multiple NF sessions modify performance in engineering design ideation tasks?
3. In the case of increased oxy-Hb, do changes in the fluency and endurance of design solutions follow?

Based on existing research findings presented in the literature review about the effects of neurofeedback on cognition, the following hypotheses were made.

Hypothesis 1. Findings will show an increase in oxy-Hb levels in the PFC from the first session and the following sessions and that increase will be sustained in the fifth session.

Hypothesis 2. Engagement with multiple NF sessions will correspond with improvements in performance, measured as increases in fluency of design ideas and endurance within the design task.

Hypothesis 3. Increase blood flow in the PFC, specifically the right dlPFC which, correlated with performance improvements, will correspond with an increase in the fluency of design ideas and time spent on task.

METHODS

Experiment Design

Engineering graduate students (n=30) were recruited to participate in the study during the fall 2022 and spring 2023 semesters. The cohort was composed of civil engineers. Participants were compensated $20.00 following their first, third, and fifth sessions. With the expectation that the data for some participants may not be adequate, due to participant dropout or poor recording quality. The entire cohort received neurofeedback. I worked with the group of 30 participants over five sessions aiming to end up with 125 sessions of usable data. In the first and final sessions, I administered no neurofeedback, instead, the first session was used to establish a baseline for each participant. Analysis of the final session sought to establish whether performance continued after the intervention.

During the study, participants responded to one prompt from each of five categories: ability/disability modification, transportation, environmental systems, social systems, and alternate-use tasks. These categories were used because they cover a wide range of human needs and challenges, emphasizing inclusivity, sustainability, social impact, and creative problem-solving. This approach encouraged a more holistic view of design, pushing engineers for solutions that not only address specific issues within each category but also consider the interconnectedness of various aspects of human life and the environment. Several of the categories and prompts have been used prior. For instance, the Alternative Uses Test (AUT) a well-known measure of evaluating creativity through divergent thinking abilities [90]. The test prompts participants to list nontraditional uses for a common object. Evaluation of the AUT found that participants that produced more responses produced more novel responses, and, using statistical rarity of responses as a measure of novelty, resulted in a higher average novelty score.

Different prompts were used each session because if the same prompts were used across the five sessions, performance might be modified by increased time spent and familiarity with the question. For this reason, the prompts differed between sessions but the categories were the same. To maintain the relative difficulty between sessions, the prompts were written by a generative AI chatbot and reviewed for content and face validity by multiple engineers with industry and educational experience. While the order of the categories was consistent for all participants, the order of the questions within the categories varied. When participants were finished with a task, they were asked to raise their hand. A complete list of the prompts is located in the appendix.

Category 1: Ability / Disability Modification

"Develop as many design ideas as you can for a kitchen measuring tool for the blind."

Category 2: Transportation / Mobility

"Develop as many design ideas as you can to improve home delivery services."

Category 3: Environmental Systems

"Develop as many design ideas as you can to reduce global food waste."

Category 4: Social Systems

"Develop as many design ideas as you can to make public spaces more comfortable in hot weather."

Category 5: Alternate Use Test

"List as many alternative uses for a pen as they can think of."

Experiment Layout

The experiment design was approved by Virginia Tech's Institutional Review Board (21-597). Once engineering graduate students enrolled and signed the release form, the experiment began by outfitting them with the fNIRS headset and calibrating the device in the NIRSIT GUI. Participants who brought a smartphone or who wore a smartwatch were asked to turn off their devices and lay them facedown on a nearby table. In all five sessions, participants sat down facing a monitor. In sessions one and five, the monitor was turned off. In sessions two through four, the monitor administered the feedback in the form of the NIRSIT GUI showing the heatmap animation over the 3D brain. A microphone recorded audio during the sessions. The audio recordings were used to quantify the number of ideas generated.

Participants in the study were asked to dictate their responses throughout the experiment process. Each of the five tasks was preceded by six multiplication problems, each on a five-second timer, serving as a 30-second rest period before each task. Many neuroscience studies use a rest period for a baseline reading of neurocognitive function. Participants are generally asked to rest or fixate on a crosshair on a screen to establish a baseline of neural activity. However, participants do not always rest during this period and may engage in unintentional cognitive activities such as mind wandering, daydreaming, or reflection. These activities can result in fluctuations in neural activity and impact the reliability of the baseline measure [91]. As a result, some studies have begun to use more active baseline tasks, such as simple motor tasks or cognitive tasks with low cognitive demand, to control these fluctuations in neural activity [92- 94].

Data collection began with the first multiplication problem. All of the multiplication problems and the design prompts were read aloud to the participant by the data collector. Participants ideated verbally. At the end of a design task, participants indicated they were finished and they proceeded to the next set of multiplication problems. After the final task, the recording concluded. Each ideation process lasted on average 30 minutes.

All participants completed a survey to reflect on their experience and their perceived performance during the exercise. There were three versions of the survey. The first was a simple demographic survey following the completion of session one, without NF. Sessions two through four, with NF, all had the same survey asking about performance factors. The third survey format was for session five, without NF, and asked questions about performance and retention.

Following their completion of all five sessions, all participants we asked to answer two questions via email:

1. In reflection, do you think the neurofeedback (heatmap of the brain on screen) influenced the effort you put into the task?
2. Did you find the feedback useful?

Data Collection

During the experiment, I recorded changes in oxy-Hb, deoxy-Hb, and total-Hb in the PFC using 48 channels in the fNIRS headband. As shown in Figure 1 below, the 48 channels are divided into eight sub-regions, the right and left dorsolateral PFCs, ventrolateral PFCs, frontopolar PFCs, and the orbitofrontal cortexes. The PFC is of interest for data analysis in cognitive studies about design [34], decision-making [95], and planning [49] because of their associated cognitive function.

