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# Optimal auditory neurostimulation to alleviate visual attention deficits in Attention-Deficit/Hyperactivity Disorder (ADHD)

Gabriel Alves Castro, Axel Hutt, Anne Bonnefond

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Optimal auditory neurostimulation to alleviate visual  
attention deficits in Attention-Deficit/Hyperactivity  
Disorder (ADHD)

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# Contents

<b>1</b>	<b>Glossary</b>	<b>5</b>
<b>2</b>	<b>Introduction</b>	<b>1</b>
<b>3</b>	<b>State of the art</b>	<b>1</b>
3.1	Auditory system . . . . .	1
3.1.1	Loudness . . . . .	2
3.2	Visual system . . . . .	2
3.3	Attention . . . . .	3
3.3.1	Brain mechanisms related to attention . . . . .	3
3.3.2	Attention-Deficit/Hyperactivity Disorder . . . . .	4
3.3.3	Reaction time and protocol . . . . .	5
3.3.4	Sustained Attention experiment . . . . .	6
3.4	Beats effects . . . . .	6
3.5	Electroencephalography . . . . .	7
3.5.1	EEG for ADHD and control subjects . . . . .	8
3.5.2	EEG for the CTET task . . . . .	8
3.5.3	EEG for binaural and Monaural beats . . . . .	10
3.6	Contributions of this work with relation to the literature . . . . .	10
<b>4</b>	<b>Methodology</b>	<b>11</b>
4.1	Auditory Brain Stimulation . . . . .	11
4.1.1	Generation of Binaural Beats . . . . .	11
4.1.2	Addition of background noise . . . . .	11
4.2	First experimental protocol: simple visual attention task . . . . .	12
4.3	Second experimental protocol: continuous temporal expectancy task (CTET) . . . . .	14
4.4	Electroencephalography analysis . . . . .	16
4.4.1	data . . . . .	17
4.4.2	Pre-processing and analysis . . . . .	17
4.4.3	Pre-processing to network and context analysis . . . . .	18
4.5	Behavioral data analysis methodology . . . . .	19
<b>5</b>	<b>Results</b>	<b>21</b>
5.1	Colors experiment result . . . . .	21
5.2	Hypothesis and questions Bank . . . . .	21
5.3	Behavior analysis . . . . .	22
5.4	Evoked Response Potentials (ERPs) analysis . . . . .	29
5.5	Computational Model . . . . .	30
5.6	Innovative context and connectivity analysis . . . . .	33
<b>6</b>	<b>Discussion</b>	<b>38</b>
6.1	Interpretation of the results . . . . .	38
6.1.1	Beats effects on attention . . . . .	38
6.1.2	ERP results and relation with behavioral data . . . . .	39
6.1.3	Understanding the effects of the beats on the Brain and discussing the new analysis . . . . .	40
6.2	Theoretical discussion and hypothesis with descriptive model . . . . .	42
6.2.1	Theoretical discussion and summary . . . . .	42
6.2.2	Descriptive model . . . . .	43
<b>7</b>	<b>Future work</b>	<b>46</b>
<b>8</b>	<b>Conclusion</b>	<b>46</b>

<b>Appendix A Behavioral results for all remaining subjects</b>	<b>50</b>
<b>Appendix B Theoretical models of the Brain</b>	<b>53</b>
<b>Appendix C Questions and hypothesis bank</b>	<b>54</b>
C.1 Questions . . . . .	54
C.2 Hypotheses . . . . .	56
C.3 Possible future work for testing the hypothesis . . . . .	58
<b>Appendix D Explanations about mixed selectivity</b>	<b>59</b>
<b>Appendix E Better explanation about context selection</b>	<b>60</b>
<b>Appendix F Computational Model demonstration</b>	<b>62</b>
F.1 Introduction . . . . .	62
F.2 Clustering and computing by contexts . . . . .	63
F.3 The role of the Brain computations and feelings . . . . .	66
F.3.1 An example of Hebbian Law complementarity . . . . .	66
F.4 An example of global context computation using this model . . . . .	67
F.5 An example of local computation using this model . . . . .	70
F.6 A hypothesis about the Binaural/Monaural beats effects and Possible analysis with EEG . .	71

## Abstract

Binaural Beats (BB) and Monaural Beats (MB) are auditory tones played to the human brain on both ears. They are supposed to cause various effects on the brain, like improve visual attention. There is a very scarce literature on their effect and no consensus on the effects. The missing consensus results from contradictory experimental results due to missing experimental standardization and little understanding of the underlying neural mechanism.

In the present work, was proposed an experimental standardization of psycho-physical experiments under BB using a 64 channel EEG device, performed a series of experiments with human subjects under these conditions to identify their effect on visual sustained attention and attempted to provide some explanation on the observed effects. It is, as far as we know, the first experiment estimating the impact of BB on attention by Event-Related Potentials. The first work to present a new Brain computational modeling theory for the effects of BB and MB. And the first work to propose a context-dependent analysis to verify the effects of MB and BB, and show evidences about the theory presented.

High variable profiles of effects were found among subjects. BB was found to have a negative effect in attention, while MB and Noise have a variate positive effect. The better beat to improve attention is not clearly defined. The regions and structure of populations of neurons during the tasks were found, and paths to improve attention in future works were identified. Despite the not clear results, potential was found related to the auditory brain stimulation using these sounds, and a future experiment with neurofeedback was proposed.

**Keywords:** Binaural Beats, Monaural Beats, Sustained Attention, Response Time, Auditory Localization System, Visual System, Neuromodulation, electroencephalography (EEG).

# 1 Glossary

Table 1: **Glossary and observations.**

<b>Terminology</b>	<b>Meaning</b>
<b>Target</b>	Is the image with the longest duration that the participant should identify.
<b>Sequence</b>	Is a sequence of 225 trials, with each target appearing between 5 and 12 trial.
<b>Evaluation</b>	Is the learning phase of the sound. Consists of an experiment with two sequences;
<b>Analysis</b>	Is the experiment realization, when the participant is supposed to be in the steady-state with relation to the sound. Consists of an experiment with three sequences.
<b>Considered dots</b>	To be considered a correct response, and have a response time, the identification of the target can occur after 0.8 seconds and until 2 seconds after his zero time. It means, after 2 seconds that it appeared.
<b>Missed Stimulus</b>	When a target is not identified by the participant in the two seconds window of identification, it is considered an error of the type missed stimulus.
<b>Wrong-click</b>	When the user chose a trial that is not a target, it is considered an error of the type wrong-click.
<b>Response time (RT)</b>	The response time is calculated with the formula: If $\text{click\_time} > 0.8$ and $\text{click\_time} < 2.0$ $Rt = \text{click\_time} - 0.8$ Where $\text{click\_time}$ is the moment where the participant clicked the key with relation to the zero time of the target. 0.8 is the normal duration of a trial. 1.2 is the duration of a target. 0.3 is the duration of the time window where the participant can identify a target.
<b>Zero time of a target (t)</b>	When with relation to a target, the moment when the target appears is the t zero.
<b>Higher intensity</b>	The higher intensity consists on the last experiment phase, where the participant listen to a Beat with a higher loudness, and plays an experiment with two sequences.
<b>Detected target</b>	Is a Target with a correct response.
<b>Missed target</b>	Is a Target without a response.
<b>back-ground activity</b>	Is all activity in the Brain that is not direct related to a specific population of neurons. By means of direct synapses connections, directed particles exchanges.
<b>Context</b>	Is the Brain response in an instant t, to the set of stimulus the organism had on this instant. Whether the stimulus is visual, and/or auditory and/or tactile.
<b>EEG</b>	electroencephalography.
<b>BB</b>	Binaural Beats.
<b>MB</b>	Monaural Beats.
<b>Beats</b>	The term beats is used to refer to the set of sounds tested in this experiment: Noise, Monaural Beats and Binaural Beats.

## 2 Introduction

BB are signals carefully chosen to send to each ear a different sound, and it has been claimed from the community that they can modulate moods and attention. The auditory localization system does the difference between the signals listened by each ear, to identify where is the source of a determined sound [Cha+15]. This same effect could be used by BB to neuromodulate the Brain with a variety of possible mechanisms. One of these neuromodulations, could lead to improvements on sustained attention performance, and research of this possibility could bring new treatments and tools to improve sustained attention disorders [ACP21].

In this work, we are interested in the study of BB and MB effects on attention. The first objective of this work is to create a protocol of experimental tests to attest if the effects are real or not, identifying the necessary constraints to a successful test. One secondary objective is to collect first results and test the created protocol to verify if it works and understand how to interpret the results of BB. Also, the secondary objective is the theoretical understanding and creation of hypotheses about how the BB and MB could improve attention, and how BB and MB affects neural mechanisms.

A protocol was defined, with a good number of trials and a baseline using MB and Noise. The possible mechanisms behind the effects of BB were mapped, and a descriptive model was created. The BB could have consequences in the mechanisms of inhibition [LG14], excitation [Arn+02], synchronization [SGB01], reward [And19] of the Brain. All these effects are highly related to attention, and they have to be studied in future works.

This report is divided in the following sections: In the section 3 the auditory beats are explained, and the possible effects are exposed. The visual system, auditory system, attention and theoretical models of the brain are also explored, and related to the BB and MB effects. In the section 4 we explain how the BB were built, how the protocol was built and tested, and how it was applied. In the Results section 5 the results about the protocol are presented. In the section Discussion 6 the results are analyzed, a descriptive model and interpretation of the mechanisms behind BB are presented. In the section Future Work 7 the next steps of the research about BB and MB are discussed. In the section Conclusion 8 we summarize the most important conclusions about the results of this work. Finally, in the session Appendixes, additional visualizations and the hypothesis bank built until now during this research are added to bring a deeper understanding. A demonstration to the theoretical model is also sketchy.

## 3 State of the art

The literature on BB is not very developed, and there is a lack of standardization to measure the effects or not of the BB into the brain. This poor literature is even worse to possible benefits that BB could give to attention improvement. Because of that, the principal papers were searched and studied, but also, we extended the literature review to try to understand the possible effects and possibilities of BB, related to the known behavior of the brain.

### 3.1 Auditory system

The auditory system is composed by several parts, and is a complex system. The two principal functions of the auditory system are to receive and process the sound signals. The primary receptors of the auditory system are called hair cells, which are located in the cochlea of the inner ear. These hair cells transduce sound vibrations into electrical signals, which are then transmitted to the brain through the auditory nerve. The sound localization system of the brain works with the difference of the frequencies and amplitudes of the same sound coming from both ears. This difference can be interpreted as the distance of the signal font and the listener [ER+97].

There are several hypotheses about how these mechanisms work on the auditory system. [Liu+10] simulates and explains how the auditory system work, the author states that the signals received by one ear are excitatory signals and the signals received by the another ear are inhibitory signals. It means that both

the signals cancel one another, and the resting difference is used to find the localization of the source. The author also uses BB to simulate the system, what means that the BB could really excite the localization system of the Auditory System.

Another model also divides the Auditory System in specialized regions to define what is, and where is the source of a signal [KN05]. Also, the Auditory System works with central highly connected networks and peripheral less connected networks that interact with each other. The connections of these networks could lead to problems as the perception of sounds with the absence of a source to it as [MDV17] states. These effects could be related to the effect cited in session 3.4, where the BB could elicit the listening of a third sound, inside the brain.

### 3.1.1 Loudness

Loudness is defined in neuroscience as the brain response to an auditory stimulus. It is different from the Sound Pressure Level (SLP), a physical measure that can show the intensity of a sound in the ears. The loudness is therefore the physiological response of the brain to a SLP pressure over the ears.

The loudness dependence of the auditory evoked potential (LDAEP) can be used as a test to verify the effectivity of psychiatric treatments, by measuring drug effects into the loudness response of patients. The loudness response in the Auditory System is inversely related to the amount of serotonin in the brain and directly related to dopamine levels and N-methyl-D-aspartate (NMDA) receptors. The level of activity influences directly the release of neurotransmitters and increase the response P1/N1 (the negative/positive peaks of energy) changing the LDAEP. Also, there is a limit around 100 dB that could vary to each person, where the increasing of loudness can start to have a less strong response on the subject. [OCN08] Found correlations between the NMDA receptors and the loudness level of a sound, but do not found correlation to the 5-hydroxytryptamine (5-HT) serotonin receptors.

[Pil+20] studies the relations between the LDAEP and the serotonergic system. Particularly, the 5-HT<sub>1A</sub> (an inhibitory serotonin receptor) and 5-HTT (a protein to carry back the serotonin to the pre-synaptic vessels). The paper found that the serotonergic system is directly affected by the loudness of a sound, but the response is different between men and women.

[Zha+21] demonstrates the role of the cholinergic system, specifically the acetylcholine neurotransmitter. Proving its role in the sustained fire of a neuron. The neurons tend to have sustained fire when the stimulus is at the region of attraction of a neuron, meaning that it will respond more to this stimulus. The data collected demonstrate that suppression of the ACh is able to diminish the firing rate, and suppress the sustained fire. At the same time, the author identified that the loudness level also increase proportionally the firing rate of neurons.

These are important characteristics because it means that into the auditory localization system, the frequency but also the intensity could affect the neurons firing, and it could lead to different results into the brain. As the neurons work regionally (tonotopically) it means that if a region related to some kind of frequency is activated, it could be that this region will have a major activation with a major intensity and side effects.

## 3.2 Visual system

The visual primary information is tough to be integrated into the visual system as a convolutional neural network, where the more abstract concepts are constructed on the most deep layers of neurons. The process occurs with the integration of information of neurons from a previous layer into the next layer. For example, in the first layer the information represent points, in the second layer lines starts to be abstracted, in the third layer boundaries starts to be identified and so on. The process is not exactly as it, but this is a good illustration of how it works on the brain [Lin21]. The convolutional hierarchy of the Visual system found withstand into analysis of spike public data, and it was found that the behavior of decision and attention is also related to this hierarchy [Sie+21].



But the system is even more complex, the Visual System could also be drive by process of recurrence between the neurons, it means that the Visual system could be convolutional and at the same time a recurrent network. [Kie+19] Found evidences that some characteristics of the human Visual System can be performed only by a recurrent neural network.

The Visual System working is also affected by other systems on the brain, specifically the auditory system. It was found that attention to localization of sounds, can enhance the Visual System performance [Stö19]. This characteristic is very important because could explain the hypothesis on session 3.4 about the use of the auditory localization system to neuromodulate attention with BB. Therefore, the way that the visual system works and his connections to the auditory system are important to understand how the BB could neuromodulate the state of attention of the brain. The most abstract information from the Visual system, and the recurrence, could play an important role in the mechanisms of attention that could be neuromodulate by the BB. Finally, this information is crucial to analyze the experiment of the session 4.

### 3.3 Attention

Several mechanism and cognitive process are involved in attention. Any of them could be affected by the BB, therefore it is important to know these mechanisms and cognitive process. [And19] states that the mechanism of reward of the brain is thought to play an important role on attention. The dopamine can train the Visual System to pay attention to determined stimuli and ignore the others, searching for higher recompenses.

There are also kinds of attention, as the sustained attention and the alternating attention, in the experiment explained on the session 4 we are testing sustained attention. [Arn+02] had experimental results associating a major density of acetylcholine in the brain, mediated by the cholinergic system, with states of sustained attention. The author explain that the acetylcholine is responsible for the excitation of the relevant parts of the brain responsible for the task subject of the sustained attention.

The inhibition is also important to sustained attention, as the other stimulus have to be inhibited to the brain to pay attention to just one stimulus. The Gaba neurotransmitter plays an important role into the inhibition, impeding neurons to fire. It is also known that problems of attention could be also related to problems into inhibition on the brain [LG14].

The attention is also mediated by the synchronization of different areas, called the meet between top-down and bottom-up regions of the brain. [SGB01] explains that the synchronization of the brain plays an important role on sustained attention. The author also ensures that the desynchronization of this different areas also leads to the decreasing of sustained attention. It is knows that the states of brain oscillation are related to the cognitive functions of the brain, including sustained attention. [CYK15] studies and propose a model related to each one of the brain oscillations.

Otherwise, the gap junctions, the electrical connections between neurons in the brain are known to participate actively into the Brain synchronization, and therefore, in the mechanisms of attention. The electrical synapses are one of the most fast on the brain, and this is thought to be important to their role in the brain synchronization. Some diseases are caused by problems into the gap junctions, leading to a cascade desynchronization of the brain [BZ04]. Thus, the gap junctions also play an important role into sustained attention.

The BB could have an effect on any of these components that emerges on the cognitive function of attention. In the session 6.2 hypothesis and a discussion about these effects are made.

#### 3.3.1 Brain mechanisms related to attention

[Rig+13] argues with basis in another papers that the mixed selectivity (a neuron that responds to several tasks at the same time) facilitate the use of linear classifiers just inside the neurons. It indicates that how better is the network into use the mixed selectivity better is the Brain to solve a task well. It happens

because in the mixed selectivity is easy to separate the information with a linear classification. Moreover, the authors states a hypothesis where the mixed selectivity is also less stable, depending on the deactivation of several data coming from unrelated activities into the Brain. therefore, to use well the mixed selectivity, the Brain needs to train the deactivation of irrelevant stimulus, and improve the stability of mixed selectivity. It seems therefore that attention is highly related to mixed selectivity, as the attention will increase as better would be the mixed selectivity of a network.

[ON19] explains the cognitive process as being a process made of memories and reinforcement of decisions. The decisions are called rules, and they can be learned, reinforced or inhibited. The Brain have to select what information it should pay attention, and it make it by searching into the memory the known rules that could maximize the recompenses. The role of dopamine is therefore reinforce and maintain the sustained fire of the correct neurons. This is, to shape the working memory and also to activate the neurons responsible for the best rule and action into the motor system related to a determined context. These results are withstand by several studies that manipulates the levels of dopamine with relation to D1 and D2 receptors sensibility. This process culminates in the attention decisions the Brain should do at each context, thus making part of the cognitive process of attention.

[Gao+20] made a series of analyzes using data from several sources. The analyses had the objective to demonstrate that the timescale of the neurons responses is related to the hierarchy of the Brain, meaning that the timescale is higher from sensory regions and lower to superior areas. The authors state that this happens because the superior areas have to integrate more information, and because of that have to have a higher timescale. The author found correlation between the working memory efficiency and the delays in the firing rate timescales of networks in the pre-frontal cortex and motor system. It means that the timescale is also related to the performing of cognitive functions, as for example synchronization and attention. The author sustains that the timescale is important to hierarchical functions and complex cognitive process. The timescale increase as a consequence of sustained fire in the working memory delay, this is, when an organism is waiting to accomplish some task using the working memory to plan it. And is globally related to the attention cognitive process.

The relations to BB and theoretical analysis of these phenomena will be more developed in the sessions 3.4 and 6.2.

### **3.3.2 Attention-Deficit/Hyperactivity Disorder**

[Mir+20] characterizes the Attention-Deficit/Hyperactivity Disorder (ADHD) as individuals having difficulty of concentration, decreased attention and mood swings. It is claimed that the disorder is related to a delayed development of some Brain regions in some ADHD subjects. These subjects have also problems of inhibition, having difficult to inhibits some Brain phenomena, as the Default Mode Network(DMN). The DMN is a Brain network that is activated when the subject is not performing any activity, and deactivated when the subject is performing some kind of concentrated activity. For ADHD subjects, the DMN is not deactivated in a common way when the subject is performing activities.

The inhibition control is lower for ADHD subjects. The ADHD subjects have difficulty to inhibits interferences from the environment, being harder to them to concentrate in a task when in front of a distraction. They have also difficulty to inhibits some action, in a conflictual situation, as for example in a go no-go task. It is, when some stimulus is very similar to a reward stimulus, but is not the True stimulus, ADHD subjects have difficult to do not take an action.

[Mir+20] Also characterizes the ADHD as being generated due to an unbalancing of the dopamine and norepinephrine neurotransmitters. These are related to processes of attention and impulse control. Usual pharmacological interventions for ADHD subjects are related to substances able to increase or normalize the amount of these neurotransmitters in the Brain.

The objective of this research was to test if BB and MB could have an improvement effect on attention for ADHD subjects. Due to the explained effects in session 3.4 it is possible that ADHD subjects

could have an improvement on attention listening to BB or/and MB. We found differences related to the control condition (noise) and BB, MB responses. These results will be discussed in the session 5.

### 3.3.3 Reaction time and protocol

Reaction time is a measure about the amount of time that a subject takes to practice an action. The reaction time can be used as a measure to the level of attention because when an organism has a high level of attention to some task, it will present the fastest reaction time to this task. [Bal+14] made an experiment about choice reaction. The choice reaction means a case where the subject has to choose between different options, what is the right one, and how much time it takes to make this decision. The reaction time is related to the mental time processing, because the authors argues based on the literature that the time to nerve responses, sensors responses and machines responses are constant between tests. However, it's possible that the networks from peripheral system do not work with linear behavior, but, they can have a set of different reactions at each time given available connections, states, and contexts. As will be explained in session B. This contradiction could be a fail in the paper.

Furthermore, [Bal+14] experiment was performed just with women, and the conditions of the experiment were controlled in the sense of equidistance between buttons, strong of the colors, sounds, environment, drugs (coffee and any other), menstruation and so on. The experiment had 60 women subjects and the results were measured for 10 observations, taking out the 2 bigger and 2 minors values, the median and standard deviation, using ANOVA and Bonferroni comparisons were calculated. The results present the time reaction for red and green significantly smaller than the time reaction for yellow. The authors made a hypothesis about the reaction time of cones, where the yellow receptors have a longer reaction time than the others, and it could explain the fastest results to this color. Also is important to mention that the definition of strong of the colors on the experiment is very important, because the author explain that there are an important effect about the light amplitude on the cone's response.

[Ami+19] did an experiment with 100 girls, about time-reaction to stimuli with colors. The experiment was performed with a computer and a game, where the subject had to choose between the colors that appeared on the screen. Each color has a correspondent button, and the subject have to choose the right button, each time that a color appears. The buttons were four adjacent positions in the keyboard. The results demonstrate a confidence and correlation between all the colors, but not the yellow and blue. The confidence was calculated with a hypothesis test, with the objective to say that the response times of each color are different or have the biggest response time. It means that all the colors have different data distributions, but yellow and blue do not. The red has the biggest response time, while the blue has the slowest, and the yellow and green are in the middle.

Also, [Ami+19] results corroborate to the theory about most red receptors in retina (cones) in comparison to the other three receptors. However, did not corroborate to the influence of energy level of the waves in the cones, it is, the lowest the spectrum less is the energy. Because was expected that how more energy, more fast and strong will be the reaction, however the green waves have more energy, and they did not have the best reaction times. The author states that this result could be explained by the fact that the conjunction of these factors leads to an influence predominance of the red cone's majority. It means, the majority of red cones overfit the other factors in the final result. The biggest contributions of the work was to augment the number of subjects, and also, the number of colors tested, normally it was three colors. A possible fail of the study refers to the distance between the buttons, what was not considered. This can have some influence in the results, as the response time has the magnitude of milliseconds. Therefore, a difference between the distances of the buttons and the use of different fingers could influence the results.

[Che+17] did an experiment with 174 controls and 93 ADHD subjects. The response time variation (RTV) is higher for ADHD subjects than for control subjects. Meaning a decreasing in attention for ADHD subjects.

### 3.3.4 Sustained Attention experiment

To test with confidence the sustained attention, and the attention itself, we could use the response time but also a proper experiment. The capacity of sustained attention could be tested with a continuous temporal expectancy task (CTET) [OCO+09]. This task consists on present a random sequence of black and white chess shaped pictures for a period of time (0.8s). The task consists in identify the target image that maintains itself for a longer period of time (1.12s) than the normal ones. The subject has therefore a perception window of 0.321s. The experiment tests the sustained attention as it is made repetitively, forcing the subject to maintain the attention to the experiment as much as he can. furthermore, identify a perception window demand a lot of attention.

[OCO+09] and [Chi+21] used the CTET experiment and EEG to prove that it was possible to preview a lack of attention even before it happens using the EEG data. Also, [Chi+21] demonstrated that the process of dual-control is highly related to the lack of attention. The dual control consists in an active response, that is a planned response, and a reactive response, that is a response just in time to a stimulus. The dual-control is entirely related to attention and working memory, as the working memory is what maintain the planning and prevision of recompenses in the Brain, participating actively from both the process: The active response, when there are a match between the expected recompense and what happens, and the reactive response, when a possible recompense is identified without has being predicted.

The CTET experiment proved to be satisfying to the objectives of test BB effects. If BB have an effect in attention, it is possible that the prediction patterns to an error would change. Also, it is possible to study several kinds of attention, including the sustained attention, with this experiment.

## 3.4 Beats effects

[Cha+15] does a literature review with the objective to compare the different methods in Auditory Beat Stimulation (ABS). The MB are a modulation of two audible signals to generate a signal with the same frequency to both ears. Other way, in the BB, two signals are presented, one for each ear, with one being the carrier frequency and another a difference summed to the carrier frequency. The frequency will be perceived as the difference between the two signals, and like if it is inside the head. The paper presents the differences between the two signals, about their effects and how they can work or not. During the neuromodulation, there are different kinds of neurons being activated, and each one have different patterns in their synapses, what can indicate how the neuromodulation works and interacts with the brain. Also, the Brainstem neurons of the Superior Olivary Complex (SOC) are sensitive to phase shifts between both ears. The binaural-beat perception is caused by this neural mechanism, which enables sound localization. Therefore, the differences of binaural signals can be perceived in this area, and can provoke changes on the frequency of synapses in the brain. The change is modulated by the difference of frequency between the two signals.

[Cha+15] also states that the Auditory steady-state response (ASSR) is a state where the brain has a specific wave response about 40hz, and it indicates a state of attention. It is possible that the BB could induce this state in the brain. There were related positive effects in creativity, mood states, vigilance, memory, anxiety to the BB. But BB have inconclusive effects in attention, and some studies that do not demonstrate any effect on attention or mood. One of the causes was pointed as few time of exposition to the beats. Furthermore, there are not definitive explanations about how each result works in the brain.

[PDL20] found Binaural Beat influences in the cerebral patterns of synchronization, but could not bring results about cognitive and mood changes, what was inconclusive, claiming new researches. Binaural stimulation at the  $\theta$ - frequency band (4–7 Hz) has been associated with positive emotional experiences and introspection. Binaural  $\gamma$  stimulation (32–48 Hz) has been associated with binaural sound integration. The Phase Locking Value (PLV) measure equates 1 if the two signals are perfectly phase locked across the whole observed time window, and equates 0 if they are totally unsynchronized. The author used this to measure the synchronization of determined brain areas. What means that the BB could elicit a synchronization between different regions of the brain.

[ACP21] Reviews Isochronic and BB, after a selection of 600 papers, there were chosen 30 as the most important to the field. The Isochronic beats are beats produced by frequencies repetitions. About the results, simulations with 1, 3.5 and 5 minutes seems to elicit some change in the frequencies of the brain, but also have contradictory effects. there are contradictory results to BB, including because the tests made are not making use of EEG and a standardized protocol. There are good and bad results concerning attention, otherwise, the big majority states good results for anxiety. Also, changes in moods for BB are claimed. An interesting observation is that the sounds can be presented do not just one time, but the sound can be presented for several days and some studies bring good results about this approach. Finally, the author also states that the Isochronic beats could bring very good results to the neuromodulation of the brain.

