BRAIN ACTIVITIES INFLUENCED BY SEMANTIC FEEDBACK ON DESIGN IDEAS: AN EXPLORATIVE EEG STUDY

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ABSTRACT
Semantic measures have been recognized for their effectiveness in predicting the success of ideas in design contexts. However, the specific impact of semantic feedback on the neurocognitive processes involved in design ideation has been relatively unexplored. To bridge this gap, our study utilized electroencephalography (EEG) to monitor brain activity as participants engaged in design ideation tasks. Each participant completed the ideation task twice: once before and once after receiving semantic feedback from an instructor. We conducted a detailed analysis of the recorded EEG data, computing the Power Spectral Density (PSD) across various frequency bands—including delta, theta, alpha, beta1, beta2, and gamma—to assess the intensity of brain activities. Our findings indicate a general increase in the power spectrum across these frequency bands following the reception of the semantic feedback. This enhancement in brain activity suggests that participants were likely more engaged and focused on the ideation process after receiving feedback, underlining the potential of semantic feedback to influence creative thinking and cognitive engagement in design tasks positively.

Keywords: idea generation, semantic feedback, EEG, frequency analysis

1 INTRODUCTION

Design is an essential component of various industries [1]. Design cognition, a critical mental process, is characterized by the capability to address complex issues and generate necessary solutions. It encompasses the cognitive functions of design activities, necessitating a comprehensive understanding of physical objects, behaviors, and governing rules, and this knowledge is integral to devising intentional plans that fulfill diverse requirements [2, 3].

Creativity plays a pivotal role in design activities, and it is commonly evaluated based on two primary dimensions: novelty and usefulness [4]. The production of ideas that are both creative and successful is fundamental to effective problem-solving [5]. Much research in this area has traditionally employed ad hoc methods to assess creativity [6], for example, the co-valuation model [7], and protocol analysis employed to understand the design process [8]. However, semantic analysis offers an alternative approach by examining words through the computation of semantic metrics such as Polysemy, Abstraction, Information Content (IC), and Semantic Similarity. This methodology is considered valuable for quantifying and comparing different aspects of the design process and its outcomes [5].

Researchers have explored whether semantic metrics can accurately predict the generation of ideas [9], and this approach has been extended to analyze the semantic content of conversations [10]. For instance, Georgiev and Georgiev [9] utilized 49 semantic measures in a real-world conversation to facilitate problem-solving. Their findings suggested that a semantic similarity divergence, increased information content, and reduced polysemy could predict successful creative idea generation [5, 9]. Despite these advancements, the neural underpinnings of using semantic methods to enhance idea generation remain largely unexplored. Understanding this neural basis could enable researchers to develop more effective semantic-based methodologies to probe this phenomenon's underlying mechanisms.

The electroencephalogram (EEG) is an investigative technique that monitors brain activities by recording the electrical potentials generated by electrodes placed on the scalp [12]. Notably, EEG devices are characterized by a high sampling rate, providing them with an exceptionally high temporal resolution. This feature makes EEG particularly useful for examining temporal processes and brain activities involved in creativity [11-13]. However, EEG techniques face limitations in detecting brain activities from deeper cerebral sources [10]. Consequently, researchers employ EEG to measure the neurocognition and neurophysiological activations specific to design processes [14-16]. Spectral analysis is a fundamental technique utilized in the quantification of EEG data. The power spectral density (PSD) is particularly critical in this context as it represents the frequency composition of the EEG signal, detailing signal power distribution across various frequencies [19]. This measure allows researchers to assess the intensity of brain activity within specific frequency bands, providing insights into the changes of bran activities during different cognitive states or tasks. Researchers within the design field have broadly explored and contributed to understanding the relationship between design creativity and brain activities [18-20].

However, many design studies have traditionally neglected the role of semantic feedback in the ideation process, particularly regarding whether semantic feedback facilitates design ideation and how it influences brain activity during ideation. This research introduces a novel experimental paradigm designed to bridge this gap through a structured three-session approach. We performed the frequency-based analysis to explore the brain activities in different frequency bands and answer the research question:

RQ : How does semantic feedback affect brain activity during design ideation?