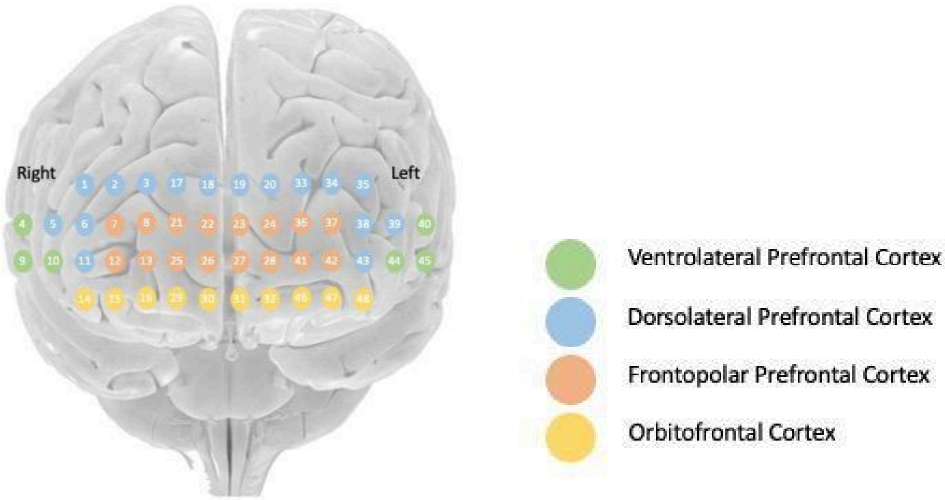

Figure 1. OBELAB fNIRS Channels and Corresponding Subcortexes

Data Analysis

I explain how I will assess the design solutions and neuro-cognitive activation in the following sub-sections. What I came to realize in analyzing the data was that individual sessions could be cut out from the data set if they did not measure up to the necessary quality for assessment and comparison without throwing out the entire participant's set. If a participant had sessions one through four intact, assessment of those sessions averaged into the session 1, 2, 3, 4 recordings could take place; or, comparison between sessions one and four could take place. Even if some sessions were corrupted, the rest of the data from that participant was still viable.

Due to the variance in the data set across different participants, it is valuable to look at the trends with outliers removed. The large variances rendered a lot of the test results insignificant. What emerged from the data when this was accounted for was of particular significance in the performance data. The mean number of participants whose oxy-hb means qualify as outliers is 8.8 per session, a significant portion of the population. For that reason, the total data has not been scrapped but instead contributes to the context of how these questions were answered fully and honestly.

Measure Change of Oxy-Hemoglobin In The Prefrontal Cortex

To measure the change in oxy-Hb data in the prefrontal cortex, the first step was to process the data with a bandpass filter. A MATLAB script was used for preprocessing. A third-order Butterworth filter of 0.01Hz – 0.2Hz was applied to remove high-frequency instrumental noise and low-frequency physiological noise. It then applied an independent component analysis (ICA), using a coefficient of spatial uniformity (CSU) of 0.5 to remove motion artifacts. These parameters in data processing are based on prior research [96, 97]. Only oxy-Hb was analyzed and reported since oxy-Hb has a relatively higher amplitude and is more sensitive to cognitive activities [67].

To describe the change of oxy-Hb in the prefrontal cortex among engineering students, I compared the mean oxy-Hb and average change of oxy-Hb, the area under the curve (AUC) of the change in oxy-Hb. The average oxy-Hb for the design task is limited in its ability to describe change over time. So, I also used the positive change in area under the oxy-Hb curve (AUC) for each participant. AUC is a proxy for cognitive activation because it represents the total increase of oxy-Hb for a given period [98-100].

Average Change of Oxy-Hemoglobin In The Prefrontal Cortex

I began by separating the preprocessed Hbo and Hbr data and averaging the oxy-Hb levels across every channel for each participant to get session means. These were then stored in Excel and averaged across all the participants to compare oxy-Hb between sessions across the entire participant population. I then plotted with error bars capturing the standard error.

This superficial read of the data across the entire PFC allowed me to answer the first and second research questions. Exploring neurocognitive changes began with regional analysis, looking into eight sub-regions of the PFC and identifying which experienced the most significant change in oxy-Hb levels. I used multiple statistical techniques to describe the effect of neuro-cognitive feedback on oxy-Hb. Each of these methods is described in more detail below.

To answer research question one about the effect of neurocognitive feedback on brain activation, I used paired t-tests and ANOVA tests to compare the change of oxy-Hb between groups. ANOVA tests were used to compare all five sessions, the first and fifth, the first and second, the neurofeedback sessions two through four, and the first and fourth. Paired t-tests were also used for those comparisons listed relating only two sessions. The first and fifth Sessions were compared to examine the overall effectiveness or impact of the NF treatment across the entire study period. It helped assess if there were significant changes from the beginning to the end of the study, providing insights into the long-term effects or trends. The comparison between the first and second session focused on the evaluation of the immediate or short-term effects of NF. It helped to understand whether there were immediate changes following the initial session. Neurofeedback sessions two through four comparisons explored the consistency or stability of the NF effects during this intermediate phase of the study. Comparing the first and fourth sessions addresses the intermediate-term effects of the NF intervention. It provided insights into whether there were sustained effects or if there were fluctuations in the measured variables over this period.