[ACP21] An important mechanism that is studied is about brain entrainment. The brain is paired with external signals, and this induces the wave state in the brain, this is one of the explanations of the effects of the BB. The brain has mental states, for example, in a state of attention the brain will work in a frequency of 13-35hz, what is called beta  $\beta$  frequency. In a state of relaxation, the brain will work in a frequency minor than 7hz, the alpha frequency. Therefore, the entrainment of the brain with an external signal can be used to enforce a mental state on the brain. following this logic, the BB could enforce these states using the sound localization system of the brain, that have an entrainment with the difference between the signals coming from the two ears. As the ear cannot listen to frequencies behind 20 Hz, we could use a carrier frequency and a plus seven frequency, to enforce the alpha frequency on the brain. The systems will be better explained on the session 3.1.

### 3.5 Electroencephalography

The Electroencephalography(EEG) consists of a device with a certain number of electrodes distributed over a soft helmet that is put on the head of a subject. The Brain generates electromagnetic waves as a consequence of the activities of ion currents around a neuron when it fires. The electrodes are able to capture the activity of big ensembles of neurons, indicating that some region of the Brain is working.

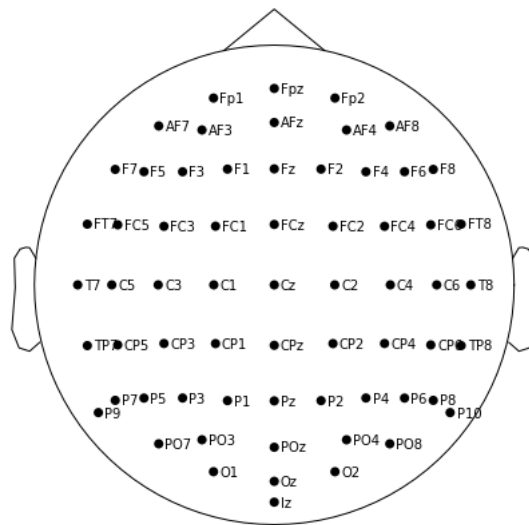


Figure 1: **64 Electrodes EEG device.** The Electrodes are distributed over the head of each subject with a pattern position. The pattern position ensures that the electrodes will capture the potentials of the correct Brain regions.

The signals captured by an electrode are not exclusively originate in just one Brain region, all the surface Brain regions have influence in each electrode. The influence is proportional to the inverse of the

square of the distance, as defined by the electromagnetic laws.

Therefore, in order to analyze the EEG signals, there are two common approaches. The Evoked Response Potentials (ERPs) that consists of analyze the patterns of the potentials generated before, during and after an event on time. The second way to analyze the EEG data is analyzing it in the domain of frequencies, trying to find components and patterns of activities. In this work, we focused on the ERPs analyzes, being the first work to analyze ERPs for BB and MB in the context of attention. Complementary analysis are also made, concerning the theory created to explain the phenomena.

### 3.5.1 EEG for ADHD and control subjects

[Sha+15] States that For inattention subjects in go-nogo experiments, there is a reduction in the amplitude of the P3 response for young adults. It means that the potential peak over 300 milliseconds after the onset of the target is lower for inattention subjects than control subjects. The ADHD subjects had a lower activity for the go targets. And a higher for the frontal electrodes for the no-go targets. The P3 peak on the frontal and parietal regions reflects the Brain activity related to Attention.

[Che+17] did an experiment with 174 controls and 93 ADHD subjects. It was found that the P3 amplitude is lower for ADHD subjects than for Control. Also, The Contingent Negative Variation (CNV) amplitude is lower for ADHD subjects than for control. The CNV is related to the motor preparation, and is usually measured around the electrode *Cz* on the motor cortex. How higher is the peak of the CNV higher is the motor preparation and the attention. The author also states that the P3 amplitude is related to the decreasing of the response time variation (RTV) for ADHD and Control subjects. The CNV amplitude is related to the P3 amplitude, but not directly to the RTV amplitude.

### 3.5.2 EEG for the CTET task

[OCo+09] and [Chi+21] investigated patterns of omissions and detections in the CTET task, explained in session 3.3.4, using EEG. The Evoked Response Potential (ERP) was taken in consideration in order to study the response of subjects when they answer correctly or wrongly to the target. Both discovered different responses for omissions and detections in the contingent negative variation (CNV), central, Parietal, Occipital and Frontal regions.

[OCo+09] identified that it is possible to preview an error before it happens using the ERPs from these regions. [Chi+21] discovered different responses between control subjects and subjects with schizophrenia. It was possible to identify that subjects with schizophrenia have more reactive responses, than planned, by comparing the activation of the frontal and parietal regions.

The CTET task has two main phases of response. The first one is the target appearance, generating a positive peak after 300 milliseconds (a P3 response) in the occipital region. This response is due to the fact that the occipital regions is responsible to process the visual information, and therefore it is possible to detect a physiological response from this region with the appearance of a new image.

The second phase is composed by the CNV response. It is related to the motor preparation to click the button. The response is usually a negative peak during the moment where it is possible to identify a target.

### C. Healthy controls

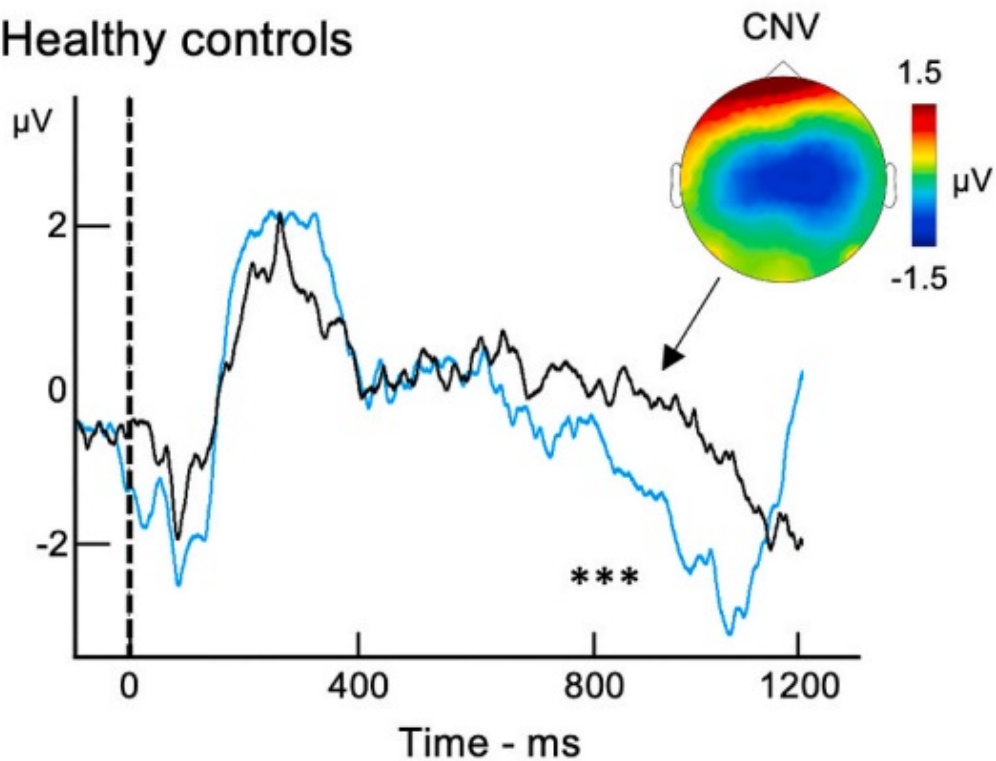


Figure 2: CNV response to the target. The black lines are the ERPs for the omissions and the blue lines are the ERPs for correct responses. Image taken with authorization from the authors [Chi+21].

The second phase has also another responses in the Parietal and Frontal regions. Both regions have a P3 response after the onset of the target. It is, after the target surpass the time duration of a normal trial. The parietal region is related to the time synchronization on the brain, taking care of counting the time to identify the target. While the frontal region is related to the planning, it is, is actively establishing the goal that in this case is the target.

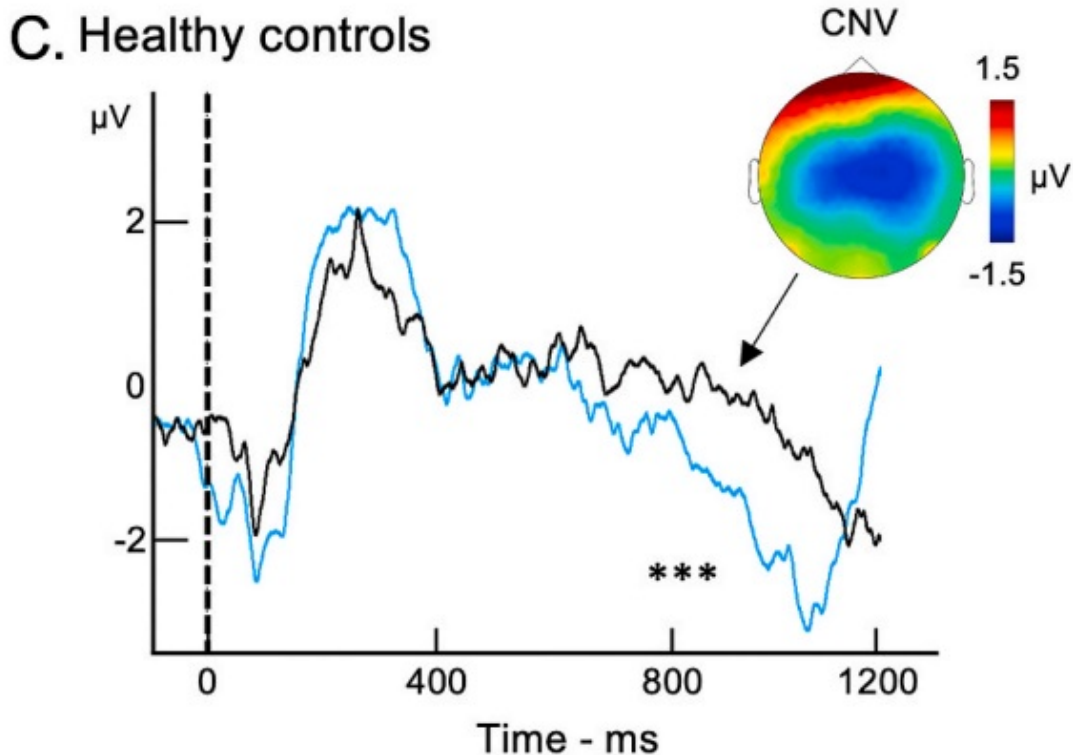


Figure 3: P3 response to the target. The black lines are the ERPs for the omissions and the blue lines are the ERPs for correct responses. Image taken with authorization from the authors [Chi+21].

### 3.5.3 EEG for binaural and Monaural beats

[UYA19] tested the ERPS for Binaural beats using modified BBs in order to be able to identify the effects. The modification was made because the BB could generate MB effects and vice versa, the own effects of BB could be overlapped or canceled by the intermittence of presentation of the beat.

[UYA19] found that BB have a N1/P2 response, it is, a negative response peak after 100 milliseconds and a positive peak after 200 milliseconds in the cortical regions. The effects are related to the system of localization, where the BB is interpreted as being composed of both the original sinusoidal signals, and also from a third nonexistent signal, corresponding to a signal with the difference of frequency between the two signals composing the BB.

The cognitive effects of BB and MB are unknown. The effect of BB of generating a third nonexistent signal is known to be related to the localization system.

## 3.6 Contributions of this work with relation to the literature

As said before, the literature about BB is scarce. There are not any standardization concerning the protocols to test BB. Also, there are very few considerations about the loudness effects in the results of the experiments. A last lack, is that the discussions and interpretations of the phenomena are all very superficial.

This work tries to solve these three lacks in the literature: (i) First, developing a proposition of standardization in order to create protocols to test the effects of BB with a proper experiment. (ii) Second,



inclusions of loudness considerations in the protocol and analysis. (iii) And finally, an extended investigation of the possible effects of BB in the brain mechanics using EEG, physiological experiments and descriptive models. As far as we know, this is the first time that EEG, ERP's and the modeling we did was applied to Binaural and Monaural beats in the context of sustained attention.

## 4 Methodology

To create a protocol, an experiment and also to ensure that each part of the process was correct, a lot of steps were executed. In this section, we will explain how the BB were created, and tested. Why and how each parameter was chosen to construct each signal. How the experiment was thought and how it was built to test the BB and MB effects on attention. Also, the protocol used and the steps of cleaning and methodology used to analyze the EEG data will be explained.

### 4.1 Auditory Brain Stimulation

#### 4.1.1 Generation of Binaural Beats

The first step was to find and understand how to generate BB. It was firstly made by the search of signals available online for free. We verified if the signal was really what the sources were promising. To do that, we used *python* and the *SciPy* package to import and evaluate the components of the signal.

The BB are sounds registered in files with two stereo channels, each one corresponds to one ear, and transmit an independent signal to each ear. To verify if the BB have the correct difference of frequencies due to the carrier signal in one channel, and the highest frequency on the other, it is necessary to analyze which frequencies are present in each signal, and identify if they correspond to the expected difference of frequency. Also, the signal cannot have another components of frequencies, but be a pure sinusoidal wave.

The BB were generated with a sinusoidal function. A carrier frequency of 500 Hz was generated and a summed frequency of 515 Hz was added to the second channel. This leads to the neuromodulation of 15 Hz  $\beta$ - frequency band into the brain, and it was chosen with relation to the [PN69] work that tested what are the parameters that could affect more the brain in terms of loudness.

#### 4.1.2 Addition of background noise

Also, to make the signal more comfortable, we added the same pink noise to both channels. The pink noise has a sound similar to that of a rain, and is known into the literature that it is pleasant for humans. The pink noise is a signal with high concentration into low frequencies, figure 4b. There are a lot of options to do a summation of signals, but each one has different trade-offs.

As we saw in session 3.1 the loudness can be very important concerning the effects of the sound. Because of that, we decided to make the normalization of the signal with relation to the loudness, what will be explained in the session 4.3. Physically, the sound level pressure (SLP) means the energy level of the sound, and it can be measured in terms of decibels. First, we generate a sinusoidal signal and a noise signal normalized to the desired loudness of -35dB. After, we summed both signals and made a new normalization in order to obtain a final signal with -35dB. It was made with the three signals. The equations to make the normalization can be view below:

$$RMS = \sqrt{\frac{\text{sum}(\text{signal}^2)}{\text{length\_signal}}} \quad (1)$$

$$dB = -20 * \log(RMS) \quad (2)$$

$$\text{gain} = 10^{\frac{\text{target\_db} - dB}{20}} \quad (3)$$

$$\text{normalized\_signal} = \text{gain} * \text{signal} \quad (4)$$

Where RMS is the root mean square of the signal, a measure of the energy level. dB is the dB level of the signal, target\_db is the desired new dB, and normalized\_signal is the signal after being normalized. Gain is how much it is necessary to multiply the signal in order to obtain the desired dB. The gain equation 3 comes from the manipulation of the log into the dB equation 2, inserted in an equation with the normalized\_signal dB and the own original signal dB difference.

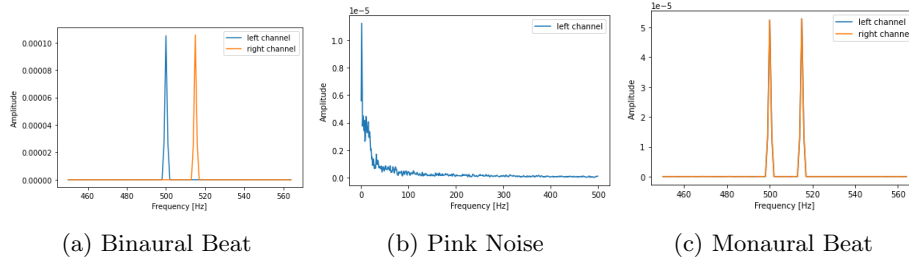


Figure 4: 4a Power spectrum of the left channel in blue and right channel in yellow. We cannot perceive the components of pink noise because they are concentrated in the smallest frequencies. Looking at the binaural beat, we can perceive that the carrier frequency is 500 Hz on the left channel, and the summation frequency is of 515 Hz, as expected. This means that, securely, a good signal was generated to the experiment. 4b Power spectrum of the noise signal. The noise was presented in both channels. The lower frequency components have a much higher amplitude, as expected. 4c FFT transform of the monaural signal. A summation between the carrier and the higher frequency was presented in both channels. We can perceive that the monaural beat has two components in each channel, one has 500 Hz frequency and another 515 Hz, as expected.

Also, we built a pure noise signal to be used as a control test. The signal was also normalized. To ensure that we had a pink noise, we also applied an FFT transform, and generated the figure 4b.

Finally, to generate a comparative condition, we generated a MB, with the previous carrier frequency being presented in both the channels. To ensure that the data is really a MB, we applied an FFT transform and obtained the figure 4c.

The *Audacity* software was used to the experiment. Because it has the capacity to change the SLP of the sound, what is necessary in the protocol. By changing the SLP, it means the dB of the sound starting from the same reference, to the higher SLP yet comfortable to the subject, we are actually founding the loudness response of each subject. Therefore, each participant had a dB level adapted for his comfort. The software was also used to augment the dB level of the sound, In order to test a higher dB level in the final of the experiment.

In order to approximate the SLP generated by the sound using audacity, the lowest SLP that each subject was able to hear was measured. The SLP level is the difference between the chosen SLPs and the minimum SLP for each subject. The demonstration to this relation concerning *Audacity* software can be found in the following link.

## 4.2 First experimental protocol: simple visual attention task

The experimental protocol is a fusion between the visual experiments and the binaural beats experiments. We used the Python package *Psychopy*<sup>1</sup> to create a choice experiment. The experiment consists of visual colored images being presented on a screen, where the user had to press the button S, E and F if the screen

<sup>1</sup><https://www.psychopy.org/>

showed a red, yellow, and green image, respectively. One time that the color appears, the user has to choose the most fast possible the correspondent keyboard.

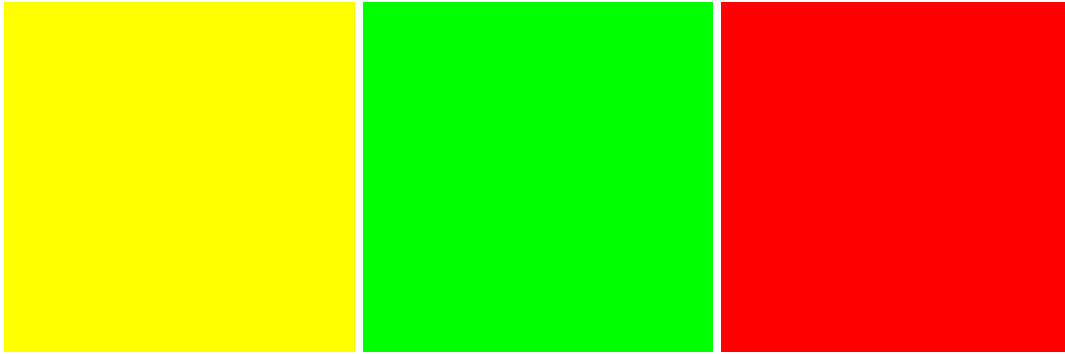


Figure 5: **All possible screens of the experiment.** All the colors were generated having identical luminosity, because this can influence the response time, as mentioned in the session 3.3.3

The program created is able to capture the response time, the color, and the buttons chosen. All the data is registered automatically into a directory. It is possible to choose how many trials will be exhibited at each initialization of the experiment, the number of the participant and the number of the session. These data are registered together with the others' data of the experiment.

The experiment was divided into seven phases, as demonstrated in the table 2.

Table 2: **Seven phases of the experiment to each participant.** To collect good results, it is necessary to make the participants arrive to the steady-state with relation to the experiment and the sounds. To do that, a learning phase is made before all the experiments, to ensure that the participant have understood the experiment, and learned to chose well. Also, each sound is presented for about ten minutes, as mentioned into the literature this is mentioned as a good time to arrive to a steady-state. After, for each sound, the experiment is executed while the participant continues to listen to the signal.

Phase	Number of Trials	stop criteria
learning phase	until the participant feels comfortable	answer of the participant
noise presentation	-	after 10 minutes listening signal
noise experiment	30	after the 30 trials
monaural presentation	-	after 10 minutes listening signal
monaural experiment	30	after the 30 trials
binaural presentation	-	after 10 minutes listening signal
binaural experiment	30	after the 30 trials

The number of trials was low to do not make the participants tired. Also, the main objective of this first experiment was just to test the experiment by itself, the protocol, and the signals. With the conclusions obtained with this experiment, an improved protocol was constructed and executed with a bigger number of participants.

### 4.3 Second experimental protocol: continuous temporal expectancy task (CTET)

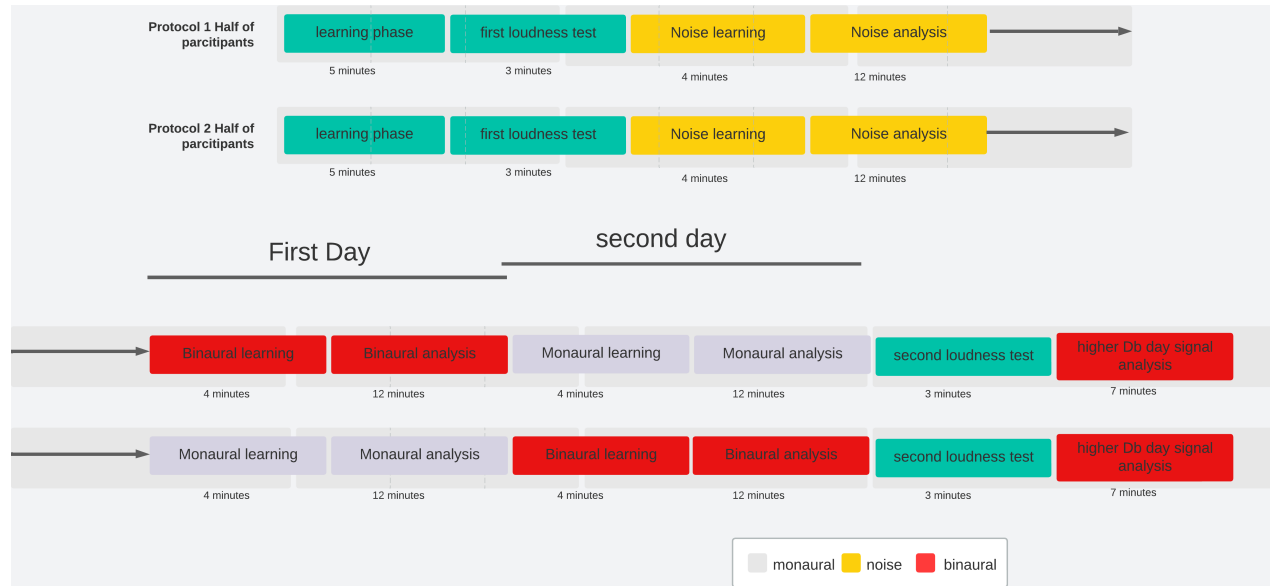


Figure 6: **All phases of the protocol.** Including the two days. Each participant participates two times, each time the order of presentation of the monaural and BB are changed.

The experiment is based in the experiment explained in the session 3.3. The experiment was implemented by the author from scratch for this thesis with the *psychopy* [Pei+19] package in *python*, in order to be able to be applied outside the EEG laboratory. Also, the code of the CTET experiment in *matlab* using the *psychtoolbox* developed in the laboratory INSERM1114 was totally modified by the author to be adequate to the protocol. The messages between the EEG device and the *matlab controller* were corrected, the collection of response times was modified to consider more than one click in each trial. The duration of the sequences, options of sessions, and collection of data were totally modified to be adequate to the experiment protocol. Also, the registering of the data was improved to automatically generate a unified table with all the performed experiments, independent of the *matlab* session.

Four chess shaped images were generated as in the figure 7. The experiment consists in show each figure by a time of 0.8 seconds. Between the figures, any one of the four figures, will appear as a target, and will rest for 1.125 seconds in the screen. When such a figure appears, the user has to press 't' in order to say that he identified the target.

The experiment is then divided in sessions, and sequences. Each session corresponds to a phase of the experiment protocol. Regarding the figure 6, The experiment is therefore divided in five sessions: Test, first loudness test, Noise session, Binaural session or Monaural Session and second Loudness test. In the Test, the participant is therefore asked to perform the experiment without hear any sound and choose rightly all targets in a sequence of 45 trials. If the participant can chose correctly, the experiment continues, if not the participant cannot perform the experiment. The participant has five chances to chose rightly all the targets in a sequence of 45 trials.

Each target appears randomly between 4 and 10 trials after the last target has appeared. After this phase, a test is performed in the software *audacity*. The BB is presented, and the loudness is changed in steps of 5dB, until the participant find the plus high but comfortable level of loudness. When the comfortable level is found, it is registered and all the beats are presented with this same loudness level to the participant. the search for the highest comfortable level of loudness is due to the literature review conclusion that how higher the loudness, higher the Brain response 3.1.

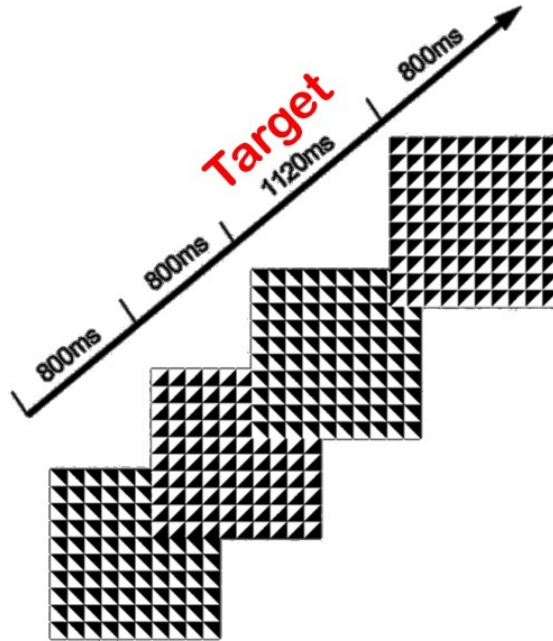


Figure 7: **The CTET experiment consisting on the presentation of trials with 0.8 seconds of duration and targets with 1.12 seconds of duration.** The trials are presented as a random positive or negative rotation of  $90^\circ$  with relation to the previous chess image. The target appears randomly between 4 and 10 trials. A trial with a duration of 1.12 seconds is therefore a target.