2 METHOD

2.1 Participants

Nine healthy participants (four females and five males) were recruited from the University of Oulu. The participants were all right-handed, had normal or corrected-to-normal vision, and were free of neurological disorders or illnesses. Two participants were excluded from a subsequent analysis due to their insufficient sketching results. Seven participants (three females and four males) were incorporated into the formal analysis. The study has been approved by the Ethics Committee of Human Sciences of the University of Oulu. The experimental-related information was disclosed to each participant in advance, and they were required to sign a consent form.

2.2 Experimental Design

In order to investigate the influence of semantic feedback on design ideation, an EEG experiment was divided into three distinct sessions. Participants participated in a design task for a period of ten minutes during the initial session. Subsequently, they were permitted a brief period of relaxation, following which they were obligated to communicate their design concepts to an instructor concisely. The second session lasted approximately five to six minutes, during which the instructor provided customized semantic feedback based on the participants' design outcomes. Participants completed the identical ideation task for an additional ten minutes after receiving feedback. In this session, they were given the choice to either refine their initial design or conceptualize a completely new product, taking into account the feedback they had received. Figure 1 illustrates the experimental procedure.

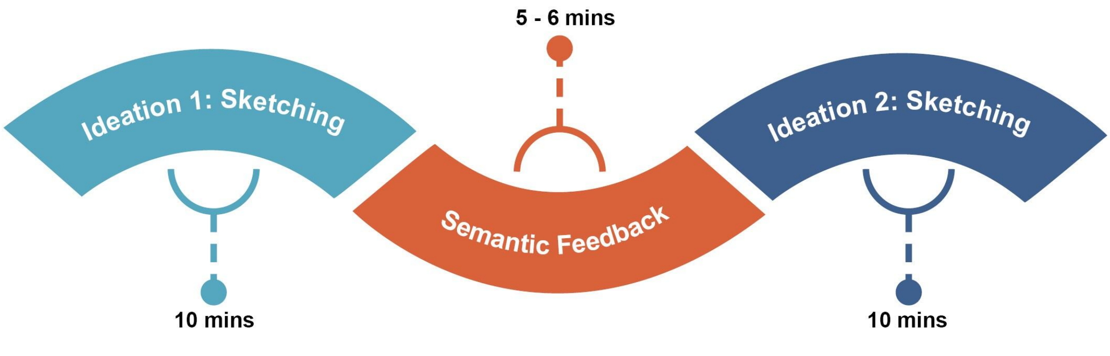

Figure 1. Experimental procedure

2.3 Design task

The design task is: "You are a designer. You are invited to design an amphibious bike. You can sketch and annotate as many ideas as you have. The vehicle can be any kind of bike, such as a bicycle or a motorbike. Amphibious vehicles are suited for both land and water. You can design several options for the product features and functions, such as the propulsion system and the number of allowed passengers."

2.4 EEG recordings

During the experimental period, participants were equipped with EEG devices to monitor their brain activity continuously. Brain Products, Germany (https://www.brainproducts.com/), supplied a 32-channel active electrode system with standard distribution to capture EEG signals (Figure 2). Utilizing sintered Ag/AgCl sensors that were integrally integrated into the cap, this system operated at a sampling rate of 1000 Hz. The impedance of all channels was maintained below 10 kΩ to guarantee signal clarity. The online reference and ground electrodes (GND) were strategically positioned at the FPz and FCz sites, respectively. In order to mitigate potential noise during the design ideation and feedback sessions, participants were advised to maintain a calm facial expression and minimize movement. The entire experiment was conducted in a chamber that was specifically designed to prevent external noise interferences, which was specialized for EEG.