Regional Analysis

I repeated the averaging process above with each channel group that corresponds with the right dorsolateral prefrontal cortex. Looking into this subregion of interest in the PFC allows us to contribute to the canon of research about the significance of different regions in this type of task. The ANOVA tests were repeated for the DLPFC and held to a Bonferroni-corrected significance threshold of alpha is 0.025 to account for the two tests performed.

For the right dorsolateral prefrontal cortex, ANOVA and paired t-tests were performed additionally for sessions one and four and one and five. Comparison between sessions one and four were of interest to see the change in performance after the total amount of administered feedback, in a feedback session. Likewise, with session five, we are able to evaluate if three feedback sessions is enough to make a lasting difference in performance while designing. The comparison between these two sets of results could be of value for future studies planning to employ a greater number of feedback sessions.

Temporal Analysis

I withdrew the time each participant spent on each question for every session. These values were averaged first across the session, the five questions producing a session mean for that participant. This was run for each participant and then averaged to showcase the population trend of time spent ideating as the sessions progressed through the experiment.

I then performed an ANOVA to understand whether there was a statistically significant difference between the time spent in ideation for each session. I repeated the ANOVA process as well as performed paired t-tests to compare sessions one and five and one and four.

Comparing Fluency During Ideation

To keep the computation and qualification of new ideas consistent, I used OpenAI's Playground workspace. I used GPT-4 and entered the following user input: "You will be given text from someone engaged in a think-aloud design activity. The text is placed in the <text> tag below. The participant will be asked to produce as many design ideas as possible. Return only the integer number of ideas produced, do not return the categories or the ideas."

Under the text tag, I pasted the transcript that was output from OpenAI's Whisper software which I ran using Python in Terminal. With this method, I reviewed each transcription and flagged the file if a block of text repeating one word of the same phrase took place. If the rest of the file was intact, I removed the repeating words and ran the system. I stored all the numeric outputs in Excel. I had 103 complete audio files.

Some audio files were unclear and discarded. When entering the value in Excel, I divided the total number of ideas produced by the number of prompts they responded to in full. Eleven files were too corrupted to use and had to be thrown out. Twelve participants had sessions one and five intact to compare pre- and post-intervention performance.

From these results, I compared the change in the number of ideas produced per session across the population as well as individual changes in each participant. Given the unequal number of intact recordings for each session, I compared the difference in the number of ideas generated in sessions two through five with session one using two-sample t-tests instead of paired. Examining the population variance of each, the t-tests were performed under the assuming unequal variances condition.

Survey

Surveys followed each session of data collection. The first survey asked basic demographic questions: handedness, first language, age, and gender identity. In the surveys following the three NF sessions, I aimed to get a better sense of participants' perceived performance. Some questions were asked directly, such as: "Did you make use of the feedback,' whereas others included the word "perception" in the question prompt. In total, 86% of participants claimed they "made use of the neurofeedback provided." The same percentage of participants answered yes when asked if they focus on "making the brain red" during the sessions. Only 59%, however, answered yes to the perception question "did you succeed in increasing the amount of red on the brain heat map." For context, 58%, answered yes to the question asking if they thought they spent more time with the questions overall when compared to the previous sessions. The corresponding quantitative data shows an overall increase.

It is important to note that varying the prompts between sessions does not mean that participants might very well see performance increases simply from practicing the task style in the experiment setting. However, this thesis reports on the results as they are measured and which is why the quantitative temporal and biological data are presented alongside the qualitative results from the post-surveys. To the question “Did you perform better in this session than in your previous session,” 64.4% responded yes. This question was followed up with “If you answered "yes" to the previous question, do you think you performed better because of the practice of the task/familiarity with the task,” which saw 79.5% of responds agreed. The final question of the survey asked about other factors that might have affected their performance in that day’s recording.

RESULTS

In pursuit of a sufficient and complete answer to research question one, I compared the mean oxy-Hb levels from the experiment time, meaning the portion of the recording when the participant was actively working with a prompt. As visible in figure 2, there is not a significant increase or decrease in oxy-Hb across the entire PFC throughout the five sessions.

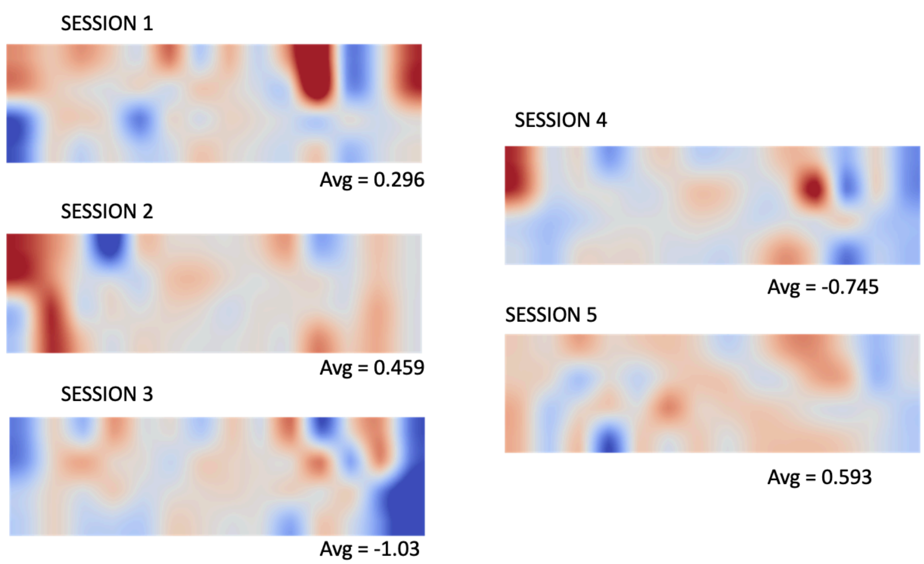

Figure 2. Heat map representations of mean oxy-Hb levels across

The results are shown below in Figure 3 with the standard deviations, which are outside the extrema of this graph, displayed in Table 2. Results across the entire PFC indicate no trend.