To the beats' presentation, we have a subdivision between two phases: The evaluation and the analysis. The evaluation is the learning phase of the beat, where the participant will have a time of 4 to 5 minutes listening the beats, and is expected to arrive to the steady-state related to the beat. During the first three minutes, the participant also performs the experiment for one sequences, each one with 225 trials, it means 3 minutes. The objective is to study how the steady state can affect the Brain and how is the difference between the lack of steady state and the steady state. After, in the analysis phase, the participant continues to listen the same sound for four sequences, each one with 225 trials. The objective in this phase is to analyze the effects of the Beat after the Brain has already adapted to it.

Finally, there is a last session called loudness test. With the BB or the Monaural beat, depending on the beat that was presented at the day. The *audacity* is used again, but this time to augment in steps of 5dB the loudness until the participant say that it is supportable yet. After the test, the participant performs two sequences with 225 trials of the experiment while listening to the BB or MB with a higher level of loudness. The objective here is to augment the level of loudness the participant listens, in order to test if the loudness can have some effect in the participants' performance.

Each participant is called two times, with an interval of at least 14 days, to perform the experiment. This interval is necessary to try to clean any long-term effect the participant could have with the beats' presentation. There are two options of order of presentation: With half of the participants, after presenting the noise, we present MB, and with another half we present BB. In the second participation, we change the signal presented to monaural or binaural, maintaining ever the noise as the first sound to be presented.

The participants should be just men, as there are a lot of differences between the man and woman reactions to sound and visual stimulus, as said in session 3.

The experiment has been performed in a computer supplied by the University of Strasbourg with 22 participants according to the rules set up by the Ethical Committee for Research of the University

of Strasbourg (*Unistra/CER/2022-52*). Each participant has provided a written consent authorizing the realization of the experiment and the collect and analyze of their data. Also, it was explained to each one that there are no risks concerning the participation of the experiment. The EEG data collection was made using the Biosemi Active Two system and the experiments were performed in the INSERN 1114 laboratory.

The selection of subjects was based on the scores obtained from the Adult Self-Report Scale [Kes+05]. The ASRS is a self-assessment scale for symptoms of ADHD. It consists of 18 items assessing the frequency of occurrence of inattention symptoms (9 items) and hyperactivity/impulsivity symptoms (9 items) over the past 6 months. For each item, the subject must choose from five possible responses (never, rarely, sometimes, often, very often), scored from 0 to 4, respectively. Two scores are obtained, one for inattention and the other for hyperactivity/impulsivity. A high score ( $> 23/36$ ) indicates a strong likelihood of presenting the symptom. The scale was distributed via an online survey to all students at the University of Strasbourg. Based on the responses provided in this survey, the two subject groups (control group and inattentive trait group) were formed.

The control group consists of subjects with a score of 16 or lower on the 9 items evaluating inattention symptoms (reflecting a low probability of presenting these symptoms) and a score of 16 or lower on the 9 items evaluating hyperactivity/impulsivity symptoms (reflecting a low probability of presenting these symptoms). The subjects in the inattentive trait group have a score of 24 or higher for inattention symptoms (reflecting a high probability of presenting these symptoms) and a score of 16 or lower for hyperactivity/impulsivity symptoms.

For all subjects, exclusion criteria including the presence of neurological and/or psychiatric disorders, regular cannabis consumption, as well as the use of antidepressant and/or antipsychotic medications were verified. Each participant provided informed consent and received compensation for participating in the study. The study was approved by the ethics committee for research at the University of Strasbourg.

All the experiments were performed by the author with technical help of the staff from the laboratory, in an experiment room. The room is divided in two isolated parts: An observation part, and an experiment part. In the observation part it is possible to control what will be the experiment, when it will start and what are the data to be registered. It is also possible to follow the EEG trace and triggers, in order to verify the performance of the subject, if there is some problem as if the participant is moving too much, sleeping or if the signal is artifacted. The experiment part is where the Biosemi Active Two device is, the subject sits on a chair and perform the experiment with the door closed. Ideally, there is no sound interference in the room, but as there was a renovation of the building some participants witnessed some noise from outside during the experiment, what was reduced by the use of phones to hear the beats presentation.

All the personal data was encrypted with a code prepared in *python* and *cypher package* by the author before be shared at cloud. the key was maintained in security in a proper place, and was not registered at the same repository from the encrypted data.

#### 4.4 Electroencephalography analysis

The EEG analysis was focused on the Event Related Potentials (ERPs) related to attention, and in the connectivity analysis of the Brain network. The objectives can be listed as:

- Find if the Beats can elicit changes in the attention related ERPs.
- Compare if the response is different Between subjects with ADHD and controls.
- Investigate the structure of connections of the network related to context influences.
- Verify if the Beats could change the context-dependent temporary networks.
- relate the previous results with the subject performance in the CTET experiment.

All the code was made by the author using the *MNE package in python*, and wrote from scratch for this thesis. The steps of importation, transformation, generation of images and analysis were all implemented from scratch and automatized to be reused or have the parameters altered as necessary.

#### 4.4.1 data

The data is made of 48 EEG bdf files, concerning the control subjects and 36 EEG bdf files concerning the inattentive subjects. Having eight control subjects and six inattentive subjects. Each subject has six bdf files, that are: Two bdf files captured while listening noise in the first day, the bdf file captured while listening binaural beats, the bdf file captured while listening the higher intensity binaural beats, the bdf file captured while listening the monaural beats and the bdf file captures while listening the higher intensity monaural beats.

Each one of the EEG data files has seven kinds of events: missed target, detected target, trial, correct response, wrong response, start of a sequence and end of a sequence. Corresponding to the triggers sent by the matlab program, developed for this experience, during the realization of the CTET experiment.

#### 4.4.2 Pre-processing and analysis

The data was analyzed using the MNE package from python. The data was filtered in the domain of frequencies, letting just the frequencies between 0.1 and 30Hz in the signal. It was done in order to filter artifacts, as the current source influence, and any another kind of periodic signal. Also, most of the interesting activities in the EEG data happens in this frequency interval.

The data were therefore fitted by an Independent Component Analysis provided by mne. 26 components were chosen as the pattern. The results permit to identify the correct moments where there was an artifact, as for example an eye blinking or a muscle movement of the participant. These reactions interfere with the EEG signal, and are usually several times higher than the potential coming from the Brain.

The components coming from the eye blinks artifacts were used to reject the moments where this artifact happened, using an automatic autoreject function provided by the mne package. The data was therefore divided in several kinds of epochs, each one using a threshold of  $100\mu V$  for rejection, in order to reject the epochs with artifacts. The epochs are as below, with relation to the target zero time:

Table 3: **Epochs of analysis.** In order to analyze the Evoked response, the EEG data is divided in small pieces of data around an event. On this case, the epoch was chosen to be in the moments exactly after the appearance of a target. The baseline is chosen in order to normalize all the epochs, in this case, it was chosen with relation to the exactly period before the target appearance. The epochs facilitate the analysis of the responses generated in the brain, by the occurrence of a determined event.

Kind of Epoch	Interval (s)	Baseline	Threshold
After target	-0.1 to 1.8	-0.1 to 0	$90\mu V$

The baseline is chosen because the signal is analyzed concerning the differences of the signal with relation to the baseline. Therefore, a mean is taken out from the baseline, and after subtracted to the remaining time of the Epoch. Due to the amount of data, the cleaning process takes more than 12 hours to run and generates more than 60 ERPs files at the end, one for each subject, day, and condition.

Finally, the Evoked Potentials were taken from the Missed Target and Detected Target Epochs by meaning all the Epochs for each subject. The subjects that presented inconsistent results as not-a-number values or very high potentials were discarded from the analysis.

The EEG data were analyzed concerning the Event-Related Potentials (ERPS) to the After target epochs. In the After target epochs, a grand-average ERP was made for each one of the groups and each one

of the conditions. The grand-average ERP is made averaging the ERP's of the subjects of each group, in each condition.

For each condition was created a grand-average for three Brain regions: The parietal region, involving the electrodes Pz, P1, P2. The Frontal cortex, involving the electrodes FCz, FC1, FC2. And a contingent negative variation (CNV) involving the electrodes Cz, C2, C1. The parietal region indicates the level of attention, with a peak after around 300ms from the onset of the window of detection, this kind of peak is called P3 in the literature. How higher is the peak, higher is the attention or the compensation (subject effort). The Frontal cortex ERP also indicates the level of attention with a P3 peak, with the same logics, but indicating the planning of the subject. The CNV is related to the motor preparation, and is a decreasing in the potential. How lower is the CNV, higher is the motor preparation, and therefore higher is the attention.

The grand-average was made for epochs where we had a detected target. As the ERPs are different from detected target Epochs to missed target Epochs, and could be used to identify an error or not, as commented in the 3.5. The curves were smoothed with a window of size of 100 ms in order to make easier the analysis for the human eyes, and then compared by group and condition.

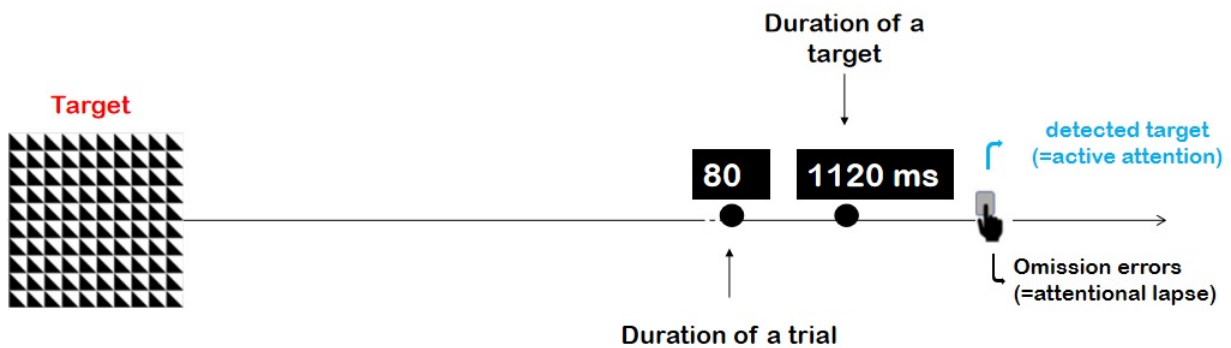


Figure 8: **window of detection.** The window of detection is the interval of time when the target has a higher duration than the trials. At this moment, it is possible for the subject to identify that the image is a target. When a new target appears, a trigger is sent to the EEG device. When the subject detects a target, the space button is pressed and a trigger is sent to the EEG device. The epochs were created around the triggers, indicating a new target appearance. And were divided between detected target epochs and missed target epochs (the omission), using the absence or presence of a trigger indicating a response of the subject.

#### 4.4.3 Pre-processing to network and context analysis

Regarding the theory presented on the session 5.5 an additional analysis was created in order to test the theory, and withstand the interpretation about the beats influences on the brain. the analysis is novel with relation to the literature, and was created by the author. Therefore, it should be taken in consideration with reservations. The analysis was also created using

In order to verify the evoked characteristics of the populations of neurons activities, measures of correlations between the electrodes should be taken. These correlations also can be used to find an approximate correlation between the back-ground activity of the brain, by the mean potential value of electrodes, and specific populations of neurons. These concepts will be better explained in session 5.5.

It is also well known by the literature that the process of cleaning the EEG data concerning the application of these correlations has to be different. This happens because the electrodes can exchange small currents during the experiment, and these currents could be interpreted as a correlation that do not come from the brain population activities. In order to filter these networks, two process were made on the EEG



data:

- The reference of the electrodes was taken as the average activity of all the electrodes. it means that, for each electrode, was subtracted the mean of all the electrodes potentials. Therefore, diminishing the influences of undesired currents between the networks, and also, the influences of the activity of another populations closer to another electrodes.
- The projections of one electrode in the around electrodes was also subtracted using Gaussian of each specific electrode. It helps to clean the undesired currents projections on the electrode.

The cuts on the frequency were made from 1 Hz to 400 Hz, a high frequency cut was chosen because the analysis searches the influences of electrodes one to another, and therefore even high frequency activities could be interesting for the analysis.

For the automatic Independent Component Analysis(ICA), a 99% components analysis cut was chosen. It means that just the independent components corresponding to 99% of the variance of the data were chosen. Also, a free number of components was chosen, meaning that the ICA analysis approximate the best number of independent components to decompose the data.

All the other details were chosen exactly as the cleaning process of the session 4.4.2. With exception to the threshold that was chosen as being  $150\mu V$ , in order to avoid the maximum as possible, the loose of information.

Table 4: **Epochs of analysis.** In order to analyze the Evoked response, the EEG data is divided in small pieces of data around an event. On this case, the epoch was chosen to be in the moments exactly after the appearance of a target. The baseline is chosen in order to normalize all the epochs, in this case, it was chosen with relation to the exactly period before the target appearance. The epochs facilitate the analysis of the responses generated in the brain, by the occurrence of a determined event.

Kind of Epoch	Interval (s)	Baseline	Threshold
After target	-0.1 to 1.8	-0.1 to 0	$150\mu V$

The analysis created with this process of cleaning is exposed in session 5.6, and is considered a result of this research, with the capacity to open new possibilities on the analysis of EEG data and neuromodulation.

## 4.5 Behavioral data analysis methodology

The behavioral data was analyzed regarding the Response Time and the errors. Both the measures are important to verify the attention of each subject. It is known as saw in the session 3 that the Response Time distribution is not normal, being possible to have peaks outside the mean. Therefore, the non-parametric Mann-Whitney U test was used to measure the differences between the Response time between the groups being inattentive subjects and control subjects. And between the conditions, being the ones already explained before: Binaural beats (BB), Monaural Beats (MB) and noise.

With relation to attention, a difference in the response time for one phase of the experiment to another phase, for example while the subject was listening to BB in comparison to when the subject was listening to MB is an evidence of significant effects on attention. AS we have a non-parametric test, the median was used as the region of higher probability of a response to be observed. And the standard error is used as the estimate error on this measure. Therefore, if the median in a condition is lower than the median under another condition and the test has an alpha lower than 0.05 we can say that the response time in this condition was faster. A faster response mean a higher attention, as stated in the session 3.

All the comparisons were made using just the data from the analysis phase, discarding the evaluation phase where it is considered that the subject did not arrive to the steady state in relation to the beat. In order to generate the plots of the median and statistical differences, the Matplotlib in python was used.

The error was measured in two different ways: First, dividing the number of Missed stimulus to the total number of stimulus on the analysis phase. And second, getting the intervals of time when an error was not made. It is, a period starts and continues until an error is made, this period is saved as a period without omissions. When a new error happens, a new period starts to be counted until the next error happen or the session finishes. After that, the periods are used to make statistical differences using the Mann-Whitney U test. The general error measure comes from the Grand-average of all the periods without omission over a determined condition. How bigger is this Grand-average bigger is considered the sustained attention, as the subject stay more time attentive to the experiment.

Before doing all the analysis, the participants with much more than 50% of errors without considering conditions, were excluded. This decision was taken because this high amount of errors can mean that the participant is not really dedicated to the experiment or that the participant did not understand well the experiment. Therefore, these participants cannot be trusted as a good source of information. Also, the participants with more than 65% of errors for a specific beat were also excluded. As it can mean that the participant was not dedicated to the experiment at this phase of the experiment.

## 5 Results

After the execution of the experiment, the data was generated and archived in a proper place. The author developed a script for importation, cleaning, transformation and analysis to the behavioral data using the package *Pandas* in *Python*. The script was produced with the objective to automatize the analyses of the experiment.

### 5.1 Colors experiment result

The color experiment was performed with two control subjects as a test about an alternative to build the protocol. Here are the results concerning the error rate obtained on the test for MB and BB conditions:

Table 5: **Error rate to each color.** The error rate is a great way to measure if the attention was improved, because as more attention, as fewer mistakes are made, as we saw in session 3.3.3. We can observe that BB had a better result to each one of the beats, with a smaller error rate.

participant	color	beat	error rate
1	red	binaural	0%
1	red	monaural	10%
1	yellow	binaural	0%
1	yellow	monaural	0%
1	green	binaural	0%
1	green	monaural	9%
2	red	binaural	9%
2	red	monaural	10%
2	yellow	binaural	0%
2	yellow	monaural	0%
2	green	binaural	0%
2	green	monaural	9%

### 5.2 Hypothesis and questions Bank

A bank of hypothesis and questions was made and is continuously actualized during the research work. It can be found at the appendix C. The literature review and the results are being linked in the hypothesis banks. The next steps of the research will decide what are the most important questions that can be answered/tested.

The most important hypothesis reached is about the descriptive model of the phenomena, and the planning to access the hypothesis with the EEG and RT data. This model will be discussed in session 6. The other assessments and objectives will be future works, as the EEG data is being collected yet.

### 5.3 Behavior analysis

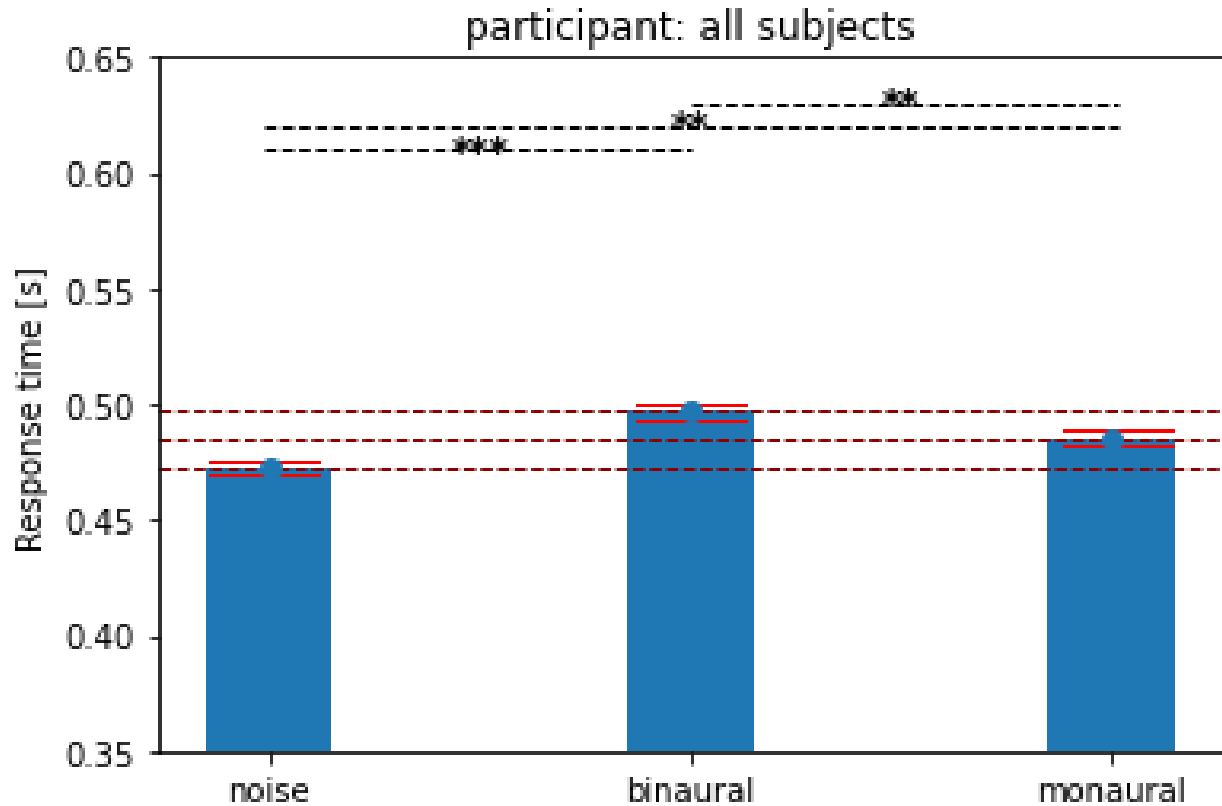


Figure 9: **Grand-average analysis of the response time without considering groups.** We can observe significant differences between all the signals. Noise has the fastest response time, followed by MB. BB has the higher response time. \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

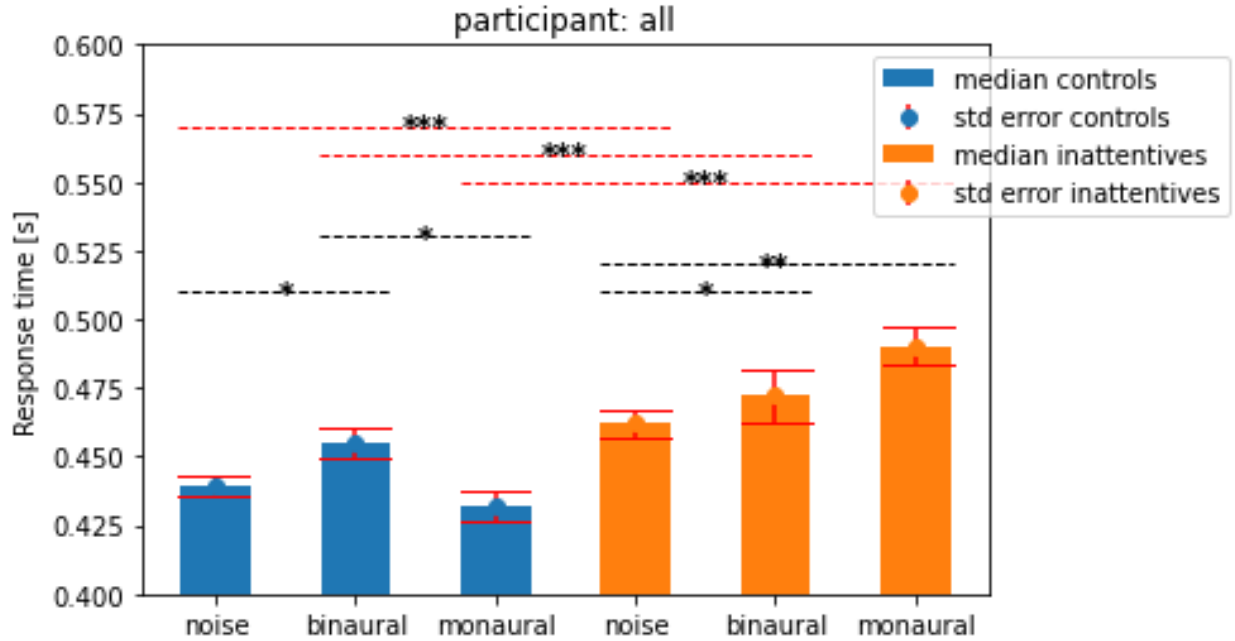


Figure 10: **Grand-average analysis of the response time. significance between groups and conditions. control group is identified as blue, inattention group is identified as orange.** The inattention group presents significant higher response times. For control groups, BB increases the response time and is different from noise and MB. For the inattention group, noise reduces the response time and is different from BB and MB. \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

Table 6: **general error rate.** Noise presents the fewer errors for both groups. MB has fewer errors than BB.

group	monaural error (%)	binaural error (%)	noise error (%)
Inattentive	31.8	38.2	28.4
Controls	26.2	26.9	23.5

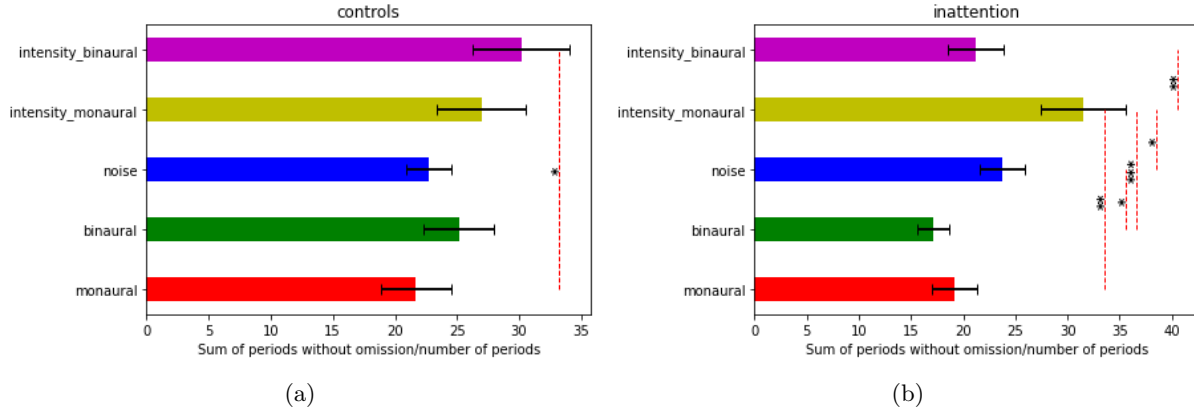


Figure 11: **Mean time of periods without omission. Analysis considering two analysis sequences to compare the beats with a higher SLP intensity, intensity\_binaural and intensity\_monaural.** For the control group, the BB with a higher SLP improve the periods without omission with relation to MB, but is not different from all the other beats. For the inattention group, MB with a higher SLP is different from all the other signals, and improve the period without omissions. For the inattention group, the noise is also different from BB, despite the same result cannot be found in the analysis of figure 12. \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

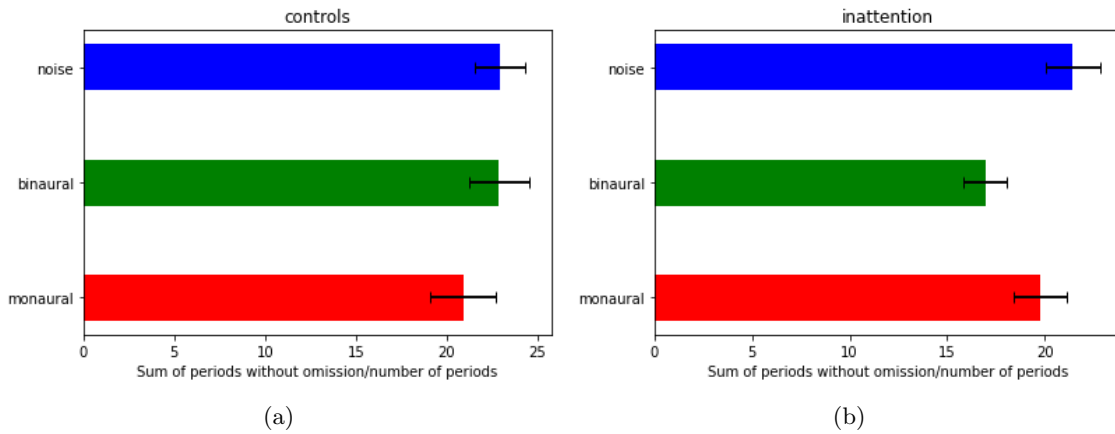


Figure 12: **Mean time of periods without omission. Analysis considering four sequences from the analysis phase to compare the signal with a higher intensity.** The pattern of omissions is equal for the three signals, indicating that the beats do not affect the omissions pattern. \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

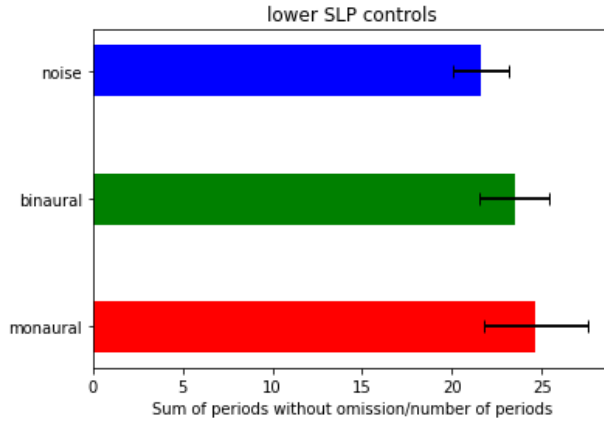


Figure 13: **Omissions for the control subjects with the SLP lower than the median. These are the participants with a higher loudness response, as saw in the session 3.** For the control subjects, the situation changes regarding the mean of periods without omissions that is higher for MB. But, there are not any difference between the three beats. \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

In order to verify if there is a significant difference between the RT when the participant was listening to each beat, the non-parametric Maan-whitney U test was made. A non-parametric test was used because the RT can have a non-normal distribution. The remaining participants result can be founded in the section A.