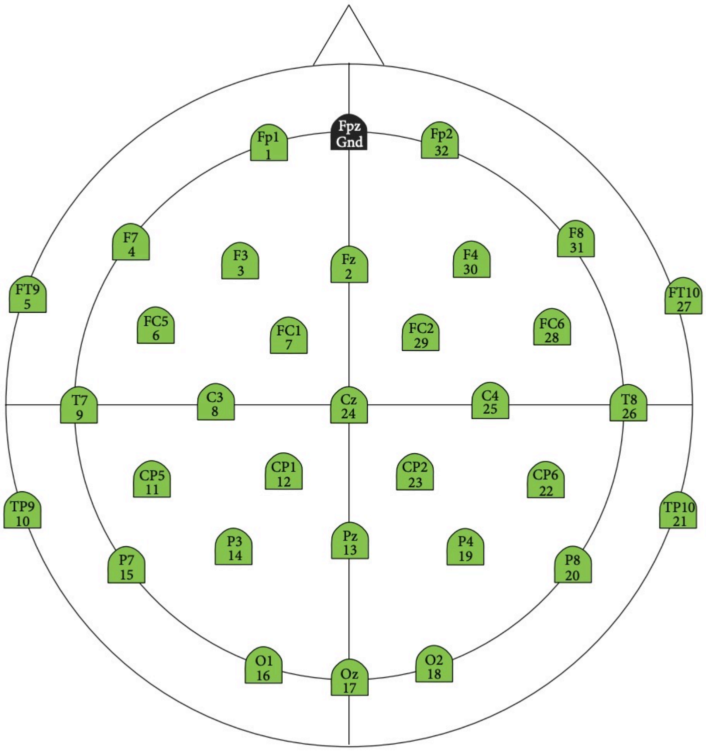

Figure 2. EEG channel distribution

2.5 EEG data analysis

2.5.1 EEG data preprocessing

All The Electroencephalogram (EEG) data collected during the study were processed and analyzed using MATLAB software (MATLAB 2022b, MathWorks, Inc.). The EEGLAB toolbox (EEGLAB v. 2023.0) [18], along with customized scripts, facilitated the preprocessing of the EEG data. During preprocessing, the continuous EEG recordings were filtered using a 1 to 40 Hz bandpass filter to enhance signal clarity by eliminating frequency components outside this range. Following filtering, the data were segmented into epochs of 2 seconds each to facilitate detailed analysis. Head motion artifacts were identified and manually removed to ensure the quality of the EEG data. Independent Component Analysis (ICA) was then applied to correct Electrooculogram (EOG) artifacts, which arise from eye movements and blinks, thereby preventing them from confounding the EEG signals. Additionally, an automatic detection method was employed to identify and remove EEG segments containing wavelet amplitudes greater than 100μV, indicative of aberrant electrical activity. Finally, the data were re-referenced to the average of all brain electrodes, excluding the FT9, FT10, TP9, and TP10 channels.

2.5.2 Power spectrum density analysis

The PSD (power spectrum density) was calculated for each data by periodogram MATLAB function with parameters with NFFT as 2048. The original unit of calculated PSD was in μV ^ / Hz, and then the index was multiplied by 10*log10 to transfer the unit to dB. Mean PSD was calculated for each interested frequency band by the definition of 1–4 Hz, 5–7 Hz, 8–13 Hz, 14–20 Hz, 21–30 Hz, and 31–40Hz as Delta, Theta, Alpha, Beta1, Beta2, Gamma band respectively [21, 22].

2.5.3 Statistics

The Paired-T test was implemented using MATLAB function *ttest* to compare the difference of PSD between Session 1 (Ideation 1) and Session 3 (Ideation 2) for 12 interested channels (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, O2) in each frequency band defined above (Delta, Theta, Alpha, Beta1, Beta2, Gamma). The False Discovery Rate (FDR) multiple comparison corrections were performed using the MATLAB function made with the method of 'BHFDR' [25].