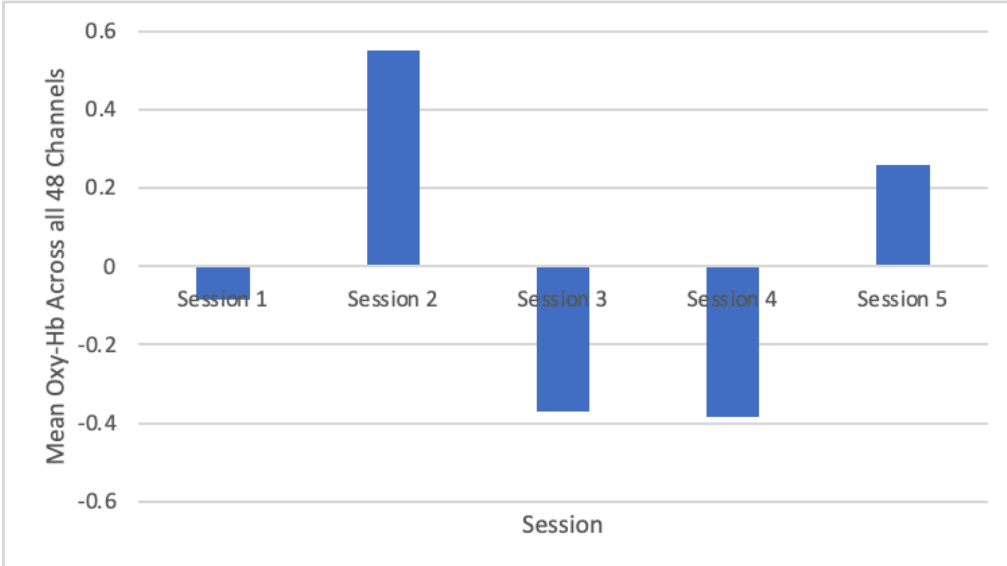

Figure 3. Mean oxy-hemoglobin (oxy-Hb) across all five sessions

Table 2. Mean Oxy-Hb values

Session	Mean	SD
1	-0.085	1.57
2	0.550	0.849
3	-0.370	1.02
4	-0.390	1.27
5	0.260	1.37

The large variances rendered a lot of the test results insignificant. What emerged from the data when this was accounted for was of particular significance in the performance data.

ANOVA tests across all five sessions did not indicate significantly different behavior between the five sessions with a p of 0.0807. I repeated the same treatment with sessions four, the end of the intervention, and five, the retention session as well as performing paired t-tests for each. The ANOVA rejected the hypothesis but the paired t-tests produced a p's of 0.0676 comparing sessions the intake session with the first intervention, 0.2551 and 0.2290 when comparing sessions one and four and one and five respectively.

I also calculated the mean area under the curve (AUC) values for all of the participants for each section, similarly with rest time when the participants responded to times tables removed. The results, shown below in Figure 4, are similarly inconclusive; however, with the outliers removed, the trend more closely resembles the oxy-Hb means in Figure 3 above. ANOVA tests, with outliers removed, resulted in p-values of 0.1042 for all five sessions, 0.0523 for sessions one and four, and 0.4721 for sessions one and five. I performed two-sample t-tests assuming unequal variance comparing the two session couples mentioned above, both of which resulted in p-values above alpha (0.05). The AUC trend is displayed below in Figure 4.

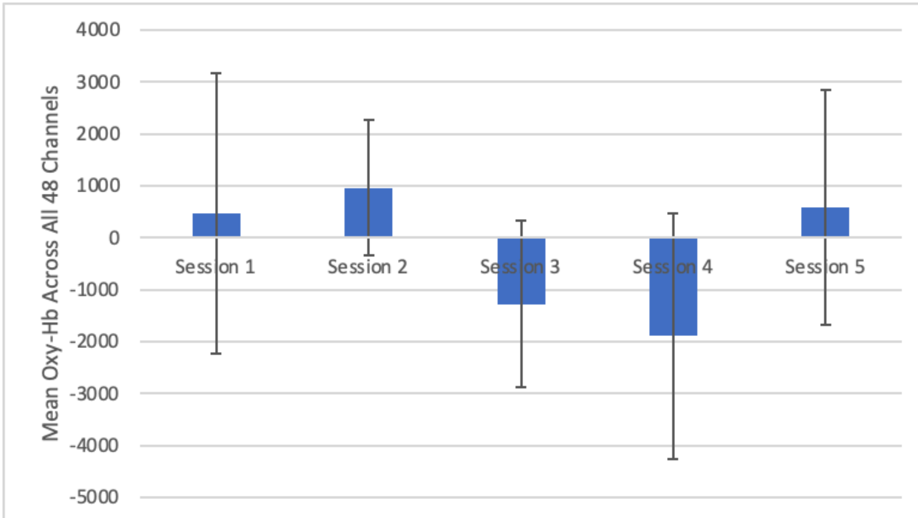

Figure 4. Means of Oxy-Hb AUC values averaged across participant population

Looking at the oxy-Hb mean and AUC results in Figures 3 and 4, a trend is apparent visually where a drop in blood oxygenation occurs in sessions 3 and 4. From the statistical tests conducted, however; there was no significant difference in mean or AUC oxy-hb levels across the PFC between the five sessions or comparing the introductory session with the fourth and fifth sessions. A glance at figure 2 of the heatmaps echoes this ambiguity in the assessment of the entire PFC. The hypothesis that findings would show an increase in oxy-Hb levels in the whole PFC from the first session and the following sessions and that the increase will be sustained in the fifth session is not met.

