

Time-Frequency Analysis of Electroencephalogram Signals in a Perceptual Decision-Making Task of Random Dot Kinematograms

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Abstract

Purpose: Perceptual decision-making is the act of choosing one option from a set of alternatives based on available sensory information. Regarding the serious role of this act in human personal and social lives, the neurophysiological analysis of the brain during this type of decisions is of great interest. In this research, the underlying neural mechanism of these decisions is investigated using a perceptual decision-making Electroencephalogram (EEG) dataset with a perceptual discrimination task.

Materials and Methods: An online available dataset containing the pre-processed EEG signals of 24 healthy participants during the perceptual decision-making task of Random Dot Kinematograms was used. After a secondary pre-processing stage, clean EEG signal was divided into 1.3-second segments and averaged for Event-Related Potential (ERP) and Event-Related Spectral Perturbation (ERSP) calculations. The task engagement index was also calculated and averaged among all participants.

Results: According to the results, the amplitude of the N200 component in O1 and O2 channels was larger for correct choices than incorrect ones. Furthermore, in the O2 channel, it was observed that the average alpha power near 200 milli-seconds after stimulus onset was slightly higher in high and low confidence choices than medium confidence choices. The beta band power in the PO2 channel was also higher for correct choices rather than incorrect ones in this interval. Moreover, the results represented that the task engagement index was higher in medium confidence choices, especially in occipital and parieto-occipital channels.

Conclusion: The larger N200 amplitude and the higher beta power for correct choices, and the lower alpha power for medium confidence choices may be due to more attention of the individuals to the stimuli. This phenomenon can be observed in the task engagement indices as well. This could be because the user expended more effort in medium confidence to bring one of the choices to the decision threshold.

Keywords: Perceptual Decision Making; Electroencephalogram Signal Processing; Event-Related Potentials; Event-Related Spectral Perturbation.

1. Introduction

There are many situations in which one must decide to choose between a number of possible choices using existent sensory information from the noisy environment. Deciding whether crossing the street on a foggy morning, in poor visibility, is safe [1], or to stop or accelerate through an intersection by observing a traffic light [2] are examples of perceptual decisions. Perceptual decision-making is the process of deciding the identity of a stimulus, typically between a fixed number of possible alternatives [3]. This type of decision remarkably influences adaptive behavior [1] and is called “Perceptual Decision-making”, which is the basis of this research.

Choice confidence, or an individual's subjective assessment of decision correctness, is a crucial aspect in adaptive behavior; nevertheless, the brain functions of choice confidence during decision making remain unknown [1]. The amount of information gathered from the noisy environment and the individual's attention [2] are the main factors that affect the choice confidence [1] and the outcome of a perceptual decision.

Several studies have sought to unveil the role of attention and confidence of individuals during perceptual decision-making tasks. Theoretical and experimental evidence implies that neural computations resemble a type of probabilistic reasoning with the certainty of choice [4]. Non-human primate studies [5, 6] have demonstrated that, in addition to decision-making, the brain makes an appraisal of the quality of evidence during the decision-making process. In [7], it was shown that spatial and feature-based attention enhances humans' certainty in perceptual decisions making (visual motion discrimination task) more than accuracy. These findings revealed segregation between decision accuracy and confidence.

As a measure of subjective perception, confidence is believed to be closely related to stimulus awareness. The observer can have more confidence in his or her appraisal of a stimulus when they are aware of it [8]. The relationship between personal confidence indicators and performance has attracted few studies, especially when it comes to how they are modulated by attention. This is noteworthy because the speed of perceptual processes, as measured by reaction time, is regulated by both confidence and attention [9]. According to [10], there seems to be no noticeable difference in confidence between

attended and less or non-attended stimuli. This finding might be regarded as a lack of confidence in attended stimuli or an excess of confidence in unattended ones. Nunez et al. aimed to elucidate the effect of attention on visual decision-making. In this study, measures of attention obtained from Electroencephalogram (EEG) recordings were shown to explain per-trial evidence accumulation rates and perceptual preprocessing times during a bar field orientation task. The EEG measures were features of the Evoked Potential (EP) to the onset of a masking noise and the onset of a task-relevant signal. P200 and N200 components were observed to the onsets of visual noise, and visual signal, respectively, as single-trial evoked EEG responses, which explain single-trial evidence accumulation and preprocessing times [2].

In this study, the Event-Related Potential (ERP) and Event-Related Spectral Perturbation (ERSP) were evaluated while performing a perceptual discrimination task with correct and incorrect choices, as well as low, medium, and high levels of confidence in the decision made. In addition, the user mental engagement index was calculated and assessed as a quantitative scale at various levels of confidence.