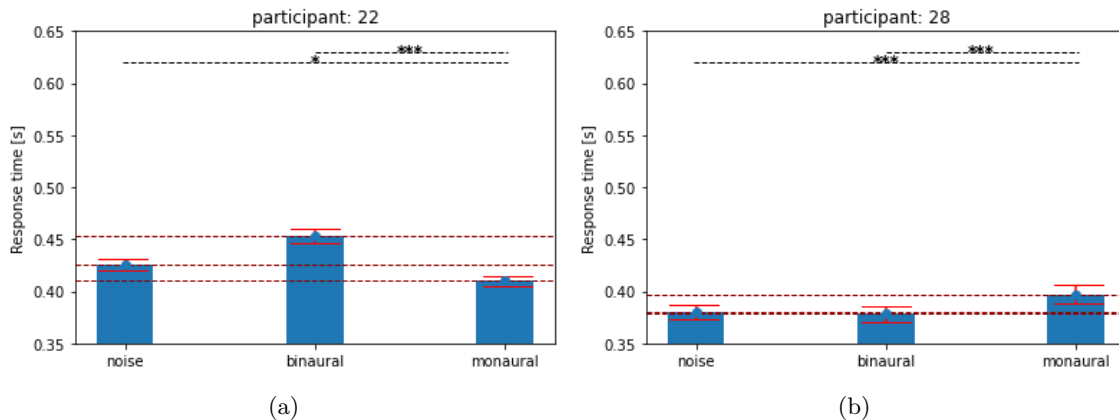


Figure 14: **Control participants with contradictory effects to MB.** In figure 14a participant has a decrease in response time for MB with confidence in relation to BB and noise. In the figure 14b participant 28 has an increase in response time for MB with confidence in relation to BB and noise. \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

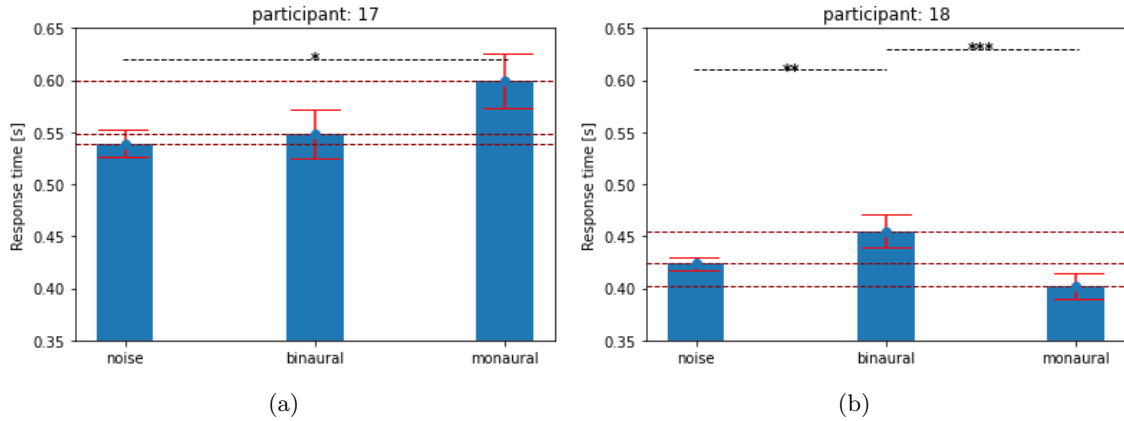


Figure 15: **Control participants with effects to BB and MB.** In the figure 15a participant 17 has an increase in response time to MB with relation to noise. In the figure 15b BB has an increase in response time with relation to MB and noise. \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

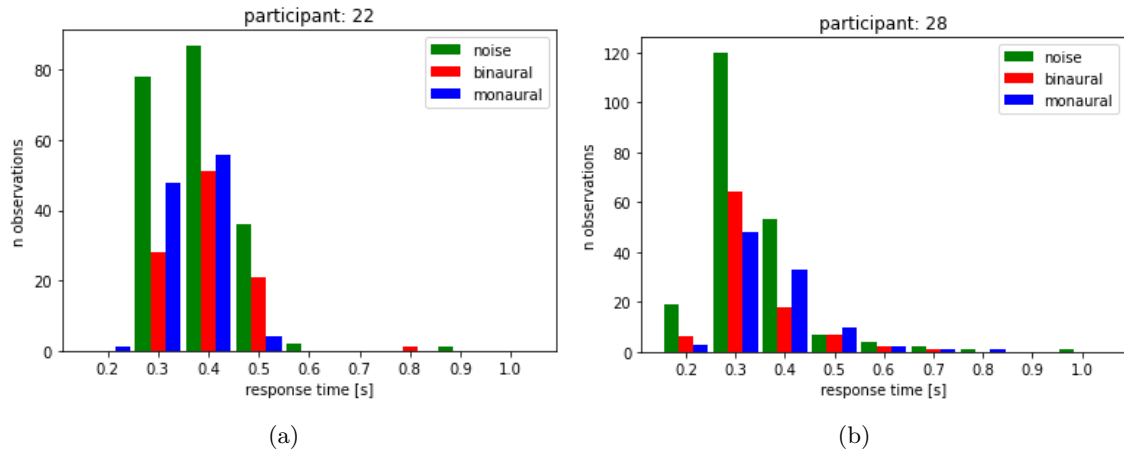


Figure 16: **Histograms of response time to control participants, with contradictory effects to MB.** In figure 16a participant has a higher concentration of responses between 0.2 and 0.4 seconds. Corresponding to the difference in the distribution with relation to the other beats. In figure 16b participant 28 has a more spread response time distribution, corresponding to the difference with relation to the other beats.



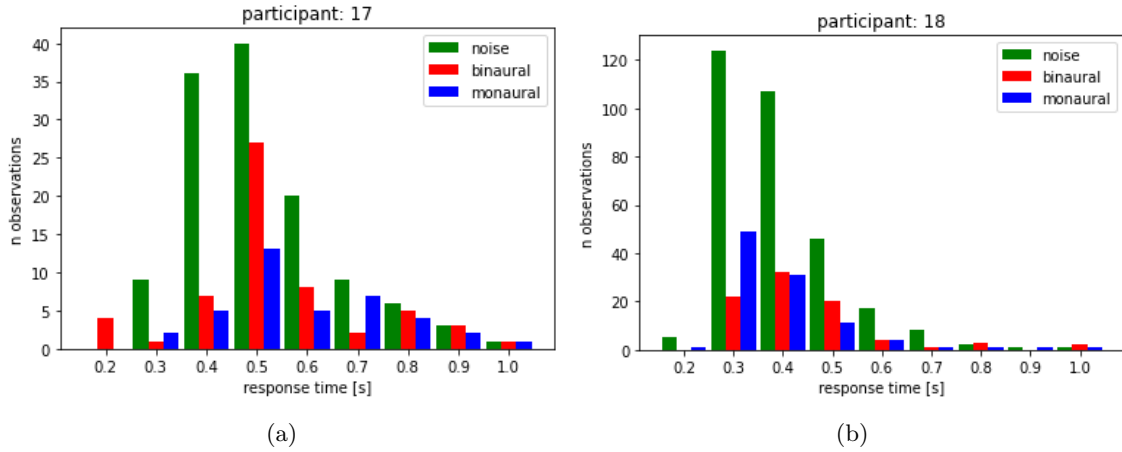


Figure 17: **Histograms of response time for control participants with effects to BB and MB.** In the figure 17a participant 17 has a very spread distribution, but MB has few examples with less than 0.4 seconds. While participant 18 has a peak to BB on 0.4 seconds, while the other two beats have in 0.3. As expected, BB response time is slow in relation to another beats.

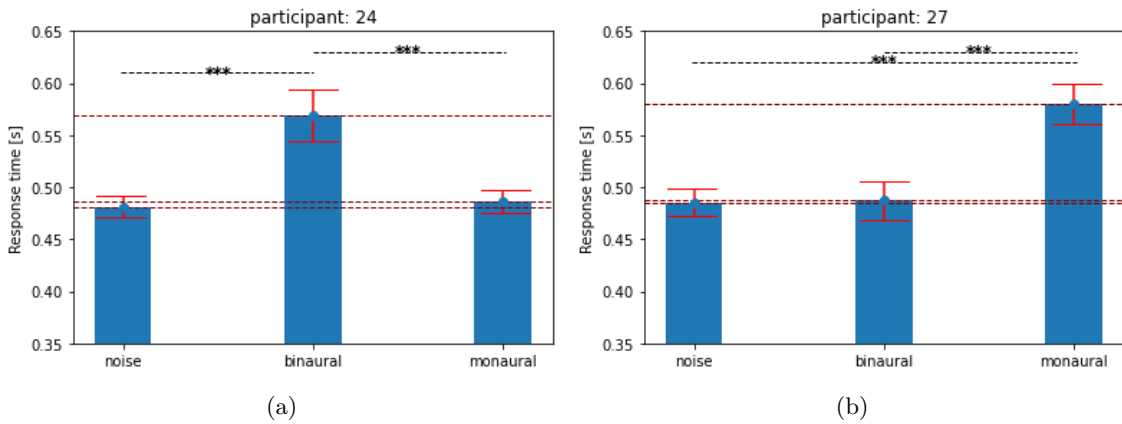


Figure 18: **Inattentive participants with effects to BB and MB.** In figure 18a participant 24 has a BB response time slower than the response time of the two other beats with significance. In figure 18b participant 27 has a MB response time slower than the two other betas with significance. \*\*\*:  $p_{value} < 0.001$ , \*\*:  $p_{value} < 0.01$ , \*:  $p_{value} < 0.05$

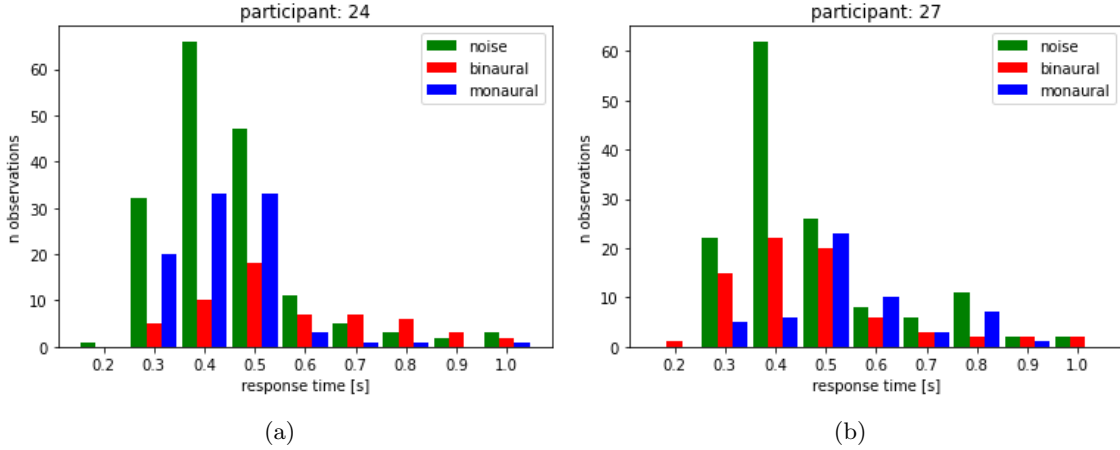


Figure 19: **Histograms of response time for inattentive participants with effects to BB and MB.** In the figure 19a participant 24 has a slower response time for BB having a peak on 0.5 seconds. While the other beats have a peak on 0.4 seconds. There are also a small second peak around 0.8 seconds. While in the figure 19b participant 27 has a peak for MB at 0.5 seconds, being slower than the another beats that have a peak at 0.4 seconds. There is also a second peak around 0.8 seconds for noise and MB. The two distributions are in accord with the significance difference presented in figure ??.

The error rate is defined as the percentage of trials in which each participant chooses a wrong key. Table 7 provides the corresponding values.

Table 7: **Error rate to each beat and intensity of presentation.** The error rate is a great way to measure if the attention was improved, because as more attention, as fewer mistakes are made. We can observe different responses to each subject. For three control participants 28, 18,17 and two inattention participants 26 and 28 we have fewer errors for noise. For 3 control participants 22,13 and 12 and for one inattentive participant 24 we have fewer errors for MB. For one inattentive participant 27 we have fewer errors for BB. Overall, considering the errors, MB and noise sounds to have better effects in attention for more subjects, while BB tends to have a negative effect on attention for more subjects. It is hard to say if MB and noise are different. Concerning the intensity of the signal, the higher intensity signal is presented with 10 Db of increase with relation to the chosen Db level here presented.

Group	Participant	Db	higher Db	MB error (%)	BB error (%)	Noise error (%)
control	28	65	75	15.5	10.0	7.4
control	22	60	70	0.1	9.7	8.1
control	18	45	55	12.2	23.3	7.0
control	17	65	75	62.0	43.0	39.0
control	13	65	75	21.4	23.0	27.6
control	12	45	55	45.7	50.4	59.2
Inattention	26	75	85	45.5	57.7	41.8
Inattention	27	75	85	45.8	32.1	35.7
Inattention	24	70	80	19.5	43.7	22.5
Inattention	28	65	75	17.1	18.9	13.4

## 5.4 Evoked Response Potentials (ERPs) analysis

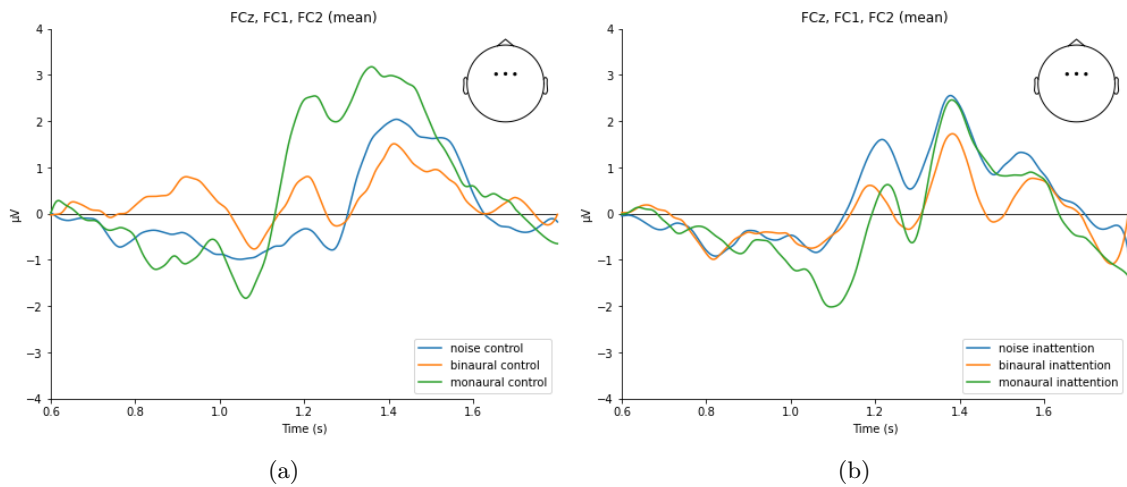


Figure 20: **Grand-average Frontal Evoked Response Potential curve for inattentive and control subjects for each condition.** Regarding figure 20a we can see that control subjects have a stronger P3 Frontal response for MB, and a lower P3 Frontal response for BB. The curves have the shape expected by the literature. In the figure 20b inattentive subjects have a lower P3 response for BB, while the two other beats are equal. The curves have the shape expected by the literature

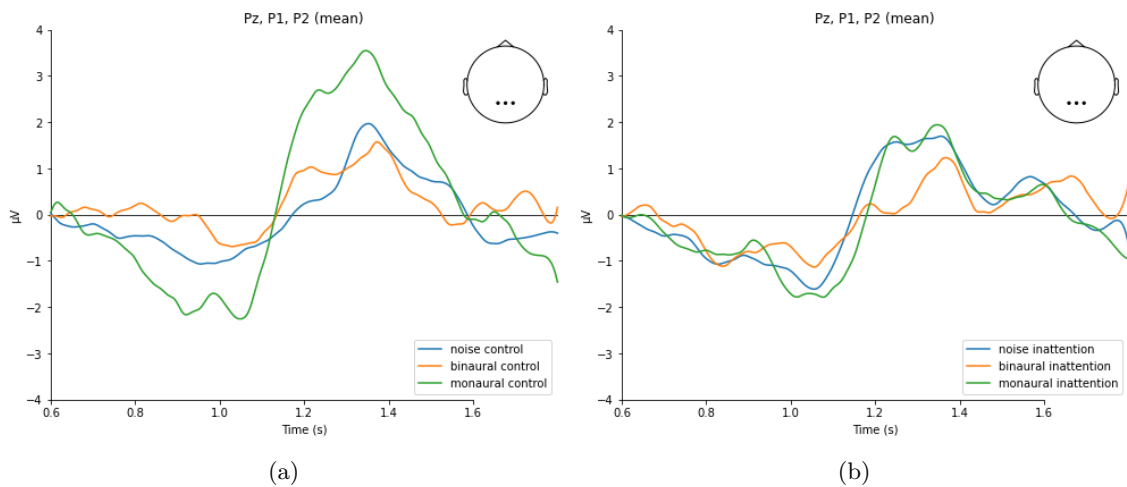


Figure 21: **Grand-average Parietal Evoked Response Potential curve for inattention and control subjects for each condition** In the figure 21a control subjects have a stronger P3 response for MB while the other two beats response is almost the same. The curves are as expected in the literature. In the figure 20b inattentive subjects have an equal response for BB and noise, while they have a weaker response for BB. The curves are as expected in the literature.

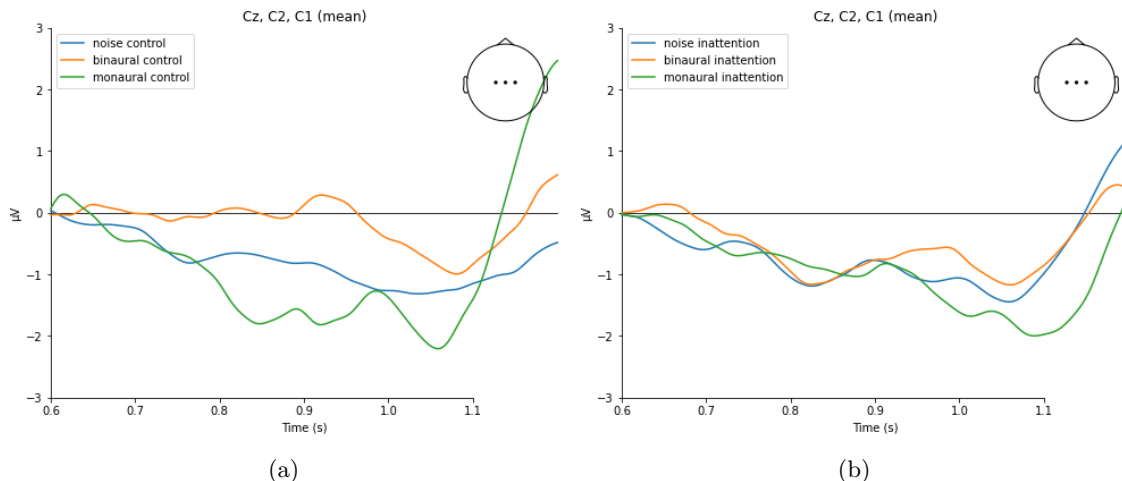


Figure 22: **Grand-average CNV Evoked Response Potential curve for inattention and control subjects for each condition.** In figure 22a we have three different CNV responses for control subjects in the following order of amplitude from the higher to the lower: MB, noise and BB. MB also starts to increase before the other two beats. The curves are as expected in the literature. In the figure 22b we have a higher amplitude for MB, while for BB and noise they are almost the same. MB response also starts to increase after the other two beats, indicating a slower response. The curves are as expected in the literature.

## 5.5 Computational Model

Considering the data results and the literature review about the phenomena, an analytical model here called computational model of the network as created by the author to explain how MB, noise or BB could affect attention. This is a novel model in the literature, that tries to unify concepts of individual neurons to explain populations of neurons. A challenge that has been showing itself very hard in the last years. A complete discussion about the theory with some mathematical proofs, and explaining how the function was built is presented in the appendix F.

Considering the brain, let us define context as being the set of information being captured by the brain in a determined moment in time and being the activity generated by this information. With relation to a neuron, the activity of another neurons and outside phenomena is called back-ground activity.

We can say that the background activity is divides in two: Local context, it is the back-ground activity very close to the neuron that cannot be reduced in an approximation to a very high population of particles and neurons. And in global context, it is the activity that is far from the neuron and can be reduced to approximations for a very high population.

Here, we will approximate the activity of a neuron by a simple perceptron modified model:

$$S = Threshold(A(X + C)) \quad (5)$$

Where

$$Threshold(F) = \begin{cases} 0, & \text{if } F \leq 0 \\ F, & \text{otherwise} \end{cases} \quad (6)$$

here

$$F = A(X + C) \tag{7}$$

And A, B and C are unknown functions that perfectly represents the activity of a synapses in the shape of S in equation 5 defined as follows:

$$A = f1(local\_plasticity) \tag{8}$$

$$X = f2(local\_context) \tag{9}$$

$$C = f3(global\_context) \tag{10}$$

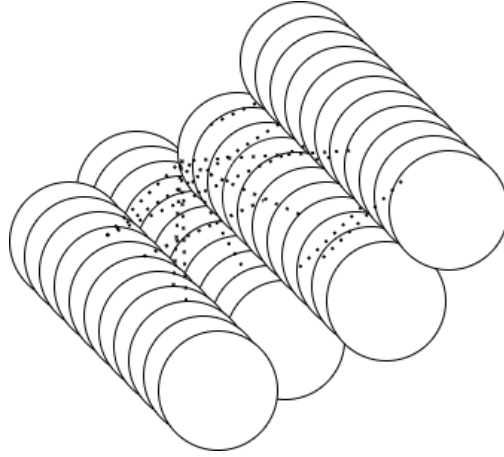


Figure 23: **Illustration of a network of neurons with free connections.** A network on the brain can have free connection between neurons, here represented as the dotted lines. Specifically, in the cortex, the network is also organized in columns.

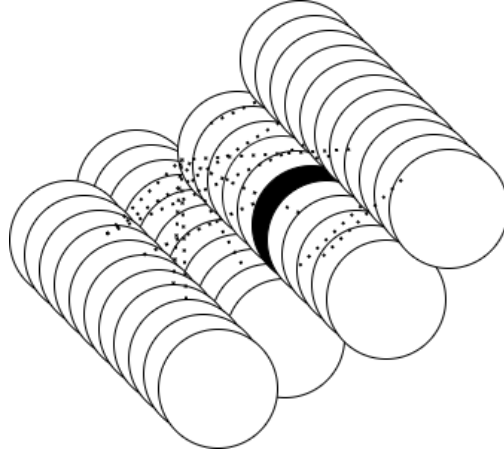


Figure 24: **Neural selectivity.** A neuron, in black, with selectivity to a determined context is **activated**. Considering a determined context, some neurons will activate or not. The contexts to what a neuron is activated are called the selectivity of a neuron. Considering a task that generates several distinct contexts provided by events, a neuron can have a mixed selectivity. It is, the neuron activates for several contexts of the same task.

Within this model, we can say that the selectivity is represented by the neurons that are sensitive to a determined context. It means that the interactions between the parameters  $A$ , that represents the neuron plasticity, with the parameters  $X$  and  $C$ , that represent the context, is higher than 0 for this neuron for this specific context.

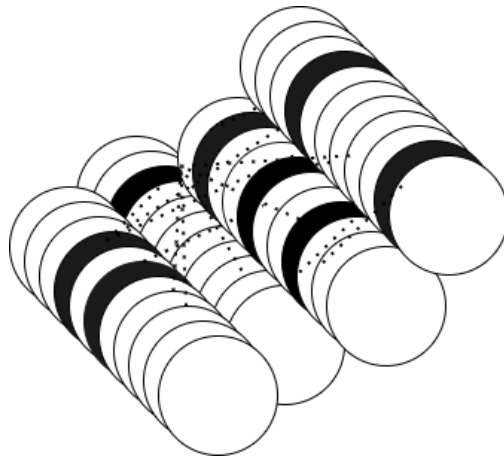


Figure 25: **Temporary network activated by a determined context.** The ensemble of neurons activated by a context shapes what is here called a temporary network. The temporary network is specialized in the response to this determined context. Therefore, the selectivity determines how the brain store and retrieve information between neurons. Here is evident, that within the model presented, the global context  $C$ , it means, the background activity on the Brain is utilized to shapes the temporary networks. It is, is much easier to activate neurons with a correct synchronization using the parameter  $C$  as an information of the global network, than by sending information by synapses. It is easier to see that if we make  $X = 0$  on the equation 5, it became clear that the  $C$  parameter can alone generate an activation. When  $X$  is not zero,  $C$  can influence the activation, changing it probability to happen. As  $C$  comes from a high population of neurons, it changes few in a small interval of time, meaning that the network can rely on the global context background activity to specialize the temporary networks.

As X is defined as the local context, what includes the activity of the presynaptic inputs and the particles around the neuron, we can say that it is highly improbable that an influence of the beats would be significant in the parameter X for a high majority of neurons. Therefore, we can say that the influence of the beat is over the parameter C.

As it was presented in the session 3.3 the Brain works in several frequencies. We can state here that these frequencies are governed by the interaction between the unknown distribution of the plasticity (A parameter) of the populations of neurons with the local and global context (X and C parameters) distribution of the population of neurons. Therefore, it is probable that the beats could influence the distribution of the parameter C, and therefore change the brain state.

## 5.6 Innovative context and connectivity analysis

Using the mne software, a new method of analysis was proposed. The method consists of some steps. The first one is the use of the Phase-Locking Value (PLV) to measure the relations between electrodes. given by the equation:

$$PLI = |E[\text{sign}(\text{Im}(Sxy))]| \quad (11)$$

Where E denotes average over epochs and Im the imaginary component of the spectral domain. X and Y are the two signals being analyzed, in this case, two electrodes. The analysis is made in the spectral domain. This analysis is supplied by MNE and was not created by the author. The objective of the analysis is to verify how one region of the brain influences another region. What together with the knowledge from the literature can help to discover differences in the response to different stimulus. The measure does not have a significance test, and it would be very computer expensive to add a permutation test, therefore the significance is not taken for this measure.