3 RESULTS

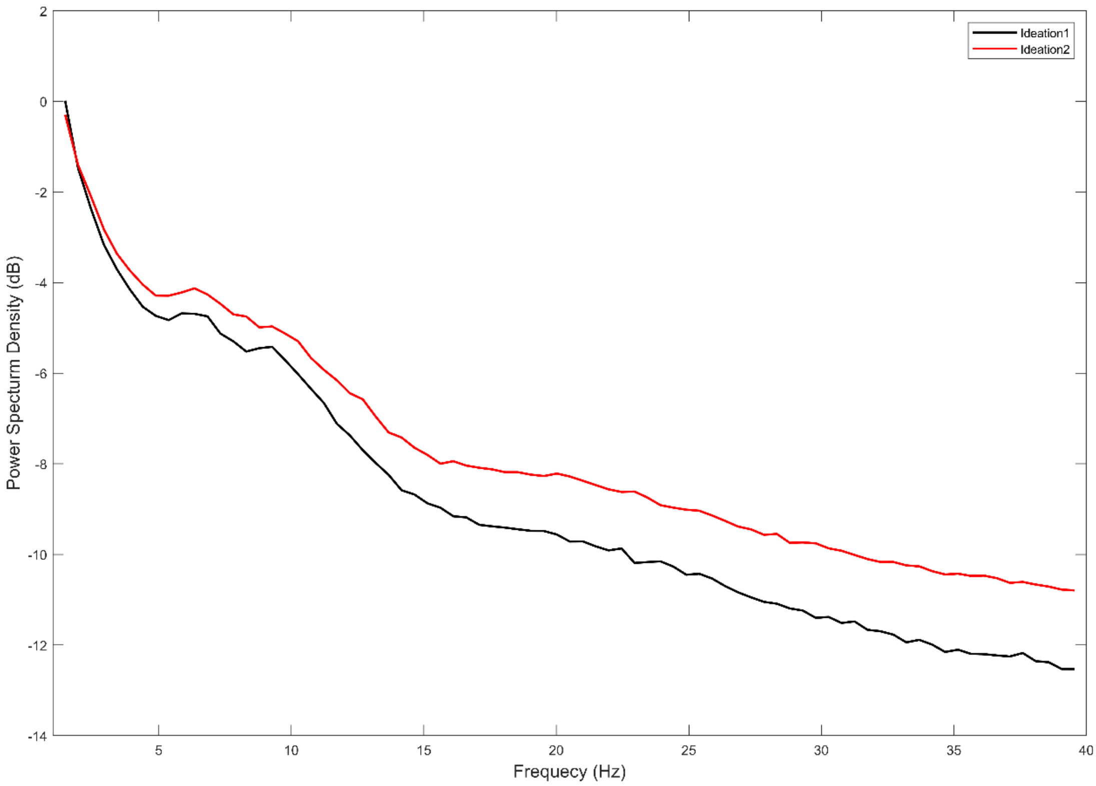

Figure 3. Group averaged PSD across 12 channels.

The group averaged PSD across all participants and interested channels (12 channels), calculated for all frequency points in the 1 to 40 sessions. As shown in Figure 3, the PSD was generally higher in Ideation 2 compared to Ideation 1.

Table 1 below shows the statistical results between two sessions: Ideation 1 vs. Ideation 2. Specifically, In the Delta frequency band, the PSD of C3, P3, and P4 in Ideation 2 was significantly higher than Ideation 1 (corrected $p < .05$).

In the Theta frequency band, the PSD of Fz, F3, C3, Pz, P3, P4, Cz. C4, F4 in Ideation 2 was significantly higher than Ideation 1 (corrected $p < .05$).

In the Alpha frequency band, the PSD of Fz, F3, C3, Pz, P3, O1, Oz, O2, P4, Cz, C4, and F4 in Ideation 2 was significantly higher than Ideation 1 (corrected $p < .05$).

In the Beta1, Beta2, and Gamma frequency bands, the PSD of all interested channels (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, O2) in Ideation 2 was significantly higher than Ideation 1 (corrected $p < .05$).