2. Materials and Methods

2.1. Perceptual Decision-Making Dataset

Pre-processed EEG and behavioral data from [11] were used in this study. Twenty-four participants (aged between 20 and 32 years old) performed a speeded perceptual discrimination task while their EEG signal was getting recorded. As depicted in Figure 1, participants were asked to judge the motion direction of random dot kinematograms (left vs. right) and report their confidence on a 9-point scale. The main experiment consisted of 2 blocks, each containing 160 trials.

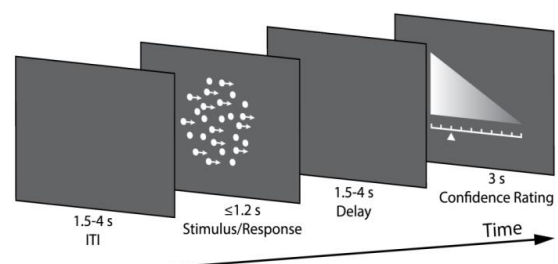


Figure 1. Schematic representation of the random dot kinematogram task from [1]

As stated in [1, 11], the EEG signals were recorded using the Brain Vision Recorder software at a sampling rate of 5000 Hz with 64 Ag/AgCl scalp electrodes positioned according to the 10-20 standard electrode placement system. The EEG data were then down-sampled to 1000 Hz.

2.2. Secondary Preprocessing Stage

The available data is pre-processed based on the provided description. The entire pre-processing procedure is described in [11]. However, due to the presence of some high-frequency components in the signal power spectrum, a secondary signal preprocessing was performed in this research. To this end, a 5th order elliptic low-pass filter ($f_c = 40\text{Hz}$) was used to remove some high-frequency components after inspecting the frequency spectrum of the signals. A sample of EEG signal butterfly plot and Power Spectral Density is depicted in Figure 2 and Figure 3, respectively. The data were then segmented into 1.3-second intervals (-300, 1000ms) time-locked to stimulus onset, and the confidence ratings reported by the participants (available in the behavioral data) were divided into 3 groups: low (1-3), medium (4-6), and high (7-9) confidence responses [1]. Ultimately, the data were prepared for ERP and ERSF calculations based on the accuracy and the confidence of responses.

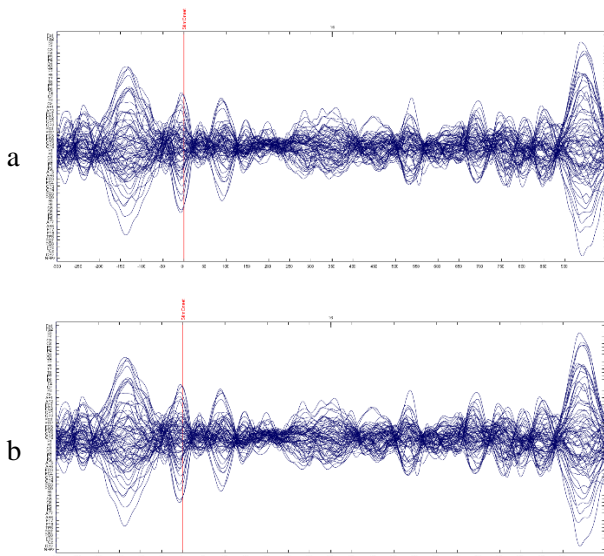


Figure 2. A sample of EEG signal butterfly plot (a) before and (b) after secondary pre-processing stage (subject number one)

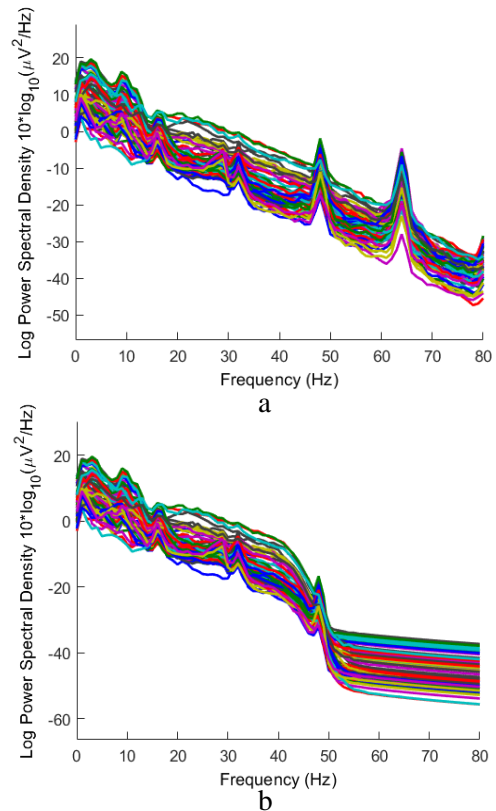


Figure 3. A sample of EEG Power Spectral Density (a) before and (b) after secondary pre-processing stage (subject number one)