In the second step, in order to validate the hypothesis of the background activity influence on the behavior of a specific population, as stated in the session 5.5 a method was created. It was used the spectral imaginary coherence to measure the correlations between the background activity and the electrodes. Here, the background activity was approximated by the mean of the potential activity of all chosen electrodes, without considering the own electrode over analysis.

This approach was chosen because the imaginary coherence can capture non-linear correlations, while the mean of the electrodes can approximate somehow the general influences of the populations of neurons in just one population, corresponding to its specific electrodes. The mean is able to capture influences of all electrodes, and therefore, a correlation with the mean indicates that the electrode over question is correlated to the general activity of the brain. Finding or not finding these correlations is not a proof that the theory is correct, but is an evidence corroborating in this direction.

The imaginary correlation is given by:

$$C = \frac{\text{Im}(E[Sxy])}{\text{sqr}t(E[Sxx] * E[Syy])} \quad (12)$$

Where E denotes average over epochs, Im the imaginary component of the frequency domain and x and y the signals under analysis.

In order to measure the significance of the imaginary correlation of an electrode with all the other chosen electrodes, it was made a permutations test. As this kind of test is highly computer expensive, it was chosen a number of just 500 permutations and an alpha cut of 7,5% in order to reject the null hypothesis. With these parameters, the final analysis that will be soon explained took more than 72 hours to run.

To choose the electrodes of interest, two approaches were used. The first approach is data based, while the second approach is based on the literature. Concerning the data based approach, the following steps were made in order to filter the 20 most relevant electrodes to a certain event:

1. Take the derivative of each electrode potential, in each epoch.
2. Concerning the interval of interest, for example from 0 to 0.3 milliseconds, select the 60 electrodes with the lower standard deviation for the derivative. It means that the electrodes that changes with a high variation over epochs were excluded. The assumption here is that the brain response to a same event should be similar over epochs, and therefore, the standard variation of the derivative over epochs should be low.
3. In the interval of interest, from the remaining electrodes the 40 electrodes with the highest mean for the derivative in the interval of interest are taken. It means that we are selecting the electrodes that most reacts to a determined event.
4. From the remaining electrodes, in the interval of interest, the standard deviation of the potential is taken. The 20 electrodes with the lowest standard deviations are taken. The idea is the same to taking the lowest standard deviation in the derivation domain. But in this case, the electrodes with a similar profile over epochs, with means a consistent response to the event, are taken.
5. the 20 final electrodes are considered the most relevant electrodes to a determined region, therefore, the closer populations of neurons to these electrodes are the most relevant to the event.

The analysis based on the literature take directly the traditional electrodes: FCz, Fc1, Fc2, representing the frontal region of the brain, that is related to the planning of the task. The P1, P2, Pz, representing the parietal region, that is related to time dependent tasks. The O1, O2, Oz, representing the occipital region, that is related to the visual response to a stimulus. And the C1,C2,Cz, representing the central cortex, that is related to the motor response.

Finally, in order to generate a visualization to analyze this technique, a connections graph is generated using the Igraph package from python. The 30 strongest undirected connections between the traditional electrodes, or the 20 most related electrodes, are chosen. The imaginary correlations between each electrode and the remaining electrodes are taken, in order to analyzer if the activity around this electrode is related to the background activity. The length of the vertice representing an electrode is proportional to the background correlation strength. The vertices exhibited in red are the ones with a significant correlation, while the ones exhibited in green are the ones with a non-significant correlation.

To interpret the graph, each edge means a synchronization between the populations around each one of the electrodes participating in the connection. It means that these populations are working together. How much more central in the graph, it is, how much closer the electrode is printed to the center of the graph, more connections this electrode have. Meaning that this population is highly central on the processing of the task. The red electrodes can be sawed as a coordinator of the network, because they compute with a dependence of the background activity. It is, they depend on the activity of all the another populations in the network.

The coordinator electrode usually will be electrodes that represent populations that need to spread a lot of information, or receive information from multiple points. Demanding a high degree of synchronization with the entire network. Meaning that the use of the background information is highly important. Also, how bigger is the vertices representing the electrode, bigger is its dependence on the background activity, it is, the context.

As there were generated several figures, one subject was chosen to demonstrate how the analysis work, and to summarize the results obtained with the analysis. It is possible to perceive from all the figures that despite some sort of variation, the big majority of the subjects had a similar shape to the subject 18. All the other results can be found in the following link: [context dependent analysis](#). Therefore, we can use



the subject 18 to exemplify the responses to all the subjects.

The first visualization concerns the moment when a new target appears. The Brain response is therefore captured, and the spectral analysis is made for this time window, showing the most important correlations between electrodes for this time window.

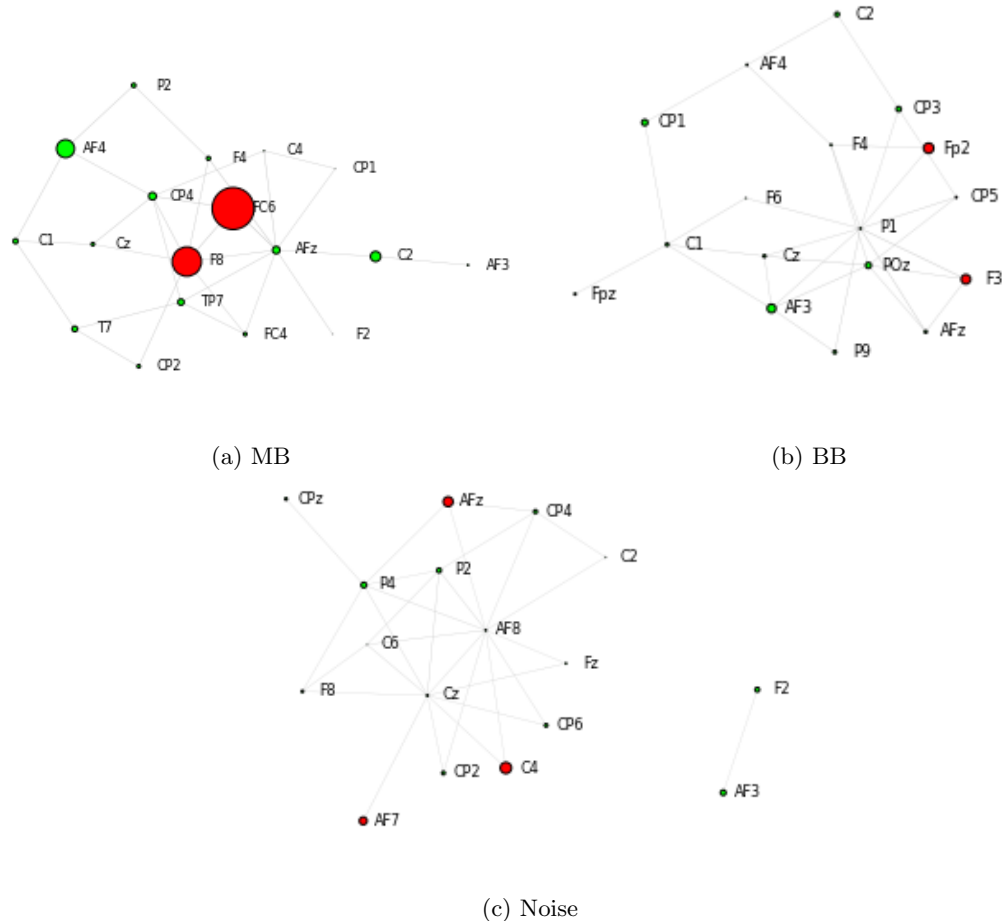


Figure 26: **Detected target epochs. Subject 18, time window: 0 to 0.5 seconds after the target appearance. Filtered electrodes.** The red electrodes indicate that the correlation of these electrodes with relation to the background activity is significant. It is possible to perceive that the frontal electrodes are the 'coordinators' of the networks for the three beats. We call them coordinators as they have a significant correlation with the network, indicating that they are using the background activity to their cognitive process, it also indicates that they can be involved in the influence of the rest of the network. Afz, Af7, F8, FC6, Fp2 and F3 are electrodes related to the frontal activity. We can perceive that for MB 26a the correlation with the network is stronger than for the other two beats. For MB 26a and Noise 26c the frontal electrodes (FC6, F8, Fp2, F3, AFz, Af7) are central on the network, meaning that they participate in more cognitive process than the average. While for BB 26b the parietal region is more central, but the frontal region also has some centrality.

Second, a visualization over the critical window was made, the two windows chosen can give an almost complete view of the brain response to the event. This time using the traditional electrodes.

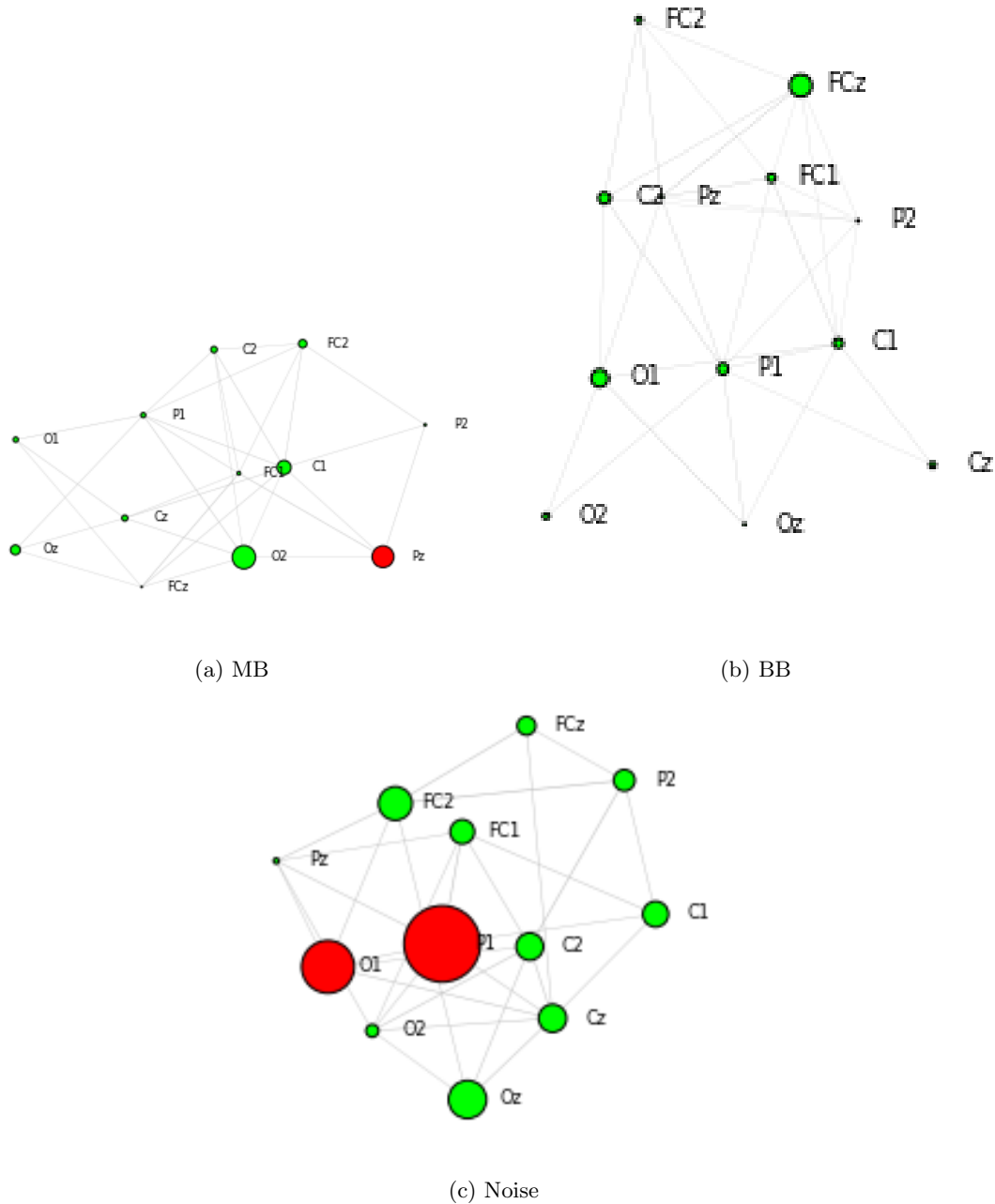


Figure 27: **Detected target epochs. Subject 18, analysis on the critical time window: 0.8 to 1.3 seconds after the target appearance. Traditional electrodes.** We can perceive that the parietal region can be considered the coordinator of this network, having a significant correlation concerning the relation to the background activity for MB 27a and Noise 27c. The Noise 27c also sounds to have the occipital region as a coordinator. Concerning the intensity of the correlations, it is stronger for the Noise 27c and weaker to the BB 27b. The BB do not have any important relation of coordinator, or it could not be captured. For the three beats the parietal (electrodes P1, Pz and/or P2) region is central in the network, meaning that it is involved with the cognitive process of more regions than the average in the network.

Finally, the omissions were studied by means of the missed target epochs, using the traditional electrodes the networks for the critical window were generated.

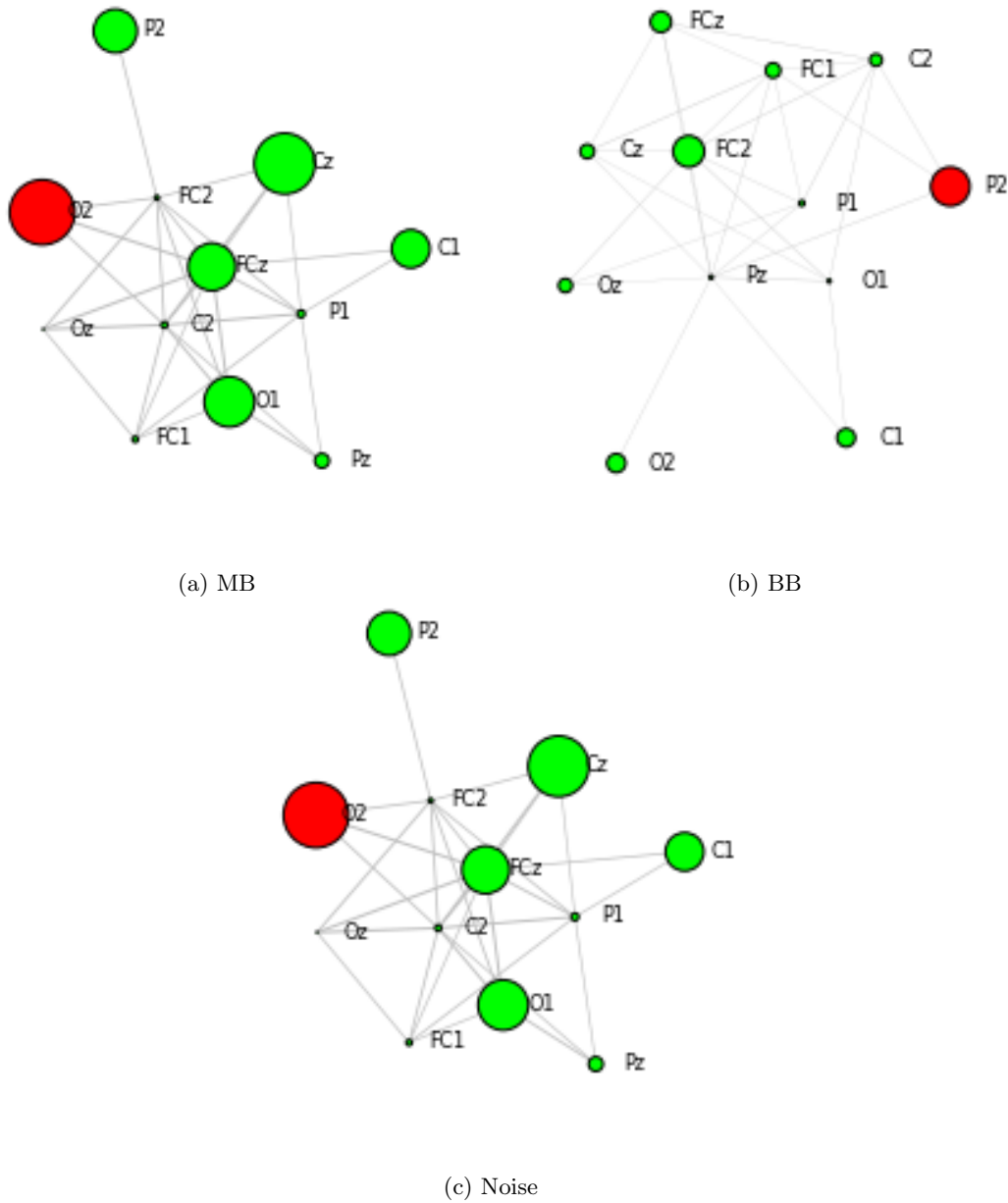


Figure 28: **Missed target epochs. Subject 18, analysis on the critical time window: 0.8 to 1.3 seconds after the target appearance. Traditional electrodes.** The occipital region have a significant correlation with the background activity for MB 28a and Noise 28c meaning that they are the coordinators of the network. While for BB 28b the parietal region is the significant region, being it the coordinator. We can perceive a high correlation for MB 28a and Noise 28c, and a lower correlation for BB 28b. The frontal region is central for the three signals, having FC1, FCz and/or FC2 as central electrodes on the network. It means that they have a higher number of connections with another electrodes, and are related to the cognitive process of more regions. Specifically for BB 28b, the parietal region is also central in the network, with the electrodes Pz and P1.

## 6 Discussion

### 6.1 Interpretation of the results

Concerning the behavioral results, we can say that Noise and MB have the fastest response times. While BB was worst in almost all grand-average measures. But concerning individual subjects, there is a big variability between results. This is the reason to having a high variability over the grand-average measures. In this section, these different results concerning the grand-average and individuals will be discussed, they will be related to the ERP responses, and explained by means of the context dependent analysis. Finally, the potential of neuromodulation for attention will be presented, and the paths to achieve this will be suggested.

#### 6.1.1 Beats effects on attention

with relation to the grand-average results. In the response time, For the control group, figure 10, MB has a lower response time, but there is no significant difference to Noise. While for inattentive group, Noise has a lower response time than BB and MB. BB has a lower response time with relation to MB, but they have no significant difference.

Taking into account the errors, Noise has the lower error in general for both groups, table 6. BB increases the error for both groups. And MB has a superior, but very close amount of errors with relation to Noise.

For BB the mean time without omission decreases for Inattentive subjects in figure 12b, but it augments for control subjects in figure 12a. Noise have the highest mean time without omission for both groups. While MB is better for inattentive group. Nevertheless, the pattern of omissions has no significant difference, therefore we cannot say that there are big differences between the conditions for this measure.

Concerning the signals with a higher intensity. MB has potential to improve attention, mean time without omissions is high with relation to another beats for inattentive subjects, as we can see in figure 11b. It means an improvement of attention for this condition, [Bal+14] and several authors recognize that a lower reaction times indicates an improvement in attention. But as we have lower amount of data, and a shorter duration for the experiment under this condition, it is hard to have a precise conclusion concerning this result.

The results for the mean time without omissions and the response time means that BB decreases attention for both groups. However, we perceive a significant improvement for BB with relation to MB with a higher intensity of the beat, in figure 11a.

For the inattentive group, the noise consistently had a better result. Having the lowest response time, the highest mean time without omissions and the lowest amount of errors. It indicates that the Noise is better to attention than the other two conditions for inattentive subjects, in the lowest intensity of the sound. This result is contradictory with the result for the conditions with a higher intensity, where the MB is the better condition. It indicates that the variation of the parameters can definitely affect how the conditions modulates attention.

It is important to see that for control subjects, when the intensity of the beat was lower, in figure 13, MB had a better performance concerning the mean time without omissions. It indicates again that the variation in the parameters of the conditions can change the results concerning attention.

We can show the variability of results with some examples. The control subject 22, figure 14a exemplifies a subject with an improvement in attention for the MB condition, having lower error and response time with relation to the other beats. The control subjects 28 in figure 14b and 17 in figure 15a exemplify subjects with a decrease in attention for the MB condition, having higher error and response time with relation to the other beats. The control subject 18 in figure 15b exemplifies a subject with a decrease in attention for the BB condition, having higher error and response time with relation to the other beats.

While the inattentive subjects 24 in figure 18a and 27 in figure 18b exemplifies subjects with a decrease in attention for BB and MB respectively. It demonstrates that the effects of the conditions can also vary over subjects. Having subjects with contradictory effects, as for example the subjects 22 and 17, that had respectively an improvement and a decrease in attention with MB.

Overall, the performance of control subjects is higher than the performance of the inattentive subjects. It was expected, as inattentive subjects are expected to have a lower performance on attention related tasks [Mir+20].

The contradictory results are in accord with the literature [Cha+15] [PDL20] [ACP21], where MB, BB, and Noise usually does not have a definitive consensus about their effects in attention. All these studies, and the study presented here, have in common the fact that they worked with static parameters for BB, MB, or Noise. We claim that this approach should change, as explained in the next sections.

### 6.1.2 ERP results and relation with behavioral data

For control subjects, for the correct responses, the frontal region has a stronger response peak for MB in figure 20a. Followed by an intermediary peak for MB, and a lower peak for BB. A stronger response in the frontal region indicates an improvement in attention, meaning that the frontal region is more engaged in the monitoring and planning of the task [OCo+09], these results are as expected from other CTET task experiments in the literature [OCo+09] [Chi+21]. It agrees with the behavioral results, as in the behavioral results we have a lower response time for monaural beats, followed by binaural, and noise in control subjects. It means that, apparently, for control subjects MB can improve attention, at least in the Response time measure. There were not taken statistical tests measures to identify if the difference is significant, because the number of examples is too low to make a statistical test.

For inattentive subjects, for the correct response, the frontal region has no differences between the peaks of MB and Noise, but has a much lower peak concerning the BB in figure 20b. It indicates that the response is very similar for MB and Noise conditions. While BB has a decreased planning and monitoring process. It agrees with the behavioral results, as Noise and MB conditions have a lower error and increased mean time without omission, with relation to BB.

The parietal region is related to the time dependent tasks and also, to the attentional process, [Doc+17] and [Gra+18] states that the parietal region is a receptor of the prefrontal control, having the mechanisms to consider time related tasks. It is, the parietal region counts the time, in order to identify time-dependent patterns. For the control subjects, in the parietal region, the response is as expected for the CTET task [OCo+09] [Chi+21]. We can see a stronger peak response for MB, followed by a very similar response for BB and Noise in figure 21a. It indicates that subjects over MB condition have a stronger attention, with relation to the other conditions. It also agrees partially with the behavioral results, where MB is better in the measure of response time for control subjects, as the parietal region is totally related to the time-dependent tasks. It indicates that MB can improve the velocity of response of the subjects, but not the error.

For inattentive subjects, the parietal region has a very similar response for MB and Noise in figure 21b. And a lower response for BB. It means that over the MB and Noise conditions, the attention is better than in the BB condition. It also agrees with the behavioral results, as the errors and mean time without omission were very similar for MB and Noise. The similar response in the parietal region, also exemplifies why the response time for MB in the inattentive subjects has not an improvement with relation to Noise.

For both groups, inattentive and control subjects the CNV response is very similar. MB has the strongest negative peak, followed by Noise and BB in figure 22, the responses shape is also the expected for the CTET task [OCo+09] [Chi+21]. It means that for both groups, the motor response is enhanced for MB. This result agrees with the behavioral data from control subjects, that had a lower response time for MB condition. Otherwise, for inattentive subjects, as there were a higher response time, it would be expected to have a lower CNV response. Nevertheless, the results for the mean time without omission and errors agrees

with the CNV ERPs. This result can indicate that MB has a potential to decrease the response time of a subject, and improve attention.

Comparing the control subjects with the inattentive subjects, we can see that all the peaks are lower for inattentive subjects, concerning each one of the regions studied. It was expected, as [Sha+15] states, ADHD subjects have lower peaks for Parietal, Frontal and CNV responses in attention related tasks. It means that inattentive subjects have a lower capacity to maintain the temporary networks activated, it is, they have a lower capacity to maintain themselves engaged in the CTET task.

The ERPs results should be taken in consideration with reservation, as the number of subjects were very low. Nevertheless, the results demonstrate that the three conditions can affect attention and are different one to another. Also, the results demonstrate that the subject and also the parameters of the conditions can dramatically affect what will be the final effect on attention. It is not clear what Beat is better to improve attention, but we can conclude that all the three beats have the capacity to change attention, and therefore have the potential to be neuromodulators.

The hypothesis is that a simple neuromodulation with static parameters will not be enough to improve attention for the generality of subjects. It is necessary to develop methods that adapt the parameters of each beat to each subject, in order to find what can work better to improve the attention of each subject. These parameters also change concerning ADHD and control subjects, but both groups could be benefited by such an approach.

### **6.1.3 Understanding the effects of the beats on the Brain and discussing the new analysis**

Analyzing the ERPs results, global effects can be sawed from the ERPs data, because the effects are the same in parietal, frontal and CNV regions of the brain. It is, the conditions or diminishes the intensity of the ERP for all the regions, or augments the intensity. Therefore, we can say that the beats have a global effect on the brain. This corroborates with the theory presented in the session 5.5.

The context-dependent connectivity analysis can help to understand how each beat affects the brain. Despite the fact that the analysis is presented just for the subject 28, all the another graphs can be found in the link presented in the results. The results for another subjects have a very similar profile to the subject 28. With some variations, but we consider that the response for subject 28 can illustrate the response for all the control subjects.

In the appearance window for correct targets figure 26, the MB has a stronger planning than the other two beats, because it has stronger frontal coordinators. It means that the frontal electrodes are more related to the background activity and have a higher capacity of synchronization. This is important to having a correct response, as it means that the response is more planned and is not reactive. For BB and MB the response is also more frontal, but the parietal region have a higher centrality to these beats. What means that the time dependent processing is very active at this window for these conditions. We can conclude that even with the occipital response to the stimulus, that is the region responsible to interpret the visual stimulus, the subject is focused, and is not surprised. It could indicate that, for control subjects, an improved planning generates lower response time, because MB had a lower response time for control groups concerning the behavioral data. Also, it can indicate that the Frontal region is important to coordinate a faster response of the Parietal region, as stated by [Doc+17]. The increase in synchronization by the centrality of parietal and frontal regions for MB was also detected by [PDL20], but the author also detected higher synchronization for BB, what is not the case for our results.

Concerning the critical time window for detected targets in figure 27, we can perceive a higher importance for the parietal and occipital regions for the three beats. It means that the time related parietal role is being highly activated, what is expected for this kind of experiment [Gra+18]. the parietal region coordinates the process of paying attention to the occipital region, in order to identify if the stimulus has the longer duration that is expected from a target [Gra+18]. The Noise have stronger higher parietal and occipital coordinators than the other two beats, meaning that it has some kind of improvement on the

response. The MB has a stronger parietal coordinator than BB, meaning that the parietal response with MB is enhanced with relation to BB. BB has no coordinators at all, it means that the subject under BB condition is having difficult to synchronize the brain regions, as necessary to accomplish the task. It can mean that an improved time related cognition is important to decrease the amount of errors, as Noise had the lowest amount of errors for control subjects. Therefore, a higher synchronized parietal region, in the critical window, is important to decrease the error rate, and therefore the attention. This result corroborates with the result from [Chi+21].