R-DLPFC

The same process was repeated for the subregion of interest, the right DLPFC. In the right DLPFC, ANOVA tests comparing all five sessions came back with significant p-values of 0.0293 for the total oxy-Hb means and 0.0050 for the mean AUCs. Paired t-tests comparing sessions one and two, the intake with the first neurofeedback, resulted in p-values of 0.0561 for the mean oxy-Hb and 0.0097 for the mean AUC values. In comparing sessions one and four, the final feedback session, the p-values for the mean and mean AUC values were 0.0082 and 0.0009 respectively, indicating a significant difference in the region between sessions one and four with a moderate-large effect size ($d\_mean = -0.740$, $d\_AUC = -1.04$), indicative of substantial impact. P-values in the retention session, number 5 where no intervention was administered, were not significantly different from session 1. This trend in the mean values which is echoed in the AUC values is visualized below in Figures 5 and 6.

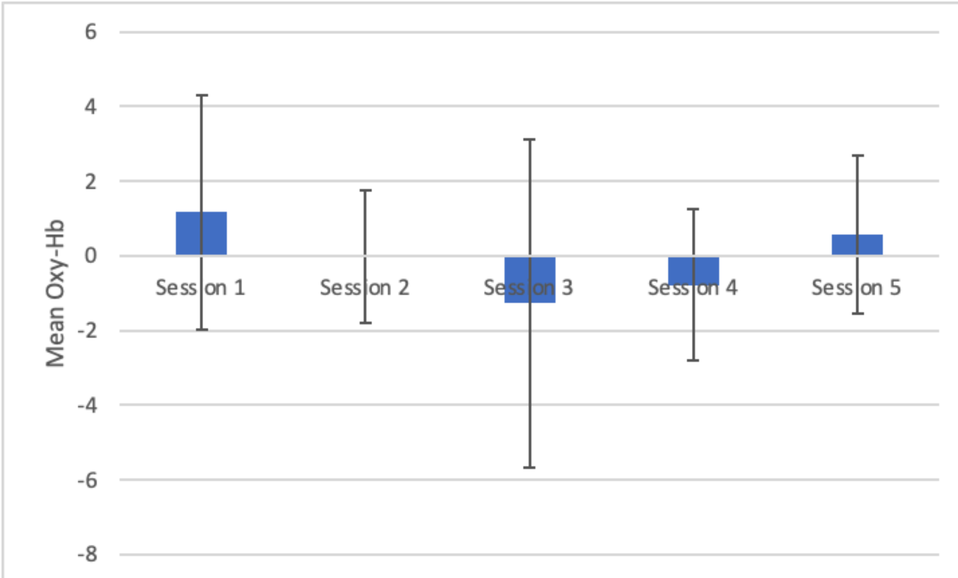

Figure 5. Mean oxy-hemoglobin (oxy-hb) in the R-DLPFC across all sessions

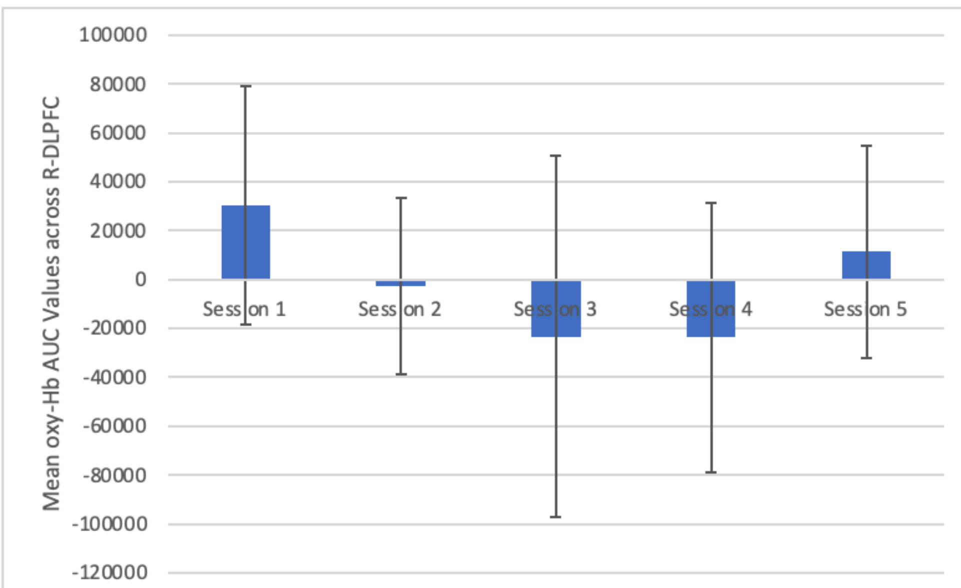

Figure 6. Mean oxy-Hb area under the curve (AUC) values across participant population for all sessions

Additionally, the tests did not however reveal a significant measured difference in oxy-Hb between sessions one and five. Session five values were higher than session four in all metrics, mean and AUC for the entire PFC and the right DLPFC, but were not consistently higher than the session one values across all metrics nor were they ever significantly greater.