Table 1. Statistic results

** Indicates FDR corrected p <.05*

	Delta	Theta	Alpha	Beta1	Beta2	Gamma
Fz	0.1029	0.0163*	0.0065*	0.0007*	0.0004*	0.0004*
F3	0.0521	0.0082*	0.0065*	0.0009*	0.0005*	0.0007*
C3	0.0161*	0.0029*	0.0031*	0.0003*	0.0001*	0.0004*
Pz	0.0521	0.0029*	0.0031*	0.0007*	0.0003*	0.0004*
P3	0.0161*	0.0008*	0.0021*	0.0005*	0.0003*	0.0004*
O1	0.9214	0.0584	0.0072*	0.0004*	0.0003*	0.0007*
Oz	0.2058	0.0813	0.0814	0.0007*	0.0017*	0.0049*
O2	0.0911	0.2610	0.0548	0.0004*	0.0006*	0.0022*
P4	0.0911	0.0039*	0.0180*	0.0020*	0.0006*	0.0013*
Cz	0.0911	0.0039*	0.0031*	0.0008*	0.0005*	0.0004*
C4	0.0088*	0.0029*	0.0041*	0.0007*	0.0003*	0.0004*
F4	0.0706	0.0039*	0.0031*	0.0007*	0.0003*	0.0004*