Concerning the critical window for missed targets in figure 28, we have stronger coordinators than in the case of a detected target in the occipital region for MB and Noise and in the parietal region for BB. For MB and Noise it indicates that the brain was not able to maintain the temporary network, it means, the planning in order to accomplish the task, having a higher reactive response relying on the visual stimulus from the occipital region and not in parietal region, what would be the expected in a functional network [Gra+18]. While the BB have a usual network, similar to when we have a correct response, what indicates that the process is not working well. It can mean that the BB are making harder to the brain to maintain the temporary network, or to execute the temporal task related to the experiment. While with MB and Noise, the brain must have achieved the limit for it sustained attention under these conditions when an omission happened. It is possible to hypothesize that for these conditions the brain is working with improved attention than in a neutral condition. But future experiments should be made in order to verify it.

There is an indication that the background activity have an important role, overall, in the activity of the regions studied. These regions are known by integrate information from several regions on the brain. Therefore, it is evident that these regions would have a higher dependency on the background activity. We can hypothesize that the theory holds for these regions, and the populations of neurons are adapting to the background activity by means of plasticity, in order to optimize their cognitive process. But we cannot say that the another regions do not have an influence from the background activity, even with non-significant correlations, because the measure is a limited approximation.

Differences between each beat could be found, and it is an indication that the beats can have a neuromodulation effect, But as saw in the connections graphs and behavior results, the brain process of attention is very dynamic, and maybe a simple static parameter is not enough to neuromodulate it, this dynamics will be highlighted in the session . Therefore, it is necessary to use a neurofeedback approach. It is an expected result, as the brain is a complex system involving plasticity. It means that each individual tends to adapt his brain networks in very specific ways, even if the global process is very similar. Also, the process of attention is a dynamical process, meaning that the pattern of provoked activations and change in the background activity should also be dynamical in order to be optimal.

The measures proposed can help to find the path to do this neuromodulation. In an experiment with neurofeedback, it is possible to identify the optimal network with which a subject can have the better performance, relating the network to the behavioral results. Following this process, an adaptation law able to change the parameters of BB, MB, or Noise could be found. The adaptation law should verify the distance of the current network, to the optimal network, and make changes on the beat in order to neuromodulate the optimal network. For example, making the brain of a ADHD subject work like a brain of control subjects.

The brain temporal regions, that are regions related to the auditory response, can also be investigated, maybe they would become coordinators of the network, after having a successful neuromodulation, what should be studied. The analysis can also help to identify in what process of cognition each beat interfere, it can help to propose new beats that combine the better characteristics of all the beats.

The new created method of analysis is therefore promissory, having an agreement with the results already obtained in the literature, and with the another results obtained in this research. They also support the theory proposed to explain the neuromodulation with MB, BB, and Noise that includes a new hypothesis about how the brain organizes its populations of neurons to perform cognitive tasks, basing part of it activation on the detectable background activities related to the context.

## 6.2 Theoretical discussion and hypothesis with descriptive model

Summarizing the literature and the hypothesis bank created, a theoretical discussion is made here. Culminating in a descriptive model created with the objective to describe how the BB or MB could affect the Brain.

### 6.2.1 Theoretical discussion and summary

The results presented previously are related to high populations of neurons. While they demonstrate how the beats could influence these big populations, they do not permit to understand the underlying mechanisms. Here we will discuss the possible underlying mechanism theoretically. These theoretical considerations allowed the construction of both the new analysis and the proposed theory. Also, they will support the next steps for the construction of a neuromodulation experiment.

We know intuitively that attention can be improved if we diminish the number of external stimulus. For example, when we aim to study, we search for a silent place to improve our concentration abilities. Furthermore, we can consider that all the time the brain maps the world and tries to predict the best recompenses. The attention, thus, emerges from the activation or not of determined areas, related to the predictions to maximize the recompenses, as explained in session 3.2 and 3.3, and it involves the neurotransmitter dopamine. As the neurons works with frequency in synapses, it could be necessary a certain kind of frequency to deactivate some areas, and the hypothesis is: The BB are able to create the necessary frequency to deactivate the neurons, and it leads the brain to concentrate more in the decided best recompense at the moment. This hypothesis can be found in the figure 31b. It would involve the cholinergic system, and the dynamics of Gaba neurotransmitters in iteration with dopamine dynamics.

The opposite could also work, as the brain needs to navigate between distinct areas and decide what information it will use, and what not, it needs to change its states from: Search, attention, store, and creation of information. For each new sensation information, the brain has to find with what previous knowledge this information is related. It is possible that the patterns of synapses, understood here as the “clock and message coordinator of the brain” govern the state of search, attention, store, and creation of information with an important participation of the gap junctions as saw in session 3.3. These patterns also could involve synchronization between different important regions, related to the realization of a task, that was previously trained to it with higher recompenses as state in session 3.3. By inducing a determined pattern of frequencies to synapses with BB, using the auditory localization system as in session 3.1, it is possible that the brain is induced to maximize the chance of the synchronization of gap junctions, and acetylcholine release increasing the importance of recompenses or making easier the synchronization. As, or the brain already use this frequency to do this cognitive process, or the signal complexity is simplified with help of BB. It would involve the dynamics of gap junctions, acetylcholine, and dopamine.

Therefore, by inducing the brain with a sound, the brain evaluation of what action it should take will be influenced. First, will be induced a search by the information most relevant, and following that, the brain will start to deactivate the less relevant areas arriving to a work state of attention, that have to be maintained. It is possible that the sound helps the brain to obtain that, by the entrainment effect saw in session 3.4, by causing in the brain the same frequency as the necessary to have the state of attention, what activate a rapid cascade effect about the other functions mentioned changing the context.

In other words, It could be possible that by inducing a right frequency of synapses into the brain, the neurons that are sensitive to be recruited in a determined context, will be more fast induced in this direction and the less sensitive neurons will be more quickly inhibited. The links between the neurons are enforced when they fire together as states the Hebbian learning rule [MP04], it means that it could be possible to generate a major level of synchronization, using a frequency that is already utilized to make the brain exchange messages between two regions. Curiously, the BB can generate frequencies into synapses using the localization system entrainment. This frequency is also involved in the mechanism of working memory, as saw in session 3.1.

Therefore, we can state a descriptive model where there are neurons, able to do synapses and



connected to another thousands of neurons. Each synapse have an adaptable clock related to message send and synchronization. The information is registered by amounts of neurotransmitters and ions in continuous parts of the neuron, and there is a predictive process: By the entrainment the neurons adjust predictions and link memories, in accord to the data received, including, having to learn time synchrony of the data depending on the task. The fast messages are directed with gap junctions and myelination. After this process, the synapse clock states could be used and selected to induces a state of sustained attention, related to specific synchronizations in synapses, induced by the mechanisms of recompense prediction, excitation and/or inhibition and context dependence.

All these behaviors can have some influence, but some or all of them could also do not have any influence. The descriptive model also demonstrates that the best synchronization signal that can be used in the BB could also depend on the task that is being performed, and the current state of the brain. Maybe would be better if it also changes autonomously in accord to these variables. It is necessary to study all these possible effects by means of simulations, response time experiments, capture of brain data, as it would lead to a better comprehension of the brain system, but also a more effective and reliable neuromodulation to sustained attention in humans. A big challenge to study this dynamics is the fact that the brain is highly coupled, so it is hard to isolate some of these possible causes, because they could work in the right way just when all of them are acting together, as it is context dependent. It leads to the necessity of less traditional methods, including new basis research in computational and mathematical fields.

### **6.2.2 Descriptive model**

Several factors can influence the firing rate of a neuron. These factors are called here context. the context is used in the brain to build the neuronal selectivity. An input, but also, the internal Brain states shape a context, influencing variables as the neurotransmitters, hormones, electromagnetic fields and so on. Each neuron becomes sensitive to a context, or a set of contexts. It means that a neuron just fires when a given context is achieved. Some of these factors are present in the figure 29. And this is a summary from what was discussed in the session 3 and in the theoretical discussion.

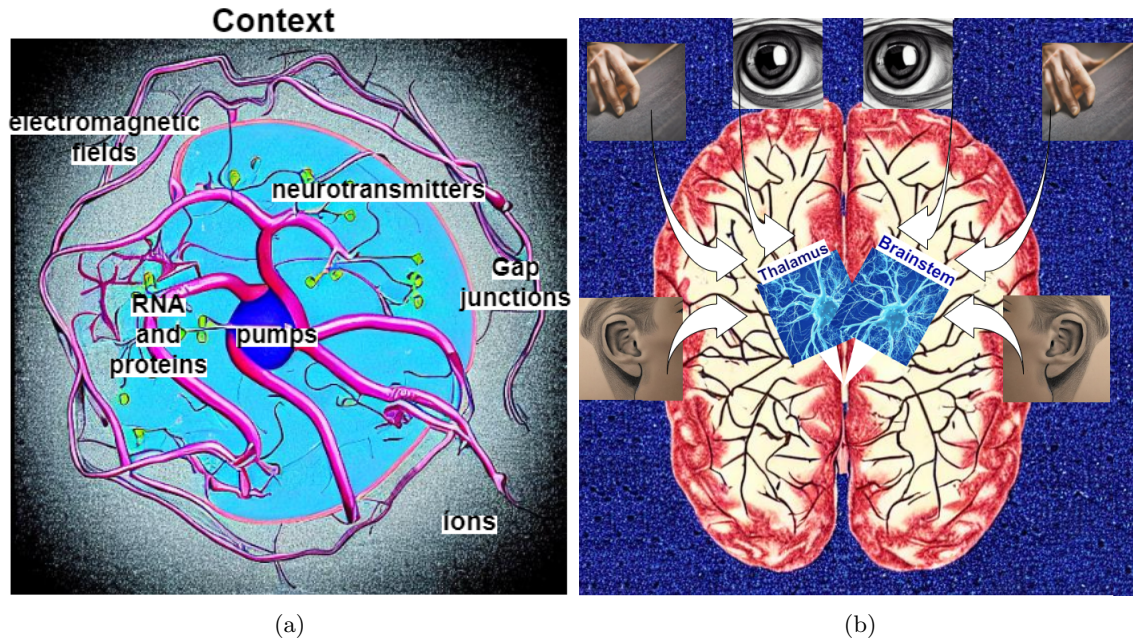


Figure 29: 29a In order to do computations, the neurons change their responses to the several factors in the context. These changes can (a) adjust the firing rate, (b) achieve synchronizations, (c) active a temporary network, (d) make abstractions (for example shape a concept of society using a set of persons) and (e) reinforce a determined decision. 29b The Brainstem and the Thalamus are the regions where the sensorial information is integrated and distributed in the Brain. The sensory input is carried to the Thalamus. Specifically to the auditory system, inputs are carried to the Brainstem region and after to the Thalamus. After arriving at the Thalamus, the input is spread in the Brain, and used to perform computations.

When the sound is listened, it is received and filtered by the cochlea. In the figure 30a The cochlea has specific regions that are sensitive to different ranges of frequency. The networks in the Brainstem responds tonotopically to the input, it means that the networks encode information based in the localization of the neurons. The cochlea in one ear listen the Beat. Each frequency region responds to the stimulus, creating a new context. This context generate two temporary networks, each one sensitive to the context of each signal.

In figure 30b One of the ears send inhibitory stimulus, another, excitatory. In the Brainstem, the two temporary networks created in each ear meet each other, generating a new context. It is known that the ears generate inhibitory stimulus that can be canceled with the excitatory stimulus from the other, as saw in session 3.1. The consequence, is the generation of a context that will provoke the firing rate to be equals to the difference between the two signals (entrainment). The difference is made in the meeting region between the two temporary networks, creating a third temporary networks that carries the signal to the Thalamus.

Therefore, in the figure 30d The MB have two signals difference, as the cochlea will respond to each frequency individually. By consequence, there will have two meeting regions, but both will have a firing rate of 15 Hz, as it was the one chose in the experiment. The MB activate the same effects as BB, but with two new temporary networks. It happens because now, we have two meetings between the two temporary networks generated in each ear.

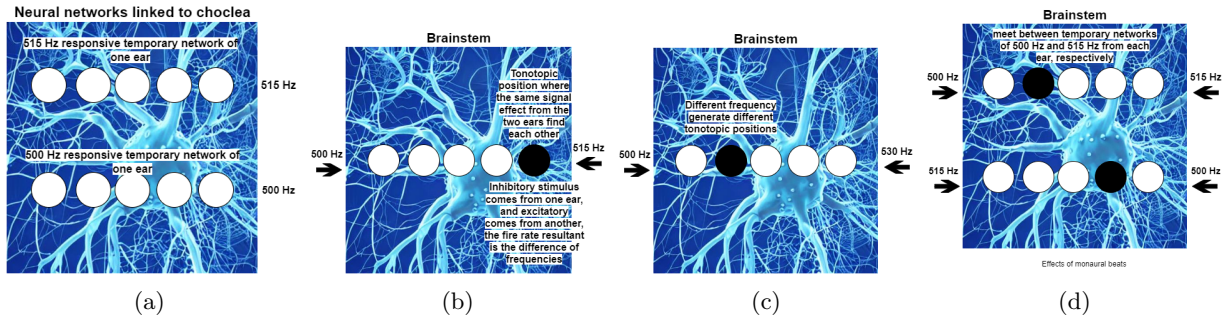


Figure 30: 30a The cochlea has specific regions that are sensitive to different ranges of frequency. The networks in the Brainstem responds tonotopically to the input. 30b BB send different signals to each ear. The signals find each other in a specific region, and a difference is made. 30c If the frequencies are different, also the neuron that will be activated and will perform the difference will be different. Another selective region to this context will be shape, and a different third temporary network will be created. 30d The MB have two signals difference, as the cochlea will respond to each frequency individually.

In the figure 31a The visual system and the motor system are activated during the experiment. A respective temporary network is activated and culminates in the creation of a temporary network of integration. The attention mechanism to what action performs, and what input is important, is related to the synchronization and frequency rate of the temporary networks. And it can work in specific ranges. A big temporary network integrates all the small temporary networks coming from the sensory inputs.

The cognitive function of attention is actively sending messages and influencing in the context of each temporary network, shaping the network to maximize the recompenses. It is known that the brain work at a  $\beta$  frequency rate when in a state of attention, as saw in session 3.4. The temporary networks are therefore maintained, making the neurons pulse in a determined firing rate with a selected context state, building the cognitive process of working memory, as saw in session 3.3. It does not mean that the context of each neuron changes, but that it changes selectively, using the mixed and single selectivity of the neurons and the Hebbian law [MP04].

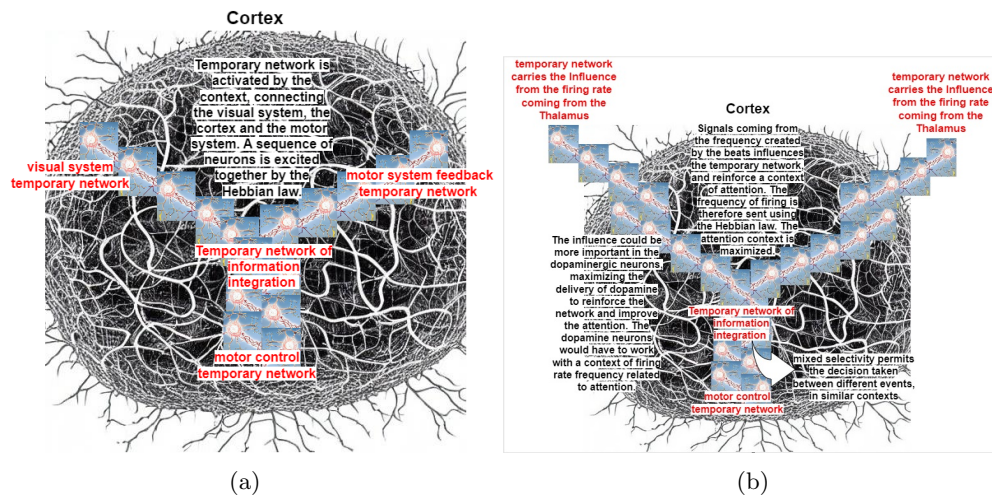


Figure 31: 31a During the experiment, a new context is generated. 31b The temporary networks carrying the difference between the signals from the Thalamus changes the context of the networks related to the task performed in the experiment. The mixed selectivity of the neurons involved is therefore changed because of the context change.

In the figure 31b When the beat is listened while the participant perform the experiment, a temporary network is added to the integration. the temporary network carries a firing rate coincident with the frequency rate of attention. This moves the context of the affected networks more closely to the context of attention. Therefore, the network has to do less effort to change the context to a context of attention, facilitating the mixed selectivity to happens and the creation of better and more stable connections, these concepts can be found in session 3.3. The connections are also enforced because the temporary networks augment the chance of neurons to fire together, as it sends the same signal to several regions [MP04]. The own neurons can adjust the delay and synchronization using the Hebbian law, the recompense and the inhibitory systems.

Therefore, there are several possible ways with that BB could neuromodulate the attention on the brain and influence the temporary networks. And it could be an effect of more than one of these reasons. There are another possible effects that have to be tested, and that are different from the proposed model.

## 7 Future work

This work opened new perspectives related to Brain Auditory Stimulation and neurosciences. therefore, the new proposed approach to analyze EEG data should be improved and combined with the behavioral data in order to create neurofeedback experiments.

These neurofeedback experiments will have the focus to dynamically find the best parameters to improve attention. Using the potential of the beats in changing the attention of subjects. As it was hypothesized that just a dynamical process of neurostimulation can improve attention with confidence to a big group of subjects, the next experiment should focus on proving this hypothesis.

The new approach together with the new theory can help to improve the understanding about the brain cognition, and therefore about how to neuromodulate it. These approaches should be developed in order to create a promissory treatment for ADHD individuals, or even, to boost cognitive process of control subjects.

## 8 Conclusion

The results concerning what signal was better to improve attention were not clear. BB clearly was worst for attention, while MB and Noise had very similar results. All the signals had a high variability of results profile concerning different subjects. While MB improves the monitoring of frontal region, Noise improves the time control of parietal region. BB difficult the work of both, the monitoring and time control in the conditions of this experiment.

Despite the fact that the BB did not have the expected result in attention, it is clear that the three beats can change attention mechanisms for control or ADHD groups. Several hypotheses about how the attention mechanism can be affected by the beats were found, and a generalist model was presented about it. The new model and analysis presents a new direction for neuroscience and Auditory Brain Stimulation. We claim that the divergent results obtained in the literature and in this experiment, are due to the brain plasticity, and the high dynamic process of attention. Therefore, despite the potential of the beats in changing attention, in order to make these changes positive, it is necessary to create a neurofeedback experiment, with more dynamical conditions. This new neurofeedback experiment can be made using a combination between the context-dependent analysis, and the behavioral data. these beats have the potential as a new treatment for ADHD individuals, with the capacity to improve their sustained attention.

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## A Behavioral results for all remaining subjects