Examining the right DLPFC, we see a significant negative change in blood flow from the region. This is apparent in the AUC value when comparing the introductory session with the first intervention session which suggests a drop even if the mean itself was not significantly lower but the oxygenated blood levels were lower across the board. Comparing the first session with the final feedback session, session four, the p-values are well below 0.05 and below the Bonferroni

(3 comparisons) corrected alpha of 0.0167. The ANOVA comparison of the five sessions also indicates significant differences in the right DLPFC between the sessions.

Table 3. Comparison of T-test P-values of PFC and Right DLPFC

	Sessions 1 and 2		Sessions 1 and 4		Sessions 1 and 5		ANOVA	
	PFC	R-DLPFC	PFC	R-DLPFC	PFC	R-DLPFC	PFC	R-DLPFC
Mean	0.0676	0.0561	0.2551	0.0082	0.2290	0.2142	0.0807	0.0293
Mean AUC	0.3456	0.0097	0.0523	0.0009	0.4721	0.0995	0.1042	0.0050

Performance

Research question two sought to understand how multiple neurofeedback sessions aided in performance gains, even in the absence of understanding how participants work with it. The avenues I report on are time spent ideating, sitting with a problem, and fluency, the ability to come up with a high number of ideas in response to a prompt.

Time Spent Ideating

An increase in time spent on a task, in cognitive capacity for patience, for bandwidth breeds more opportunities for novel idea generation. Over the five sessions, I observed an increase in time spent ideating. With and without outliers included, this trend was apparent.

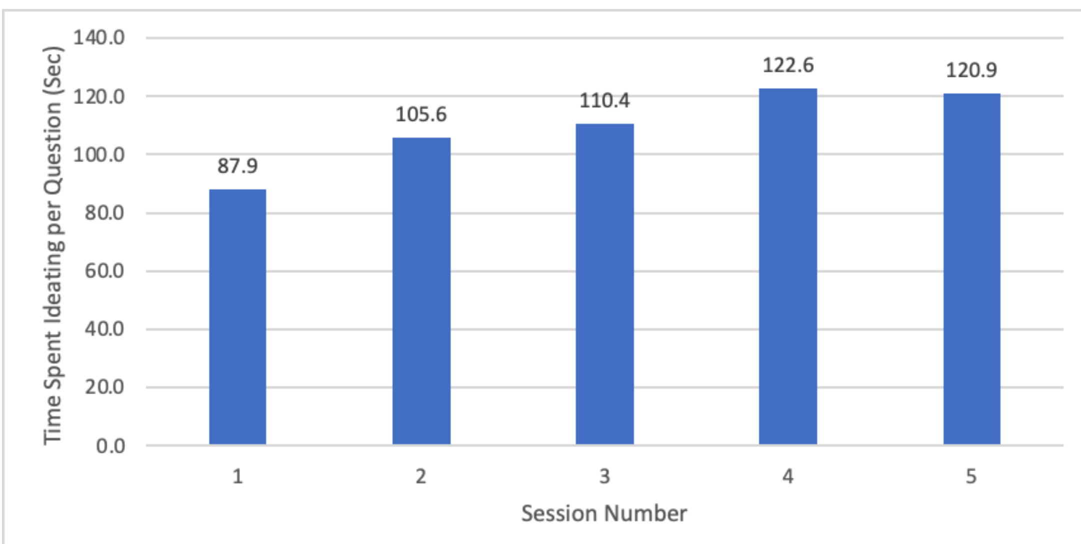

Figure 7. Average time spent with each question for the five sessions

The five-session ANOVA test output a p-value of 0.0095 and the t-tests relating sessions one and four and one and five returned p-values of 0.0014 and 0.0024 respectively, both with large effect sizes (d_1-4 = 0.902, d_1-5 = 0.900), suggesting substantial impact. All findings indicate a significant increase in time spent with the task in the final feedback session and the retention session.

Fluency

Another aspect of performance I explored to answer research question three was idea fluency. I compared the amount of ideas produced by each participant in each session and in response to each prompt. Much of the audio recording was corrupted and unable to be used. For twelve of the thirty participants, audio recordings for both the first and final sessions were intact and nine out of the twelve participants showed an increase in mean ideas produced per task across the sessions. As some recordings were only partially intact, it was prudent to maximize usable sections. For this reason, the metric reported is ideas per prompt to utilize recordings for which less than all five prompts have discernable audio.