2.3. ERP and ERSF Calculation

Because of advancements in cognitive neuroscience over the last decade, there has been a surge in research focusing on the neural bases of perception. The investigation of ERPs and ERSFs are common approaches for studying brain function. To calculate ERP, all time-locked epochs to the stimuli onsets must be averaged individually for each stimulus type [12]. The ERSF provides elements of event-related brain dynamics that are not shown by the ERP average of the same response epochs. To calculate ERSF, the average dynamic alterations in the amplitude of the EEG frequency spectrum are quantified in time and in relation to the task event [13]. In this research, ERP and ERSF figures were utilized to further investigate the brain's functioning during perceptual decision making in two different scenarios:

- 1) The difference between the two groups of correct and incorrect decisions.
- 2) The difference between the three groups of low, medium, and high confidences.

2.4. Task Engagement Index

The term "engagement" refers to effortful attentiveness and striving toward task goals. The Task Engagement Index (TEI) measures how cognitively engaged a person is in a task [14], which is computed based on Equation 1 [15].

$$TEI = \frac{\text{beta power}}{\text{alpha power} + \text{theta power}} \quad (1)$$

In this study, the TEI was calculated in each trial and examined in different levels of confidence to assess the level of individuals' mental engagement as a measure of user awareness and attention.

3. Results

In this section, the results of ERP, ERSP, and TEI observations are presented. Based on [16], six channels, O1, PO1, PO7, O2, PO2, and PO8 were chosen and studied as representations of the left and right hemispheres, respectively.

3.1. Grand-Average ERPs

According to the results, P200, N200, and P300 components can be seen in all ERP plots. It can also be found that N200 components in correct responses have a larger amplitude than incorrect responses. Figure 4 depicts the Grand-Average ERP plot for correct vs. incorrect choices and also for low, medium, and high confidences in O1 and O2 channels across all participants. The N200 component is evident in about 200 milliseconds after stimulus onset.

3.2. Grand-Average ERSPs

Figure 5 also depicts the ERSP images for both correct and incorrect choices in the PO2 channel. It can

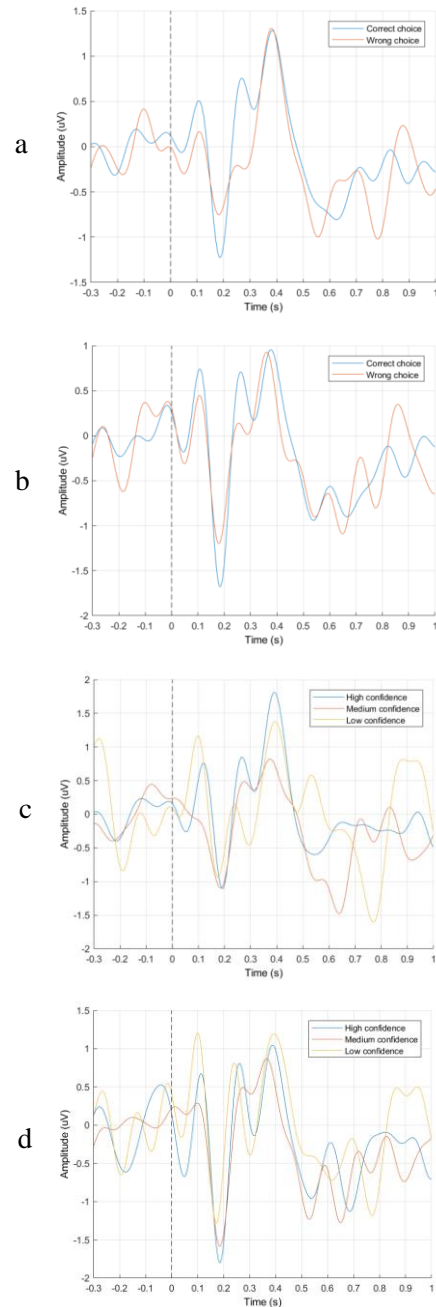


Figure 4. Grand average ERPs for correct and incorrect choices in (a) O1 and (b) O2 channels and Grand average ERPs for low, medium, and high confidences in (c) O1 and (d) O2 channels

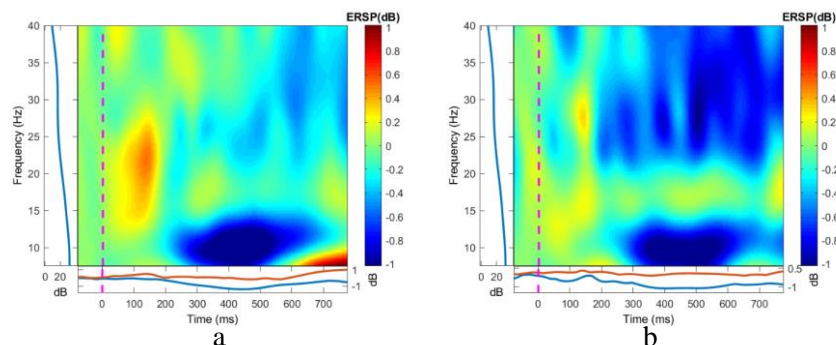


Figure 5. Grand average ERSPs in PO2 channel for (a) correct and (b) incorrect choices. Beta power is higher in the correct ones

be observed that the beta band power is higher in about 200 milliseconds for correct choices rather than incorrect ones. Furthermore, Figure 6 shows the ERSP images for low, medium, and high confidence choices in the O2 channel.