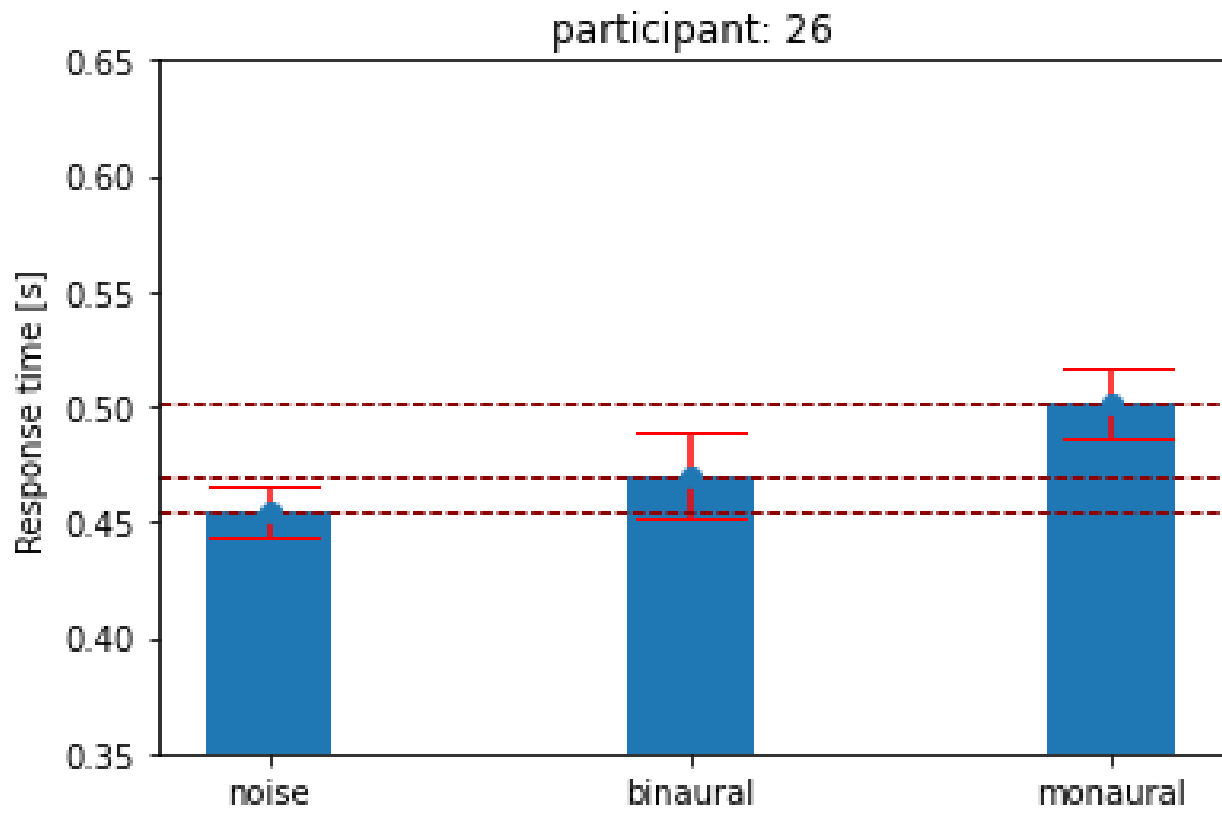


Figure 32: . \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$



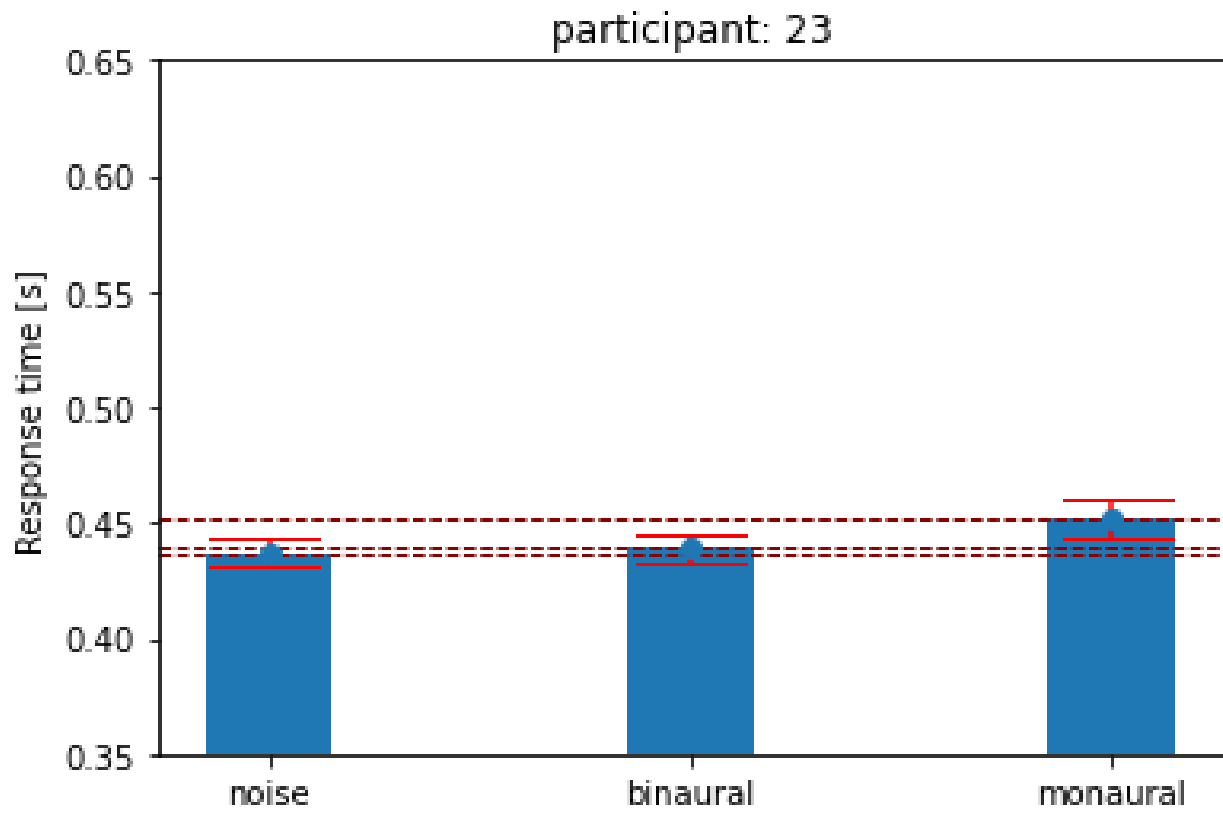


Figure 33: . \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

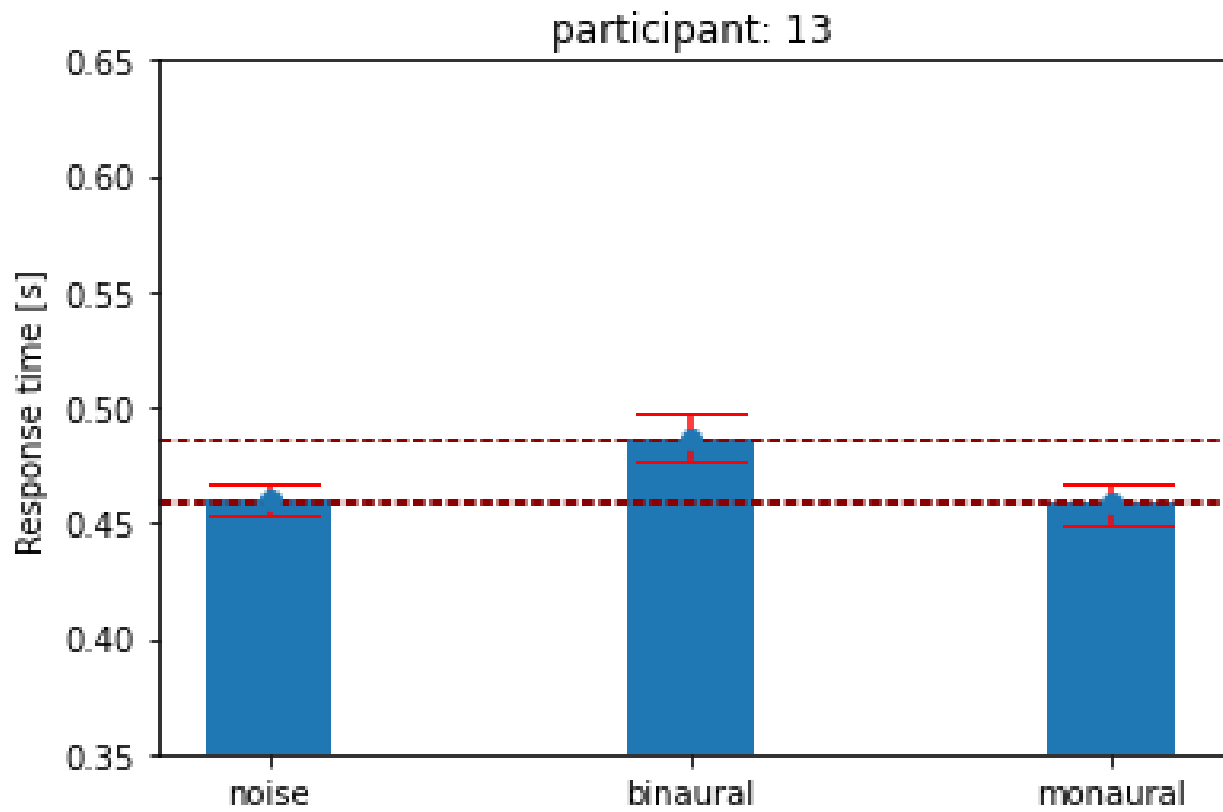


Figure 34: . \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

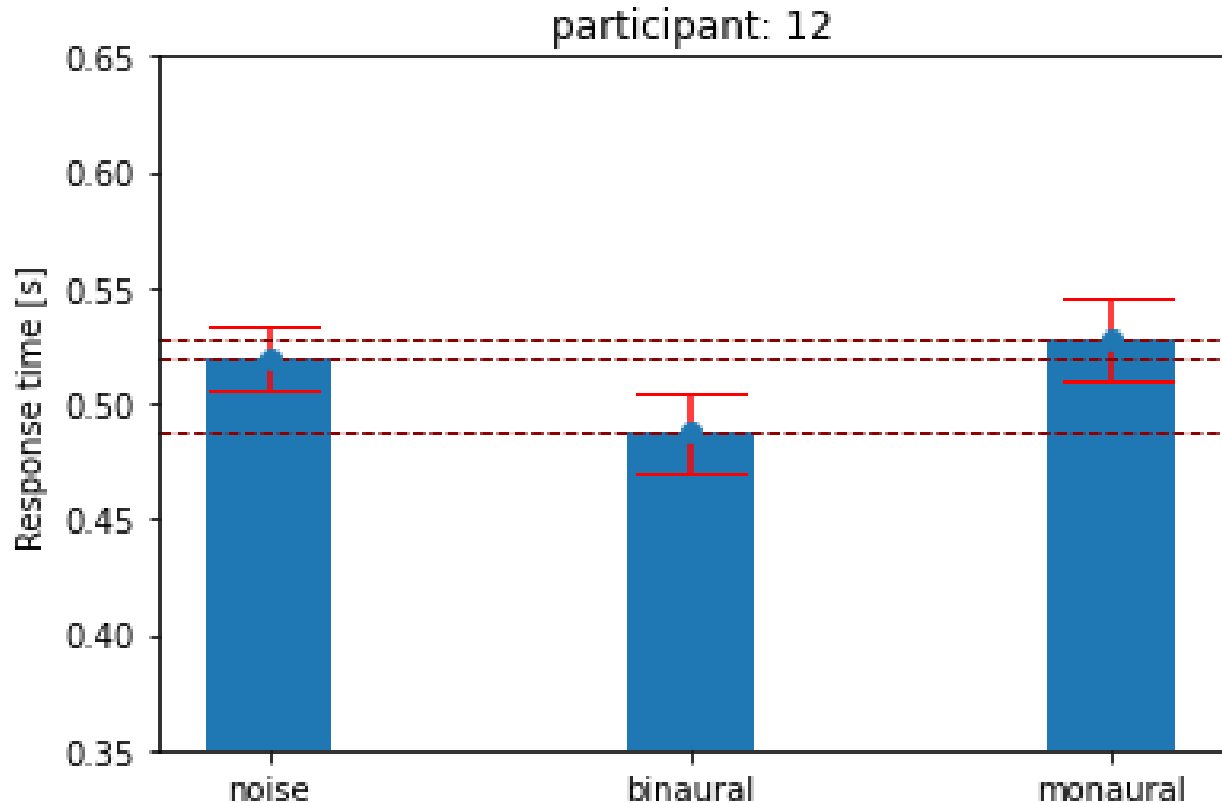


Figure 35: . \*\*\*:  $p\_value < 0.001$ , \*\*:  $p\_value < 0.01$ , \*:  $p\_value < 0.05$

## B Theoretical models of the Brain

To try to understand the behavior of the brain and interpret the results, it is necessary to understand the theoretical models of the brain. For each model, some sort of interpretations could be different, including for the response time. The Neural coding theory proposes that information is encoded in the patterns of activity of individual neurons or groups of neurons [Sha14]. The Synaptic theory proposes that information is represented in the strengths of synapses between neurons [Fus+00].

The connectionism theory proposes that information is represented in the patterns of connections between neurons. It suggests that the brain is composed of many simple processing units (neurons) that are connected to each other, constructing a bigger network [Bes+17]. The Neuronal Group Selection theory states that the brain represents information in populations of neurons. It suggests that the activity of a population of neurons, rather than individual neurons, encodes information [Ede87].

The theory of relativistic brain considers the brain as a continuous computer. The neurons process bits of Godel and bits of Shannon. It means that the neurons combine and process continuous information (bits of Godel) that makes its memories (the neurotransmitters, the ions, the electrical fields and so on) and with the all-or-non characteristics of the synapses process discrete information (bits of Shannon). The brain is a general machine of predicts the future, given a context. It means that the brain is not deterministic, and to each decision, depending on the high volatile conditions in the brain at any moment (the context), different neurons will be recruited to a computation [CN15].

These ideas are also related to the hyperdimensional computing theory [TDR21] that tries to explain how information could be split in big multivectorial spaces and retrieved from these spaces. This

theory claims that the neurons acts as hypervectors, able to represent information, splinting it in several axes. Mathematical models have been developed to explain how it could work, and is a valuable tool to understand aspects of the Brain.

Computation through neural population dynamics [Vya+20] is a theory that successfully explain how neural populations could represent information and take decisions. The theory is particularly important to understand the concept of temporary network. It states that the networks organizes orthogonal spaces, representing information and creating specific regions where the information can be treated linearly. The mission of the network is therefore to shape the orthogonal spaces, and oscillations of the network in order to improve his performance. This happens with the formation of recursive connections and selective neurons, that organizes themselves to shape the orthogonal spaces, create “objects” and “regions” able to split the information, store memories and take decisions.

Some theoretical models could lead to an interpretation that the response time will tends to a constant, and others that the response time will ever change. We do not consider any of the models as truth, but we consider that the characteristics of connectivity of the brain make it more probably that the response time would not tend to a constant. It means that the process of attention and learning will generate do not one, but several paths into the brain in each context. This makes the response time to a given task changes slightly at each time, because the brain state changed, and means that the improvement of the response time means an improvement on the quality of the connections on the brain, and therefore the improvement on the mixed selectivity, given several path possibilities to a same problem. This interpretation was used in this work to analyze the response time.

## C Questions and hypothesis bank

### C.1 Questions

#### Sustained attention experimental paradigm

**Question 1:** How do other authors define the response time ?

**Question 2:** How can this paradigm be modified ?

**Question 3:** How it has been applied to detect which effect ?

**Question 4:** Has there been various studies on attention-deficit subjects ?

**Question 5:** What has been the difference in these studies, what did they find ?

#### Loudness

**Question 6:** What is the biophysical side of loudness?

**Question 7:** What is the software implementation side of loudness?

**Question 8:** How to control the loudness level in a signal, i.e. how to normalize it to a certain level, and how to check the loudness in practice, i.e. in real-life experiments?

**Question 9:** How can we adapt the loudness to each subject and choose her/his optimal level (what is optimal) ?

**Question 10:** What does the literature say on the choice of loudness ?

**Question 17:** The intensity can affect the localization system of the brain, but how it can affect the neurons itself, and it can have consequences for attention?

**Question 18:** Can the ideal loudness level be harmful to hearing?

**BB**

**Question 11:** How do the cognitive processes of learning work? What of them are related to the BB?

**Question 12:** How to change the brain with BB in a way that the brain could gain or lose behaviors, and have a persistent cognitive improvement?

**Question 18:** The deep learning could be used to adjust, personalize, and find the best parameters to maximize the performance of each subject?

**Brain mechanics Simulation**

**Question 13:** How to simulate the brain mechanisms and understand the Brain dynamics using spike neural networks?

**Question 14:** How to use these simulations to understand the BB effects into the brain?

**Question 15:** How to relate the simulations to the experiments data and phenomena?

**Question 16:** How to use simulations to discover new techniques of neuromodulation with sounds?

**Brain mechanics Attention**

**Question 17:** How do the neurotransmitters works in attentions? And in cases of attention-deficit hyperactivity disorder (ADHD)? Specifically to these most related with the auditory system (serotonin, cholinergic system and so on).

**EEG**

**Question 19:** How to test with EEG and sets of neurons the hypothesis we created?

**Question 19.1:** How the neural activity affects the EEG? How the temporary networks of neurons affects the EEG?

**Question 20:** How to measure the stead-state of the sound and the experiment with the EEG? Separately? What are the expected results?

**Memory**

**Question 25:** How the BB affects the Brain plasticity?

**Question 26:** For how long time the BB affects the Brain plasticity?

**Question 27:** Is it possible to improve permanently the attention using BB?

**Protocol**

**Question 21:** How to variate the order of presentation of the beats between experiments, in a way that the Brain learning of each one don't affect the other?

**Question 22:** How to create the protocol to answer the selected hypothesis and questions made?

**Question 23:** How to consider and test the intensity of the beats into the protocol?

**Question 24:** How to include the EEG into the protocol?

## C.2 Hypotheses

### Loudness

**Hypothesis 1:** How much more inputs the brain have, more synapses it will produce. If there is a patterned sound, with periodic signal, that brain can adapt and do not take its attention. Hence, that would be sufficient to improve attention, as the increase of stimulus into two sides of the brain can improve attention with the induced increase of synapses, maximizing the chance of a temporary network to be created.

**Hypothesis 2:** The beat intensity effect into the brain is directly related to the mechanism of sound localization, where the intensity is differentiated into the brain. How bigger the intensity, bigger is the effect into the neuroplasticity, but also bigger is the chance of the sound to take the brain attention. Therefore, maximizing the intensity of the sound to the limit where it does not take brain attention from the task itself, would be the most effective beat to improve attention.

**Hypothesis 3:** The steady-state increase the capacity of the brain into do not pay attention to the beats as the brain is already used to its stimulus. Therefore, training the subject to arrive to the steady-state is a good tool to maximize the maximal intensity of the sound that do not take brain attention. It is, the steady-state could change the optimal intensity to be used into the beat, as the user will be used to it.

**Hypothesis 15:** The steady-state could make the brain ignore the Binaural beat. Therefore, diminishing the effects of its neuromodulation. A way to solve this problem, would be to continuously randomly change the loudness, as it would impossibility a total steady-state to the beat. As this, a deep learning could discover what is the better way to change the intensity, so that the effects would be maximized.

### Binaural Beats effects

**Hypothesis 4:** The neurons do sustained firing to generate the temporary networks, doing the synchronization between brain regions. The mean sustained firing of the neurons is directly related to the frequency states of the brain. The frequency states of the brain are coded levels of sustained firing that are each one converged to sustain a certain kind of behavior and brain state, as, for example, attention. The BB can increase, with the Lateral Superior Olive (LSO) localization, the sustained firing of neurons in any frequency, thus maximizing the chance of the brain to be into this frequency state.

**Hypothesis 5:** A context into the brain is the characteristic of the input, the mean concentration of electromagnetic fields, neurotransmitters, ions, and frequency fire rate. There are global context, as the electromagnetic field and blood, and local context as the inside's neurons ions, RNA, and neurotransmitters. Neurons that fire together learn to generate temporary networks by context, making synchronizations between regions according to the context. These synchronizations and networks are enforced by recompense mechanisms directed by kinds of neurotransmitters. Reinforcement involves the activations and reinforcement of temporary networks and neuron activations in detriment of another possible temporary networks and neurons, and therefore lies behind the mechanisms of attention. Hence, high levels of synchronization, induced or not, liberate high level of reinforcement. Therefore, the induced firing of hypothesis 4, directed to several brain regions, as the thalamus, visual system, and cortex, induce a fire rate context, that provokes the formation of temporary networks that were reinforced into this fire rate context. What, by consequence, induce the context synchronization.

**Hypothesis 5.1:** The sustained firing of the Neurons is mediated by the ACh neurotransmitter. It means that the neuron is leading with a known sound. By addition, each pattern of sustained firing can elicit the liberation of serotonin or dopamine, and it is responsible to construct more complex temporary networks, firstly in the cortex, participating into more complex, general or superior cognitive processes.

**Hypothesis 6:** The Hypothesis 5.1 involves the cholinergic system, and the dynamics of Gaba neurotransmitters in interaction with dopamine dynamics. The gap junctions also play an important role into the brain synchronization.

**Hypothesis 7:** We know intuitively that attention can be improved if we diminish the number of external stimulus. For example, when we aim to study, we search for a silent place to improve our concentration abilities. BB can simplify the signals inside the brain, and this simplification can help the own brain to select a stimulus, improving attention.

**Hypothesis 8:** The hypothesis 5 mechanism also induces the context of firing deactivation of the regions do not related to the task.

**Hypothesis 9:** In order to learn something, the brain is induced to maximizes the chance of the synchronization of gap junctions, and acetylcholine release in a determined context. Increasing the importance of recompenses related to some task, or making easier the synchronization between regions. Creating a network responsible to solve this task. The BB could provoke a context of firing of a determined task or brain state, by inducing determined frequency in the localization system. As, or the brain already use this frequency to do this cognitive process, or the signal complexity is simplified with help of BB, making it easier. It would involve the dynamics of gap junctions, acetylcholine, and dopamine.

**Hypothesis 10:** Therefore, by inducing the brain with a sound, the brain evaluation of what action it should take will be influenced. First, will be induced a search by the information most relevant, and following that, the brain will start to deactivate the less relevant areas arriving to a work state of attention, that have to be maintained. It happens because, as the hypothesis 9 states, the Brain maximizes the chance of determined neurons to be activated into the context of a specific task or cognitive process. The sound helps the brain to obtain that, by the entrainment effect, by causing in the brain the same frequency as the necessary to have the state of attention, what activate a rapid cascade effect about the other functions mentioned.

**Hypothesis 11:** Involves all previous hypothesis, is a general explanation of the phenomena (descriptive model): there are neurons, able to do synapses and connected to another thousands of neurons. Each synapse have an adaptable clock related to message send and synchronization, by the patterns of sustained firing. The information is registered by amounts of neurotransmitters, second messengers and ions in continuous parts of the neuron, and there is a predictive process: By the entrainment the neurons adjust predictions and link memories, in accord to the data received learning his pattern and specializing neurons to solve this task, including, having to learn time synchrony of the data depending on the task. The specialized neurons shape a temporary network all the times the task is performed. But as it is just a maximization, the temporary networks generated each time the task is performed are not equals but respect some constraints at each activation. The fast messages are directed with gap junctions and myelinization, accelerating the recruiting of the specialized neurons. The brain also learns to ignore or not a signal by means of the recompenses. If the task leads to a higher recompense the brain reinforces the temporary network responsible for it, if not, the brain ignores the stimulus and diminishes the temporary network. All by changing the tendency of response of individual neurons into a given context. After this process, the synapse clock states created by the brain could be used and selected by BB to induces a state of sustained attention, related to specific synchronizations in synapses, induced by the mechanisms of recompense prediction, excitation and/or inhibition. It happens because the BB induce a strongest context related to the state of attention. It maximizes the chance of activation of neurons related to attention and diminishes the chance of activation of neurons related to others conscious states. Therefore, increasing the temporary network responsible to sustain attention.

**Hypothesis 12:** The descriptive model also demonstrates that the best synchronization signal that can be used in the BB also depend on the task that is being performed, and the current state of the brain.

### **Learning and Binaural Beats effects**

**Hypothesis 13:** The repetitive effect of BB into the reinforcement of synchronizations and connections, during one task, can lead the brain to learn to reinforce even more these connections, persistently improving attention for this only task with the time.

**Hypothesis 14:** The repetitive use of BB during several tasks along the time, can create several paths and connections into the brain with strong tendency to sustained attention, leading the Brain to a general improvement into the sustained attention capacity. It happens because naturally, if neurons acts together into a temporary network, they will have their chance of activation being increased into the context of this temporary network. Therefore, each temporary network of the brain will have a tendency to maintain itself more stable.

**Hypothesis 15:** The effects of BB just happens after reach the steady-state. It happens because while the Brain did not reach the steady-state it tends to ignore the signal, and do not include it into the temporary networks. But after reach the steady-state, paths are made in the Brain, meaning the signal will influence someway the inhibition or reinforcement in the Brain.

**Hypothesis 16:** The effects of BB are just concerning attention taking. The addition of a sound, make more hard to the Brain to pay attention in some task while listening to BB.

**Hypothesis 17:** The MB has the two different signals in each ear, one of each kind. But the literature says that the auditory system is able to separate the stimulus of each ear, in matters of frequency. It means that the auditory system is able to split the frequency components of the beats presented for each ear inside the brain, and work separately with both the signals. It would mean that the same effect in the localization system that could happen with BB also can happen with MB. As the component would be separated in both the ears, and will be crossed inside the Brain, evoking the mechanism of localization that does the difference between the signals of both ears.

**Hypothesis 18:** the MB could elicit the effects of local differences of frequencies. As the two components for each ear have also a 15 Hz frequency difference. It means that the MB can entrain the Brain frequency with one more mechanism than the BB, and in two directions (the lower – higher frequency relation will come from both ears directions, while in the Binaural it will come just in one direction). It would mean that the MB cannot be considered totally different from MB, but could also be considered a special case.

**Hypothesis 19:** Summing several MB with 15hz difference frequencies, with distant different carrier frequencies (for example, more than 100Hz of distance between the carrier frequency of each Monaural beat). Would improve the effects in attention using the same mechanism mentioned in hypothesis 18, but multiplied by the number of MB presented.

### C.3 Possible future work for testing the hypothesis

**Hypothesis 4 Test:** Verify the Loudness dependency of the auditory evoked potentials (LDAEP) with EEG. Verify the frequency and intensity of activation into the LSO system, looking if it really has an entrainment with the frequency chose into the BB signals. It would be made analyzing the EEG points more close to the LSO. Also, the cholinergic system and recompense systems could be investigated, to see if there are a major activation of them, what could be good or not to the neuromodulation.

**Hypothesis 5,5.1, and 6 tests:** Firstly investigate the synchronization in the base conditions between regions thought to be related to the task: Visual system, motor system and auditory system. In this phase, the technique of mixed selectivity could be used to verify the role of each region, and also to verify if there is an increase in synchronization. How much more the neuron networks in the Brain responds together to certain stimulus, more it means that there are a certain synchronization. The mixed selectivity could help to analyze this and another questions.

In the beat condition, verify if the increasing of activity into the auditory system is provoking an increase into the synchronization of the brain into the same task. The check could be made in two ways: Doing a difference between the intensity map of the two states, and looking at the expected dynamics.

Do a graph analysis, creating power relations between the nodes of the EEG, as how much more



they play together. Also, using mixed selectivity, different kinds of node relations can be created. Therefore, we should check the evolution of the connections both into the learning phase and in the analysis phase. It would be expected more strong links between the nodes related to the task, and the auditory system. And, less strong links between the nodes that do not have any relation to the task. It means that the auditory system would synchronize with the Visual and Motor Systems, provoking with the time a best synchronization between both of them. As stated in the hypothesis, the sustained firing (attractive network) provoked into both systems by the auditory system, would elicit a synchronization between them, because it maximizes the chance of the neurons “fire together” between the two regions.

To explain how the dynamics of the own neurotransmitters and unities work, descriptive models of the neurons and small simulations could be made into the future. A small model to this case would consist into a network with the shapes of the auditory system, the visual system and the motor system. Each neuron will have neurotransmitters representing reinforcement, excitation, inhibition and sustained firing. The objective would be to show that, the entrainment of the auditory part of the network with a sinusoidal input, could elicit synchronization between the motor and the visual part of the network, by inducing sustained firing in the two regions and a coupling by context of fires (it means, if they fire together, they synchronize).

**Hypothesis 13 and 14 tests:** The change in the order of presentation between a half of the group of participants, and the 2-week interval between the two experiments will permit to verify if the results consistently improve between each internal session (order of presentation in one experiment) and external session (separated experiments). If there is a strong permanent effect, it would be perceived comparing the experimental results between each order of presentation. If the BB have a permanent effect, so the participants who saw BB before the phase with MB will have a better performance to that who saw MB first. At the same time, if the effect is durable, on the next week all the participants will have a better result. The same comparison between the two groups could be made. Into the EEG data, we could compare the map of intensities between target regions and do the difference between the two days, with the own participant data. Also, the intensities in the two days with each sound could be investigated, and a difference could be made. Into the graph, the same analysis holds, considering the analysis of the weight between the links of each node.

## D Explanations about mixed selectivity

The mixed selectivity is a concept used to measure the region of attractiveness of a neuron. It is known that the neurons answers selectively to a given stimulus/context. Given determined input, for example, the image of a cat, there are specific neurons that will be activated inside the brain to respond to this stimulus. We say that this stimulus falls in the attraction region of this neuron.

Now, considers that we have an experiment with different stimulus as for example four images. In order to measure the selectivity of a neuron or a network of neurons, we can create a vector to this neuron:

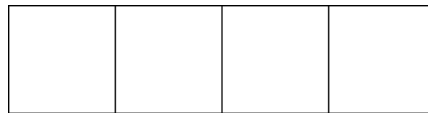


Figure 36: Selectivity vector of a neuron or a network of neurons. Each space of the vector represents one input image.

If during the experiment this neuron fires, or the activity of a network of neurons surpasses a determined threshold, it means that the network is therefore selective to this kind of input. When it happens, we add one to the respective variable space of the input. In our example, we have four variables, the four images.

We have therefore the concept of single selectivity:

50			
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Figure 37: Example of a neuron or network with single selectivity. The neuron just fires when in front of one single stimulus. Or, the network is just sensitive to one stimulus.

And the concept of mixed selectivity:

453	323		32
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Figure 38: Example of a neuron or network with mixed selectivity. The neuron fires when in front of many stimulus. Or, the network is sensitive to many stimulus.

The sensory neurons, that carries information from the sensory inputs, have normally single or small selectivity. While, the neurons participating in complex cognitive process have normally a high level of mixed selectivity. This is thought to happen because the sensory neurons abstract the information about a single stimulus, in order to facilitate the interpretation of the most important features of this single stimulus. The superior process, integrate information from many stimulus and regions to take more complex decisions.

The concept can also be changed to consider the time of the firing rates. And can be used to create graphs in EEG analysis. The objective would be to track behaviors from networks of neurons.

The concept of mixed selectivity is important to understand the concept of temporary network. When a stimulus comes, as the neurons are selective to the stimulus, a temporary network will be shaped, with the neurons that are selective to a determined input. This process is thought to be important to specialize the network and clustering the information.

The working memory is also involved in this concept. In order to maintain an information active, the neurons have to sustain the firing. It is called sustained firing. As the neurons are selective to the information, it means that they carry the information and representation of a determined concept. In order to access or maintain a planning, the neurons could be induced to maintain a sustained firing. The neurons doing the sustained firing are these who shapes the working memory, as they define what information will be used by the brain to take decisions. Also, they store the planning made by the Brain concerning a task and their information is correctly synchronized with the actions and inputs, to the organism be able to acts in the correct moment.

These process is not related to the process of a traditional computer machine. They have a different working, that here is assumed to be related to the context changing and manipulation.

These explanations are the understanding and contributions of the author with relation to the literature mentioned in the literature review 3. And inspired the construction of the descriptive model in the session 6.

## E Better explanation about context selection

The Brain dynamics is made from several components. The neurons have several components that have plasticity. It means that they can change with the time, accordingly with what happens to them. In this

work, the concept of context is used as a possible explanation to the neural selectivity. It means that the neurons learns to be sensitive to a determined context, and therefore the neurons are clustered by context.

Everything starts with the own input, that have his own manifestation as a unique pattern. For example, a chair and a car will ever manifest a different effect and patterns of activations in the sensorial response of the Visual system, in the time and in the space. These manifestations create a context inside the Brain, because a different pattern in the sensorial firing, will create different amounts of substances in the brain, and in the networks touched by these changes.

In the neuronal structure there are pumps, ion channels and synapses. And there are action potentials with determined thresholds inside each neuron. Each one of these components is affected by plasticity in several ways, and this plasticity depends on the amount of neurotransmitters, ions, RNA, and hormones inside and outside the neuron, figure 39.

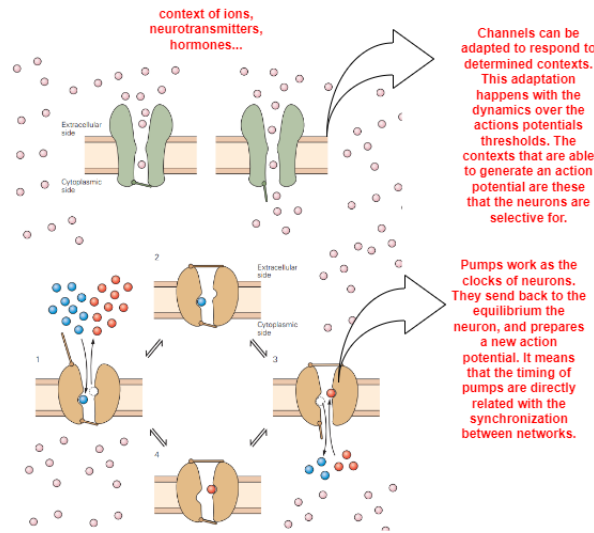


Figure 39: The ion channels and ion pumps can be changed by neural plasticity. Diminishing the excitability of a neuron to a determined context with some kind of neurotransmitter is sufficient to change its attractiveness to the context related to this input. In the other sense, augmenting his excitability is enough to augment its attractiveness to the input context. This image was adapted from [Kan+00] work.

Therefore, temporary networks are made with the right synchronization in determined contexts, mediated by the reinforcement learning. It means, when a recompense is achieved a context is considered important, and the selectivity of the neurons are increased to this determined context.

What could happen with a neuromodulator, as for example BB, is that it is responsible to facilitate the reinforcement of contexts. For example, when it is necessary to make some kind of synchronization between regions a constant generated signal that maintain active determined neurons, in a regular pattern, is a good context to be shaped with the reinforcements.