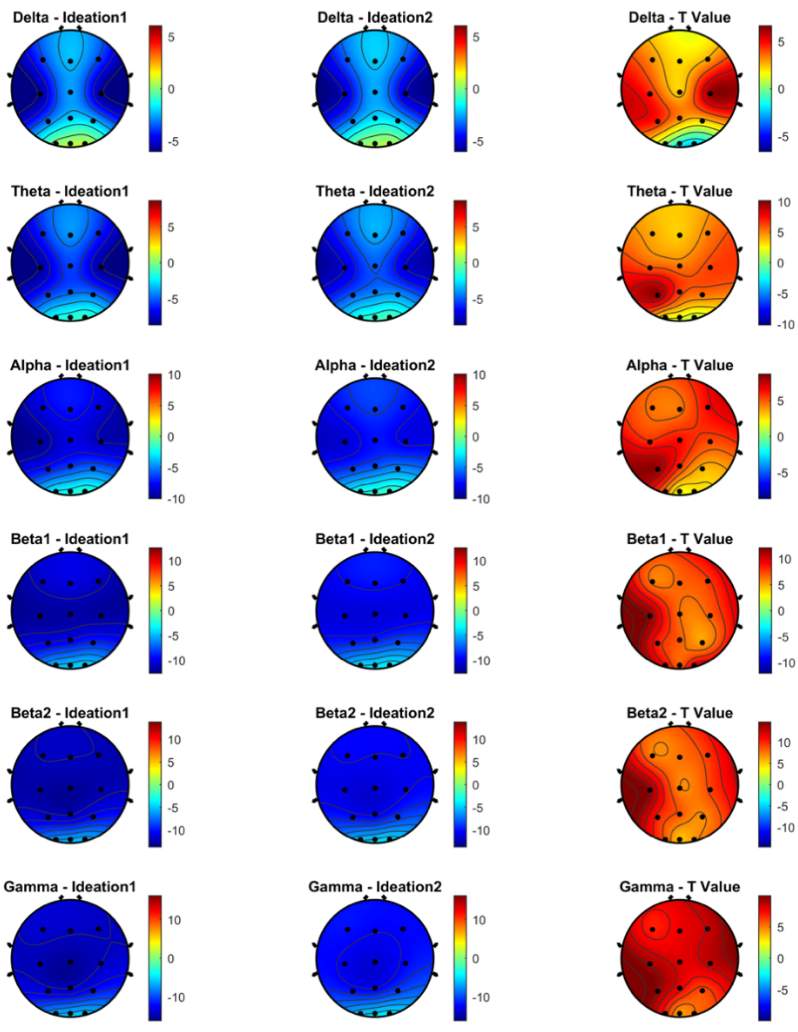

Figure 4. Topographic distribution of PSD

4 DISCUSSION

Power spectral density (PSD) is a neural index that reflects the intensity of brain activity across different frequency bands. Higher PSD values indicate stronger brain activity and different frequency bands are associated with distinct cognitive functions [26]. Figure 4 illustrates the PSD value for each frequency band of Ideation 1 and Ideation 2. The statistic T values reflect the difference between the two ideation sessions. In this study, we strategically selected 12 EEG channels to cover a comprehensive range of scalp locations, each corresponding to key brain regions involved in cognitive processing. The designations 'F', 'C', 'P', and 'O' represent the frontal, central, parietal, and occipital areas, respectively. Additionally, the numbers '3', 'z', and '4' indicate the positions on the brain's left, middle, and right sides. Based on the power spectral density (PSD) distribution observed on the topographic map, a more pronounced difference between Ideation 1 and Ideation 2 is evident from the alpha to gamma frequency bands, particularly in the central and parietal regions of the left hemisphere.

Additionally, our findings revealed that the power spectrum density (PSD) in the second ideation session (Ideation 2) was generally higher across all frequency bands when compared to the first session (Ideation 1). This increase in PSD indicates that the brain activities were more intense after participants received semantic feedback. Such an enhancement in brain activity suggests that the feedback made the participants more engaged and focused during the ideation process. This could be attributed to the cognitive integration and processing of the feedback, which may have stimulated more active and potentially creative thinking, thereby intensifying the overall brain activity observed in the second ideation session.

Furthermore, our research examined previous studies that predominantly focused on the theta and alpha frequency bands, where frontal alpha activity is associated with creative thinking, and theta activity increases during design tasks [22], [27-28].

Consistent with these findings, our study also observed significant activities in these bands within the non-occipital regions of the brain, thereby supporting the established correlation between these frequencies and creative cognition. Moreover, our investigation included the delta, beta, and gamma frequency bands, which are essential yet less frequently examined in the context of creativity and design. We found that delta activities were elevated, likely in response to the cognitive demands of the tasks [29]. Beta frequencies, known to be crucial in decision-making processes and design sketching, were prominently active [24], [30]. Additionally, gamma frequencies, which facilitate high-level cognitive functions such as information processing and memory, were also significantly engaged [31].

Finally, this research has implications for design education and extends beyond the comprehension of the cognitive processes that underlie creativity. We emphasize the potential benefits of integrating structured feedback into the design education process and the impact of semantic feedback on the enhancement of ideation-related brain activity.

5 LIMITATIONS AND CONCLUSION

This study uses EEG methodology to explore the impact of semantic feedback on brain activities during design ideation. We conducted frequency analysis and utilized Power Spectral Density (PSD) as a neural index to reflect the strength of brain activities from the delta to the gamma frequency bands. This investigation represents the initial exploration of the semantic influence on design ideation and marks our first attempt to analyze brain activities across all frequency bands comprehensively.

However, the study has several limitations that must be acknowledged. The experiment was conducted with only nine participants, and only seven were included in the formal data analysis, which may reduce the reliability and generalizability of the results. Additionally, the evaluation of design creativity itself was not incorporated, which is crucial to thoroughly examining the effects of semantic feedback on design outcomes. Furthermore, as this study was conducted in a laboratory setting, there were inherent limitations regarding the design problem and the time allotted for participants to complete the ideation process. We also face limitations in further analyzing the useful content provided by the semantic feedback, as it was customized based on the design outcomes.

Our findings indicate that brain activity increases after receiving semantic feedback in design ideation tasks, suggesting enhanced engagement and attention. These results offer new insights into the role of specific stimuli in design ideation and open possibilities for further studies on the impact of semantic feedback within design research. Future research should aim to recruit a larger sample size and include comprehensive evaluations of design creativity to more elaborately explore the effects of semantic feedback on both brain activities and creative outputs.

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