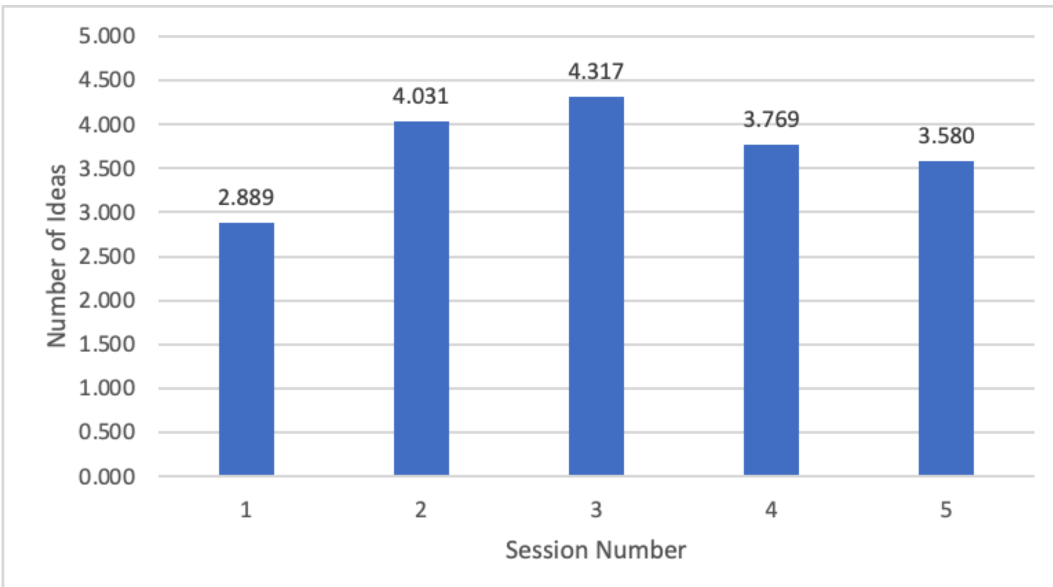

Figure 8. The mean number of ideas produced across the experiment

Outliers also dramatically skewed the results from this data set. The causes of this are entertained in the discussion section of this paper. Given the dramatic effect outliers had on the variance, they have also been removed from the analysis to achieve a clearer picture of the general behavior of the data set.

In an ANOVA test comparing the five sessions with what data was intact, there was a significant difference found between the five means ($p = 0.008$, $d = 1.08$). Directly comparing of sessions one and two, the p-value from the t-test significantly dropped below the alpha level of 0.05, registering at 0.0109. When evaluating the initial performance against the end-of-experiment performance, it is noteworthy that despite a decline from the peak observed in session three, the data still showed a significantly higher performance in the final feedback session ($p = 0.0090$, $d = 1.14$) and in the retention session ($p = 0.0222$, $d = 0.897$). All of the sessions that included or followed intervention led to significantly higher idea production per prompt. The p values and effect size measured suggest the intervention to have a marked impact on idea production.

Table 4. Two Sample T-test Assuming Unequal Variances Relating Sessions 2-5 with Session 1

Session	Mean	Variance	P
1	2.89	0.641	
2	4.03	1.82	0.0109
3	4.32	0.418	0.0002
4	3.77	0.669	0.00901
5	3.58	0.645	0.0222

Self-Reported Results

Fifteen participants responded to the follow-up questions emailed to them after they concluded their participation in the study. The questions were:

> **Q1.** Reflecting back, do you think the neurofeedback (heatmap of the brain on screen) influenced the effort you put into the task?
>
> **Q2.** Did you find the feedback useful?

Eight of the fifteen responded "yes" to both questions, that the feedback was influential and helpful to them. Three responded "yes" to the first question, explaining that seeing the red on the screen motivated them to put forth more effort but remarked in in their response that they could not confidently answer question two in the affirmative as they were unsure how the feedback worked. Only one participant responded "no" to the first question and then answered "yes" to the second. Their responses were as follows:

1. "I do not think the neurofeedback influenced how much effort was put into the task. Regardless of if the heat map was on the screen I tried my best to come up with the most and best answers possible and I can't do better than my best."
2. "That being said, I did find the feedback useful. It was interesting to see how thinking deeper could maybe light up the heatmap more, but the effort remained constant.

Table 5. Results of Post-Study Survey Questions (Note: A "1" indicates a positive answer to the question.)

Participant	Q1	Q2
1	1	1
2	1	0
3	0	1
4	1	1
5	1	1
6	1	1
7	0	0
8	1	1
9	1	0
10	1	0
11	1	1
12	1	1
13	1	1
14	0	0
15	0	0

DISCUSSION

The dorsolateral prefrontal cortex (DLPFC) plays a role in identifying important occurrences and either initiating or restraining motor reactions. It also contributes to shifting attention focus and actively concentrating on new points of interest. There is significant substantiation in the literature correlating activation in the left DLPFC with divergent thinking processes, idea generation, the AUT. A 2023 Guo et al. study, found, in stressful situations, anodal stimulation of the right DLPFC to alleviate creative roadblocks associated with stress [102]. Conversations around network control theory found divergent thinking was associated with "modal controllability" by the right DLPFC of the executive control network. The right DLPFC may play a role in steering the brain toward complex cognitive states that facilitate creative thinking [103]. While this might be an explanation for decrease in oxy-Hb correlated with improved performance, further research into the role of the right DLPFC is necessary.

Feedback's Effect on Performance

I hypothesized that engagement with multiple NF sessions would lead to performance improvements measured as an increase in fluency of design ideas and time spent on tasks. The hypothesis posits that the 'time spent on task' variable serves as a gauge for the potential to generate new ideas. This is measured in two ways: firstly, through the duration of ideation, which is the time spent thinking and creating ideas, and secondly, through fluency, which refers to the number of ideas produced in response to each prompt.

Across all metrics, this hypothesis was confirmed by the findings of the experiment. Comparing end-stage results, the final feedback session, and the retention session, with the intake session, the population saw significant improvement in both idea production and time spent on task. Of course, another explanation for an increase in time spent ideating is familiarity with the task. Having completed a session or more, participants might trust that the recording session will not go over time and feel more comfortable sitting with the questions longer. Another explanation, having practiced the process, is an increased sense of mastery of the task, and that feeling of competency encourages participants intrinsically to continue to sit with the prompts.

Reading through survey results, many participants noted inadequate sleep as a factor that might have impacted their performance during the task. Others indicated that they might have speed-walked or ran to make it to Patton in time for their appointment and speculated that increased blood flow might have impacted their performance. Both of these potential explanations have support from prior research. In a study titled *The effects of a single night of sleep deprivation on fluency and prefrontal cortex function during divergent thinking,* cognitive efficiency and smooth mental functioning were hindered after a period of sleep deprivation [105]. The findings indicate that an intervention causing temporary disruption to frontal lobe activity can negatively impact mental fluency [106]. In a 2022 study by Kimura et al., moderate-intensity exercise effectively increases PFC activity and PFC activity remained higher than the baseline level after cessation of the activity [107].