This is, if there are a set of neurons actives and capturing information related to a context that was activated by:

- an input, for example, the trial response of the visual system.
- a decision, for example, the decision that the trial is not a target.
- an action, for example, the action to maintain the attention to the trials and not press the button t.

Thus, these neurons can be shaped by the neuromodulator. It means that the neurons affected by the neuromodulator, can make easier the synchronization between regions because they supply a simple patterned synchrony between these regions. Making the final temporary network better and more stable.

The own process of formation of the brain network can be thought by means of the context selectivity. It means that the Brain is constantly clustering neurons to specialize decisions and behaviors. These networks can have been shaped by evolution, but firstly, by the process of learning during the life. The own context a neuron manifests to an input without have ever had contact with the input before can be used to represent this input when in contact with it. Economizing a lot of energy with relation to build representations. With the time, the Brain should just improve these representations in order to maximize recompenses.

These are interpretations and contributions from the author about the literature review 3.

## F Computational Model demonstration

### F.1 Introduction

The neurons respond selectively to determined inputs, what means that they are just activated to a determined input. Also, a neuron can be selective for a variety of inputs and situations, what is called mixed selectivity [Rig+13]. When a neuron is selective to a determined context, it can have a sustained firing, sending for a longer period of time information to the network [Wan+13]. Regions of the Brain can send neurotransmitters as dopamine and hormones to another brain regions, and modify computational properties of the networks affected [ON19].

The concept of selectivity is also related to manifolds and orthogonal spaces. The neurons have specific mathematical spaces where they can respond to determined phenomena given a determined manifold specific to each neuron [Vya+20] [JA17]. This characteristic would be important to present a more global specific computations to determined context in neural networks. It means, that sub-networks of neurons would shape clusters in the Brain, or temporary networks, that are specialized to do computations in a specific context, being these networks supported by the neural selectivity and manifolds. The mechanisms of selectivity and clustering can be related to the synapses, dendrites, and topological connections of the network [Kas+15] [LB19][LN08].

In a higher abstraction level, the clustering of the neurons can emerge from network interactions between inhibition and excitation [Che+12], a combination between network growth and self activity [Kle+11] and a complex interaction between several levels of abstraction in the brain [SV21]. [SV21] also proposes a new concept of active milieu, there is all the particles, neurons, glial cells and another components actives in a determined moment for a determined computation in the Brain. Concepts of volume computation, local synapses, astrocytes interactions are developed by the author in order to explore the computations from the active milieu.

[CN15] also introduces the concept of relativistic tissue in the Brain. The relativistic tissue would include the active milieu plus the electromagnetic fields. The Brain would be a machine responsible to manipulate this own relativistic tissue, in order to improve his previsions about the world and augments the chance of survival of an organism.

Here we will propose a novel possible way with which the Brain perform clustering of neurons and creates their selectivity. Making use of a simple linear model with an activation function, just as a perceptron, we will modify the model in order to explain how temporary networks are shaped and specialized in the Brain with the active milieu, the electromagnetic fields, moment and environment of an organism, here called contexts. The theory is proposed as a possible explanation and way to test the Binaural/Monaural beats effects in attention, and as a tool to analyze and be tested by electroencephalography data.

## F.2 Clustering and computing by contexts

The Neurons are composed by gates and pumps, working with second messengers, RNA, proteins creation and destruction, and action potentials. There are not any isolation between the circuitry of neurons as we have in digital circuits. So how this apparently mess is able to present selectivity and represent information? With the contexts!

A context is the set of physical quimical particles and fields present around a neuron in a determined time  $t$  generated by the active milieu [SV21]. What all this could mean? Considering a moment  $t$  where a thought  $T$  was made, a sensation  $Y$  was felt, and an action  $Z$  was taken. Each one of these computations had some influence in several factors inside the Brain: first of all, they created electromagnetic fields that can arrive to any place in the Brain. In second place, they changed the flux of blood, directing it to the most active neurons. In third place, they could send soluble neurotransmitters or hormones to several brain regions. And finally, they send localized neurotransmitters and particles to the regional active neurons.

Therefore, we can divide these mess of particles in two groups: Global particles and phenomena, and local particles and phenomena. The global particles are these that are able to influence in big regions of the Brain, let's call it macro-networks. And the local particles are these able to influence in local regions of the Brain, let's call it micro-networks or local-networks. The global particles and phenomena therefore shape a global context, and the local particles and phenomena therefore shape a local context.

Now, we will attribute a role to each kind of particle. In order to do that, let's consider a linear function  $F$  as a simple representation of the membrane potential of a neuron:

$$F(X) = AX + B \tag{13}$$

This simple representation is enough to explain the role of the global particles and the role of the local particles. Now, we can assume statistically that the amount of global particles and phenomena depends on several factors, and therefore small changes do not change so much their values for a unique local neuron. Thus, just big changes in the Brain can alter the global context, this is, the neuron individual response to the global particles and phenomena just can be altered by big changes in the Brain. It means that we can see the global context as the constant  $B$  of the membrane potential function  $F$ , it will dictate a pattern of behavior inside this value at a determined time.

Thus, in this sense, let's state that

$$B = f(\text{global\_particles}, \text{global\_fields}) \tag{14}$$

, it means that  $B$  changes very few in a small window of time. Also,  $B$  depends on the properties of the particles, the distance of the sources of the fields and so on. Therefore, all the Brain regions could influence differently the  $B$  from a determined neuron. But this influence is ever similar, because the neuron is ever at the same place with relation to all the Brain.

Following this thought, we can now say what is  $A$  and what is  $X$ .  $X$  is the input of the linear function. It means that we could state that  $X$  is the local context. It means, all neurotransmitters from the pre-synaptic neurons, and any other local influence. So, let's state:

$$X = f(\text{local\_particles}, \text{local\_fields}) \tag{15}$$

We can see therefore that  $X$  is the local data being processed at a determined time. For example, in the Visual system, it could be an object boundary that is being processed in a determined neuron. Now, of course, we have  $A$ .  $A$  is the neuron local response to the sum of the local context and the global context,

we can call it the learning factor of the neuron. It determines how the neuron will respond to a determined global context + local context. Thinking on that, we could say that the constant B is a composition between a pure constant C depending on the global context, and the multiplication of A by this constant:

$$B = A * C \tag{16}$$

The neural response A can be considered a constant in this small window because it will just change with the neural plasticity. If the neuron learned the task, it means that A does not need to change (but can), arriving to the steady-state. Now, let's explain how the context can be used as a cluster build. For it, we will have to change a few our representation, adding the representation of a spike. In this sense, we have now:

$$S = Threshold(F) \tag{17}$$

$$S = Threshold(AX + B) \tag{18}$$

or

$$S = Threshold(A(X + C)) \tag{19}$$

Where threshold is the function that determines the behavior of the threshold needed to generate a spike with the membrane potential. Let's say, in order to illustrate the proposition, that the threshold is a function defined as:

$$Threshold(F) = \begin{cases} 0, & \text{if } F \leq 0 \\ F, & \text{otherwise} \end{cases} \tag{20}$$

Let's now assume a special Brain where each neuron do not have any local context influence, it means that X = 0. But, at the same time, has a global context influence. It means that:

$$F(X) = AC \tag{21}$$

Therefore, we can see clearly that the context can act as a cluster, in the interaction with the threshold and the neuron response. It would cost much more to the Brain to transport all the information just with local contexts, it means with the synapses, in order to take some kind of decision in a right situation. If the brain uses the global context, it can have a representation of the context just in time, and it can train the neurons to be active just in the contexts of interest, clustering them. Therefore, we would have:

- a set of neurons where  $F < 0$ .
- a set of neurons where  $F > 0$ .

At this situation, we have a temporary network shaped. And it is the network of neurons that are activated to this determined context because they surpass the threshold. But it does not mean that we have a functional Brain. In order to do specific computations, it is necessary to have local contexts, to change local properties and do specialized computations. So, let's again say that our Brain has an X component. With the X component and the A answer of the neuron, we can perform computations respecting a determined

range of values, and yet maintain the global temporary network. For example, if a determined postsynaptic neuron has the following answer:

$$F(X) = 20 \quad (22)$$

We can change the value of X, and yet surpass the threshold, using local context. It means that the pre-synaptic neurons can send an X value in order to transform F into:

$$F(X) = 18 \quad (23)$$

It would generate a spike, but at the same time it would also change the final value of the spike. This difference in the final value of the spike is therefore used as a way to represent local information, and do local computations in face of a context B. Also, the same X input could mean something totally different, if the context B changes. Generating a high degree of freedom and rich possibilities of computation to the Brain. Finally, we have therefore the following function as a possible simple (and incomplete) representation of the neurons:

$$S = Threshold(A * (X + C)) \quad (24)$$

$$S = Threshold(f1(local\_plasticity) * (f2(local\_context) + f3(global\_context))) \quad (25)$$

Where:

$$A = f1(local\_plasticity) \quad (26)$$

$$X = f2(local\_context) \quad (27)$$

$$C = f3(global\_context) \quad (28)$$

Therefore, coming back to the moment t where a thought T was made, a sensation Y was felt, and an action Z was taken. We can simply say that the global context to a neuron is:

$$global\_context = T + Y + Z \quad (29)$$

Disregarding the X factor, as we saw, the neuron would or not would be activated:

$$S = threshold(A * global\_context). \quad (30)$$

Therefore, a neuron would be directed to have or do not have a spike. Thus, immediately, a cluster of neurons, here called temporary network, would have a higher tendency to be generated, starting a selectivity (Rigotti, 2013). The Brain accordingly changes the local context of the active neuron, and the own neuron adapts itself in order to perform computations inside this cluster, changing the “A” constant.

It means that the Brain can easily specialize regions to perform a determined task in a determined context, and can also store information selectively.

The resultant S function is exactly the function we have in the perceptron model, but a few more complex. It means, that by definition, the system described is able to represent any kind of information, and is also Turing complete (it is able to perform any kind of computation a traditional computer could, if there are recursions between neurons).

### F.3 The role of the Brain computations and feelings

Therefore, we can explain several mechanisms of the Brain making use of these ideas with a week formalization.

#### F.3.1 An example of Hebbian Law complementarity

The Hebbian learning can perform important factor in the maintenance (tide) of the network shaped with the contexts. It means that while the global context would activate a unspecific amount of neurons, the Hebbian law would couple the neurons and generate a more specific synchronized temporary network. Let's demonstrate these phenomena:

Considering a network of neurons, given a global context C we can say using the function F that a subset M of neurons would be activated in front of this context. The activation of these neurons by the global context can be very ineffective, related to representation of information and local computation. Therefore, the Hebbian law would work following the process:

- If a pre-synaptic neuron 1 fires, and in a small amount of time after the post-synaptic neuron 2 fires, therefore the parameter A is increased for both of them. Making use of the retro-messengers of the post-synaptic neurons. It is:

$$A1 < -A1 + Hebbian\_plasticity \quad (31)$$

$$A2 < -A2 + Hebbian\_plasticity \quad (32)$$

Where A1 and A2 are the learning factors of the pre-synaptic and post-synaptic neurons, respectively.

- If a pre-synaptic neuron fires, and in a small amount of time after the post-synaptic neuron does not fires, therefore the parameter A is decreased for both of them. Or, equally if the post-synaptic neuron fires before the pre-synaptic neuron the parameter A is decreased for both of them. Making use of the retro-messengers of the post-synaptic neurons. It is:

$$A1 < -A1 - Hebbian\_plasticity \quad (33)$$

$$A2 < -A2 - Hebbian\_plasticity \quad (34)$$

This means that just the synchronized neurons would fire in a determined context. Remembering that the constant A could be different to each context, using internal neuron properties. Therefore, a high coupled temporary network is shaped to each context. We can prove that by induction:

1. H0: A new random temporary network of active neurons M is shaped by the context C, it means that the neurons m from M have  $Am * C > 0$ , surpassing the threshold.



2. Hn: Given the same context C, the Hebbian learning is activated. It means that Am from a neuron m of the network Mn will increase if it is synchronized with another neuron m from the network, and will decrease if it is not.
3. Hn+1: Given the same context C, the number of neurons actives synchronized will be higher than the number for Hn. Therefore the network Mn+1 is more synchronized, and is also context dependent.

These phenomena could also explain the effects of Binaural/Monaural Beats. This time using the local context generated by the temporary networks influenced by the beat. A constant influence X, in the network generated by the task, from the network generated from the beat can increase the probability of coupling using the Hebbian law. It means given a pre-synaptic neuron F1 and a post-synaptic neuron F2 related to a task t, if both of them receives a constant addition to X from the Binaural beats we have:

$$F1(X)increase \tag{35}$$

$$F2(X)increase \tag{36}$$

As both have its probability of fires increased, because the threshold S will have an increased chance of be surpassed with a highest F function, therefore both would have an increased chance of have a hebbian plasticity, meaning that the A parameter of both functions will be maximized in this context. It would happen in several points of the temporary network. And therefore, the beat would generate a strongest temporary network, improving, for example, the mixed selectivity (rigotti, 2013). We can prove this effect by induction:

1. H0: Given a temporary network M activated by the task t and the beat. We can verify that M will tend to be more synchronized by the Hebbian learning, as proved.
2. Hn: The neuron m from M, directly influenced by the beat send a local context to random pre-synaptic neurons directly related to the task t. F from these neurons will be increased in a similar and predictable way, following the frequency difference of the auditory system. The chance of firing of the random neurons will be augmented in the frequency context of attention. As F will have more chance to surpass the threshold.
3. Hn+1: (1) Random neurons that was already synchronized and are active will have the A learning factor increased by the hebbian learning. And the do not synchronized neurons will have the A learning factor decreased by the hebbian learning. Therefore Mn+1 will be more synchronized than it would be before, without the influence of the beat. The number and intensity of action potentials from neurons increase by the influence of the Beat, activating more hebbian learning plasticity. (2) Synchronizations from the own Beat signals coming, also influence in a context state of attention as random pre-synaptic neurons and post-synaptic neurons activated synchronously by the beat signal, would have the A learning factor increased by the hebbian learning. And therefore would generate a frequency of fire in the frequency of attention, by the entrainment with the signal coming from the auditory system.

It is important also to observe that the beat signal is predictable and periodic. It means that the local context computations can easily adapt to it, making the hebbian learning valuable in this case. If the signal were very unpredictable, therefore the local computations would be impaired, generating no gain to the quality of the mixed selectivity, hypothetically.

#### F.4 An example of global context computation using this model

The neurotransmitters can also be viewed as influences in the global context. Talking specifically about inhibition, excitation and reinforcement learning. The Brain has central connections that are able to spread

neurotransmitters around the brain or in big regions, and that are not synaptic specific. At the same time, there are hormones that are spread all around the blood.

Following our model, it is most probable that these kinds of interactions do not have local computations, or influence in what is called the local context. It would be very hard to spread some kind of very specific information with particles travelling with freedom on the brain. But, these particles can have a strong effect in the global context. It means that for example, thinking in the basic principles of learning from behaviorism, when you have a positive reinforcement, the temporary network generated at this time has to be reinforced and its probability to appears again have to be augmented.

To do that, the brain could send neurotransmitters all around, or for big regions. These neurotransmitters would change the A parameter in order to answers better to a determined context, maximizing the activation of the already active or recently active neurons. At the same time, when a negative reinforcement comes, the Brain could send these neurotransmitters changing the answer to the global context, and making the network less active, or more aleatory. In order to it, make a reorganization again with the local computations.

A second way of computation that can happens is related to the change in the own global context by sending neurotransmitters to regions of neurons, temporary networks or all the Brain. The change could be temporary, and it can elicit some kind of behaviors by activating some kind of mechanisms. It means, for example, it would be possible to change the global context to a state of angry. What would disturb a few the temporary network, and guarantee an isolation of this temporary network in order to answers properly to the instinct of angry. With the current context and knowledge related. For example:

- A temporary network M is activated by the context of a task t.
- The cognitive instinct mechanisms of the Brain perceives a threat. Neurotransmitters and/or hormones are spread towards the temporary network M giving a shift in the context C parameters of the neurons.
- The shift permits the temporary network to isolate local contexts in order to do computations related to the state of angry, but maintaining the information in the already specialized network to the task t. Or even activating a new temporary network.

In order to demonstrate it mathematically, we would have to expand our model to add the dynamics of the gates and pumps. The pumps can work as clocks that give a reference to each neuron about time. The gates have a dynamic that goes around the threshold, they can augment or diminishes the membrane potential of neurons, depending on the kind of gate. Therefore, if the gates that augment the membrane potential surpass the gates that diminish the membrane potential, we can generate an action potential. There are also possible to influence the parameter A of the neurons.

Therefore, the influence in the parameter A would be in order to alter the gate's dynamic, for maximizing the probability of have an action potential or diminishes this probability. While the pumps determine how much time the neuron can fires in a period of time, and when it will fire, in a more continuous way. In order to understand the global context, we can abstract the working of pumps, and assumes that we have a determined function  $b(X)$  that takes the neuron back to homeostasis.

Thus, as we defined before we can say that  $A = f(local\_plasticity)$ , therefore, we can define how  $f(local\_plasticity)$  works in a more detailed manner. As this we do:

$$f(local\_plasticity) = f(positive\_gates) + f(negative\_gates) \tag{37}$$

Where the positive\_gates, and the negative\_gates can be changed by the interaction with the local context, or with the global context. It is, in the case where we have a positive reinforcement we have:

$$positive\_gates < -positive\_gates + fp(global\_context) \quad (38)$$

$$negative\_gates < -negative\_gates + fp(global\_context) \quad (39)$$

The function  $fp$  can act augmenting the gradient quantity (The force that will move the ions towards the channel) in the positive gates channels, and diminishing the gradient in the negative gates channels. It means that the probability of have an action potential will be increased. The negative reinforcement acts exactly in the contrary direction. Therefore, the  $f(positive\_gates)$  and  $f(negative\_gates)$  can be viewed as the proper composition and properties of the channels, as for example the capacitance.

Thus, we can prove by induction that the temporary network will be activated in the long term, if it is heavily reinforced, and another variables are considered constant in a determined task. We should take in account that the context to a same task variate ever in a closed set  $T$  for each neuron and that the local context does not change. Let's now consider a brain network  $M$  with  $n$  neurons.

- H0: In each small window of time  $t$  of the task, the neurons  $K$  of the network  $M$  are activated. It means that these neurons, to this task surpass the threshold in the time  $t$ .
- Hn: Given that the task  $t$  gives a positive reinforcement, the  $A$  variable from the function  $F$  is augmented. Therefore, the neurons have an increase in the probability to be activated in the task  $t$  again when it happens.
- Hn+1: when the task comes again the  $A_{n+1}$  variable of each neuron, in each time  $t$  of the task will gave us  $A_{n+1}*(X + C)$ , as  $A_{n+1}$  is higher, therefore the chance of activation is greater and the temporary network is maintained. As here,  $X$  and  $C$  are considered positive constants. , we can prove the same to the dissipation of a temporary network towards the negative reinforcement. Q.E.D. (conclusion of the proof).

Therefore, we proved that the brain also can use the global context, with plasticity, to reserve or not regions of the brain to perform computations in face of a task. It means that brain regions could have regions specialized in doing specific computations. This process is also helped by what is called sustained fire (Wang, 1999), as the context maintains itself, the neuron will ever fires when it comes back to the homeostasis, after the pumps put it back to an active state.

The second way of interfere as said is directly in the parameter  $C$ , it means, a changing in the global context of the region. It can make a shift in the function answer, moving neurons to the zone of deactivation, and another to the zone of activation. It can be showed by definition, if the  $C$  from a neuron changes due to external interference, therefore we have the following possibilities:

- The neuron continues to surpass the threshold, but his answer diminishes. It can provoke a cascade effect on the network because the  $X$  of the post-synaptic neuron will be lowered or somehow different. For example, it could be that the calcium delivered in the synaptic vesicles will be highest with a highest answer.
- The neuron surpass the threshold with a stronger answer.
- The neuron approaches the threshold, but yet, does not surpass it.

The interference in the context is important because probably the Binaural/Monastral beats are able to make this kind of interference in the context. While the influence in the plasticity is important to understand, if the beat could cause some permanent effect in the Brain. One could state, for example, that a plus high context activation generate a stronger  $A$  plasticity, generating a stronger temporary network and therefore improving attention.

This kind of computations also could be found in the EEG, at least with abductions. By associating the EEG signal to the phases of the task, studying the possible generators of influences in the context (for example the substantia nigra responsible to inhibits broad regions, or the regions responsible to delivery dopamine in also broad regions (Ott, 2019)). We could therefore see an influence in the global context by studying the clusters of the EEG. For example, a global excitation could increase the electromagnetic potential globally, and along the time. It could be studied observing the learning time, when the plasticity happens. In the learned task, it is possible that the values will respect a determined interval, without very much changes.

As the same way, a global inhibition could decrease the electromagnetic potential globally. It is important to see that the mechanisms of attention can have a limit. It means, when a determined amount of effort is made, the regions start to be deactivated even to a positively reinforced task. This mechanism can be detected by the alpha pattern of the rest state, and the beta pattern of the attention state. The global inhibition is therefore also somehow related to this possible phenomena. And a stronger temporary network can be more resistant to this kind of inhibition. It means that the Binaural beats could have an effect related to: Augment the window where a positive reinforcement can happen, increasing the force of the temporary network. And influence in the own answer to a global context, making a more cohesive temporary network.

## F.5 An example of local computation using this model

The local computations are the most complex of all, because they carry the details of computations. There are infinite possibilities to it be made, and here we will explore just some examples to illustrate this richness of a connectionist learning system. In order to do that we can again change a few of our model, this time we need something to change the output of each neuron messages to the post-synaptic neurons. These mechanisms can be found exactly in the synapses, with the vesicles and calcium dynamics. Therefore, we could add a function  $Sy$  that answers to the threshold of each neuron, for each one of its synapses:

$$Sy(K) = R * K \tag{40}$$

$$Sy(s(F(X))) = R * s(F(X)) \tag{41}$$

This is, depending on the situation the neuron could have an inhibitory synapse, with R negative. An excitatory synapse, with R positive. And could represent information or do computations with the parameter R. Let's say that, for example, as the work (Ott, 2019) propose there are two neurons representing two different rules: Click if it is a target or do not click as it is not a target. A post-synaptic neuron, that integrates both the information from these two neurons, would be able to take the decision according to the situation and the reinforcements. In order to do that, we will include the threshold of the calcium in the synapses:

$$Tsy(Sy(K)) \tag{42}$$

That is a mathematically analogous threshold as the one from the action potential, in our model. Therefore, the post-synaptic neuron would learn with plasticity to increase or decrease the R constant in a way that the threshold would be surpassed in the contexts where there is a target, and do not would be surpassed in the contexts where we do not have a target. The local context generated by both the previous neurons representing the rules would happen to decide what is the better R parameter, while the global context is responsible to reserve this network to this kind of task and context.

Therefore, when there is a target,  $Sy(K)$  is higher than 0, triggering an action. While when it is not a target,  $Sy(K)$  is lower than 0, and nothing happens. It has to be clear that it is just a simple approximation

and tool example to demonstrate the potential of local computations. These kinds of computations are very sensitive and do not could be neuromodulated by Binaural/monaural beats.

Also, we can perceive that the improvement of an answer, as the absence of a motor response when we do not have a target, can leads to a decrease in the potential of the EEG electrodes due to a lower level of activity in the network. Therefore, in order to do the analysis in the EEG it is necessary to do not associate higher activity or lower activity with a better or worst performance. What is better, is to verify a lower degree of changes combined with a higher performance of the subject, meaning that we arrived to a steady-state where the subject really learned a determined task. The changes of this steady-state, or the increase of the capacity to maintain it, due to the mechanism of inattention would be a possible neuromodulation for Binaural/monaural beats.

## F.6 A hypothesis about the Binaural/Monaural beats effects and Possible analysis with EEG

The hypothesis is that the Binaural beats can generate a constant and phasic shift in the global context, as in the second way of interfere in the example of global context computation. Depending on how it is changed, the Binaural beats would improve attention.

In the EEG it would affect the ERPs patterns, or somehow, the own temporal data pattern in a constant way. The beat could change the results in the threshold of each neuron, helping to decrease some kind of competitive context. For example, let's state that the global state of attention, in the beta frequency, generates a global context of value B in a small window of time. And the global context in the global state of rest in the alpha frequency has the value of Alpha in a determined time t.

Consider now a set M of active neurons in a determined time t, here called a temporary network. Each one has his own  $B_m$  and  $Alpha_m$  values related to the states of attention and rest, respectively. If we compose this global context with the global context  $T_m$  related to the task, we will have the global context  $C_m$  for each m active neuron from M in both situations.

Consider now a new influence from binaural beats, that generates a global context influence called  $Bi_m$ , and is added to the global context of the active neurons M, in the instant t. Now, let's visualize one neuron m from M:

$$F(X) = A * (X + (T_m + B_m + Bi_m)) \quad (43)$$

In order to improve attention, we have to observe  $B_m$ , the influence from the beta state of attention. If the neuron is sensitive to the attention state, for this task ( $T_m$ ) therefore we can help to sustain the threshold active increasing the  $Bi_m$ . It can augment the time that a neuron have to be reinforced in this context, generating a stronger temporary network. And also can affect the hebbian learning, as proposed before.

It means, the attention is an interaction with the context generated by the task  $T_M$  and the cognition. In order to pay attention to it, the Brain would have to rely on a mechanism to excite this context, and split a temporary network to it. It would be made by changing the A parameter of our function from the neurons of M, in our simple representation. Or by influencing in the global context, parameter B. Therefore, it is clear that if the beat could generate the same global context of attention, so, the attention would be improved to the task  $T_M$ .

At the same time, if we have the state of rest, or inattention:

$$F(X) = A * (X + (T_m + A_m + Bi_m)) \quad (44)$$

We can directly change the parameter  $B = T_m + A_m + Bi_m$  with the  $Bi_m$  global context influence. It means that we can put the function in a state of attention, or move the membrane potential to have an action potential. Putting the brain in a state of attention with the beat.

In order to measure that on EEG it would be necessary to use a function  $f(x)$  that is able to separate the influence of a global context or in the temporal domain, or in the frequency domain. It means that it is necessary a function as:

$$f(EEG\_clusters) \rightarrow global\_contexts \quad (45)$$

Fortunately, there are already some kind of functions to do that. The own brain states related to alpha, beta, and gamma bands are currently measures of some kind of global context. In this sense, a possible measure is verifying if the beta band is strongest with a beta neuromodulation from the beat.

Also, the Independent Component Analysis or related techniques give an idea about how to get the global contexts. In this sense, we could say that the inhibition context, the excitatory context and the Binaural Beats/Monaural Beats responses would generate an independent component in the EEG analysis, what would be the global context influence.

The analysis can also be more detailed and look for means, variances, and differences in the domain of time. It could be possible to build a proper technique to identify different global contexts influences from clusters of neurons in the network. A first approach, would be to do that statistically. And the second would involve the most fine approximation of the Brain computations.