It can be seen that the average alpha power near 200 milli-seconds after stimulus onset is slightly higher in high and low confidence choices than medium confidence choices.

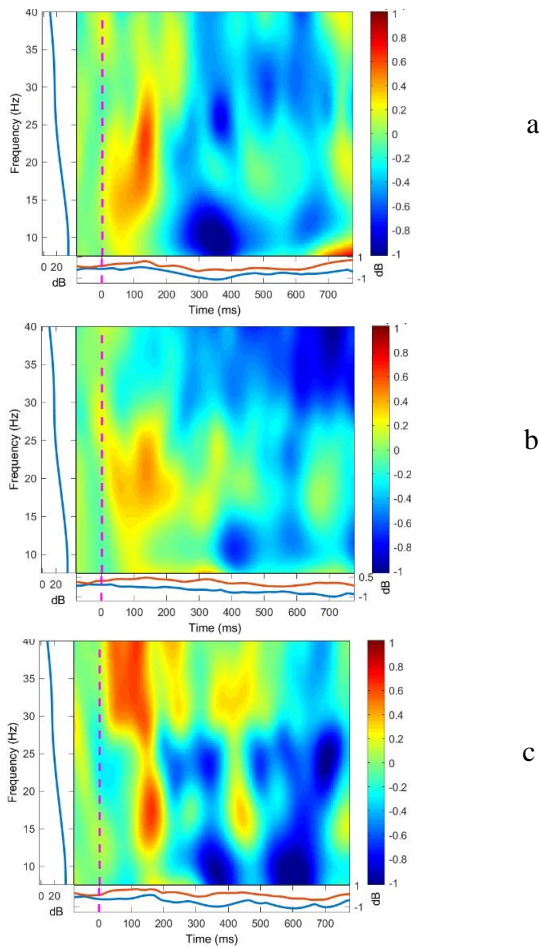


Figure 6. Grand average ERSPs in O1 channel for (a) low, (b) medium, and (c) high confidence choices. Alpha power is slightly higher in low and high confidence choices

3.3. Task Engagement Indices

In this stage, TEI was computed for each confidence group and averaged among all participants, and is depicted in Figure 7 for the 6 channels mentioned in Results section. It can be observed that except for the O1 channel, the TEI in medium confidence choices is higher than other ones.

4. Conclusion

The present study investigates the ERP and ERSP components of correct and incorrect choices, as well as considering the differences in confidence levels, in a random dot kinematogram task. The findings demonstrated that correct choices had a greater N200 amplitude (in line with [2]) and beta power than incorrect ones, which might be related to the fact that the user's attention is more involved when the decision-making process leads to the correct response. Furthermore, the lower alpha power in medium confidence choices may be related to increased attention to these stimuli. Increased power in the EEG alpha frequency range (8-13Hz) has long been recognized to be inversely correlated with the user's attention to the ongoing task [17-19]. This phenomenon is also apparent in task engagement indices. There was most likely a compromise between the evidence accumulation of choices (right or left in the random dot kinematogram task) in medium confidence choices, which increased participants' mental effort. Furthermore, there appears to be no substantial difference in TEI between low and high confidence choices. This finding could be seen as either a lack of engagement with high confidence stimuli or an excess of engagement with low confidence stimuli. According to [10], there was no noticeable difference in confidence between attended and less or non-attended stimuli. If we consider the relationship between the user's mental engagement and his or her attention to stimulation as a direct relationship, the current study's findings are consistent with [10].

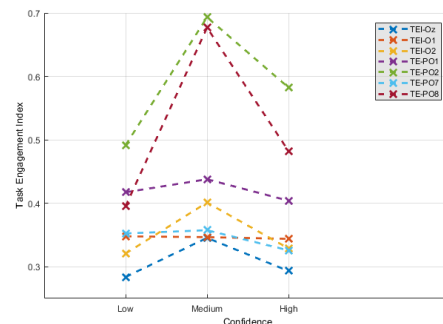


Figure 7. Task engagement index in different confidence groups for Oz, O1, O2, PO1, PO2, PO7, and PO8 channels

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