Participant Feedback

The population is also composed of a variety of experience levels. Although all individuals were engaged in graduate-level coursework in the Virginia Tech civil engineering department at the time of the study, ages ranged from 20 to 44. Differing educational backgrounds and work experiences could also have contributed to outliers if a minority of individuals had spent more time considering questions similar to prompts in the study. Different time constraints might have also played a role. Some individuals were in a rush at the time they arrived at their recording appointment and aimed to move through the questions as quickly as possible. In an ideal scenario, each participant would perform without the restriction of time pressure in their mind.

Answers to the two questions distributed in a follow-up email provided enthusiastic feedback about the tool although it would be hard not to imagine this population being swayed by the availability heuristic, particularly when considering the self-selection in this cohort of respondents who took the time to provide further information about their experience. Additionally, though the questions were designed to probe different aspects of the participants' perceptions, the first a reflection of self-perception of effort, the second a value judgement of the neurofeedback; they were perhaps too similar for the number of questions asked. The relevance of this minute detail is in the subset of respondents who responded "yes" to Q1 and "no" to Q2 where, in effect, had that individual believed the NF positively impacted the amount of effort they invested in the task, then the feedback would be, by the goals expressed in the explanation of the tasks, useful. Had I asked many questions, maybe five of each category, a discernible trend may have arisen. Providing simpler and more divergent questions in this setting might have been more appropriate. Essentially, it was asking the same question, twice.

CONCLUSION

This study presents a nuanced understanding of the functional dynamics within the prefrontal cortex, particularly focusing on oxy-Hb levels across five sessions of neurofeedback intervention. The hypothesis predicting a sustained increase in oxy-Hb levels in the PFC throughout the sessions was not substantiated. Instead, significant variations were observed, especially in the right DLPFC, highlighting a notable decrease in oxy-Hb levels during the experiment that did not persist post-feedback. This finding suggests a potential transient impact of neurofeedback on this region, although the exact causal factors remain unclear. At the advent of this experiment, one of the questions I sought to gain clarity around was how exactly engineers ought to engage with the feedback to leverage it to improve performance. Although anecdotal feedback from the study's survey provided some conjecture about the design of the experiment, the absence of a control group made a direct assessment of this process inaccessible. The presence of a control group could also clarify whether the performance improvements came from the intervention or from rehearsal. There are other independent variables that were not included in the data collection process. For example, I could have included neuro-cognitive feedback on more diverse groups, by gender, novice versus expert, or teams. This experiment will help lay the foundation for future studies in this area.

The right DLPFC, known for its role in attention modulation, decision-making, and creative thinking, exhibited a significant reduction in blood oxygenation levels. This change could hint at its involvement in complex cognitive functions, potentially aligning with theories suggesting its role in facilitating creative thought processes.

Overall, while this study offers valuable insights into the dynamic changes in the prefrontal cortex during neurofeedback sessions, it also underscores the need for further research. Different responses in the DLPFC versus the entire PFC to neurofeedback highlight the varied nature of brain activity and its modulation through such interventions. Future research should aim to delve deeper into these findings, exploring the long-term impacts of neurofeedback both in the weeks and months following intervention and the long-term continuation of intervention.

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APPENDIX

Participants received one of two sets of prompts, containing the same questions in two different orders. Across their entire participation in the experiment, all participants were asked the same questions. Questions labeled “a” were read in session 1, “b” in session 2, and so on. The version 1 order is shown below.

Version 1:

1. Ability Difference / Limitation
    a. Develop as many design ideas as you can for a kitchen measuring tool for the blind.
    b. Develop as many design ideas as you can for an alarm clock for the hearing impaired.
    c. Develop as many design ideas as you can to assist the elderly with raising and lowering windows.
    d. Develop as many design ideas as you can to assist people to get a book that is out of reach.
    e. Develop as many design ideas as you can to make drinking fountains accessible for all people.
2. Transportation / Mobility
    a. Develop as many design ideas as you can to improve home delivery services.
    b. Develop as many design ideas as you can to reduce traffic congestion in mega cities, citities with a population of over ten million people.
    c. Develop as many design ideas as you can to store and transport food so that it doesn't spoil as easily.
    d. Develop as many design ideas as you to minimize accidents from people walking and texting on a cell phone.
    e. Develop as many design ideas as you can to increase the use of public transit.
3. Environmental Systems
    a. Develop as many design ideas as you can to reduce global food waste.
    b. Develop as many design ideas as you can to reduce the amount of plastic pollution in the ocean.
    c. Develop as many design ideas as you can to reduce air pollution in cities.
    d. Develop as many design ideas as you can to reduce the spread of airborne viruses.
    e. Develop as many design ideas as you can to improve access to clean water in remote areas
4. Public spaces
    a. Develop as many design ideas as you can to make public spaces more comfortable in hot weather.
    b. Develop as many design ideas as you can to make public spaces more inviting and comfortable for people of all ages.
    c. Develop as many design ideas as you can to make public spaces more culturally inclusive.
    d. Develop as many design ideas as you can to reduce crime and vandalism in public spaces.
    e. Develop as many design ideas as you can to improve signage in public spaces.

5. Alternative Use Task (AUT): Please come up with as many different uses as you can for a ________.
    a. Pen
    b. Brick
    c. Paperclip
    d. Shoe
    e. Ping pong ball