

Identificatie van neurale markers van ‘mind wandering’ tijdens ‘breath focus’ meditatie voor de ontwikkeling van nieuwe EEG-gebaseerde neurofeedback protocollen

(Identification of neural markers of mind wandering in the context of breath focus meditation for the development of EEG-based neurofeedback protocols)

Masterproef voorgedragen tot het behalen van de graad van Master in de biomedische wetenschappen door

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The preparation and completion of this master's thesis partly took place during the period when COVID-19 measures were in effect in Belgium (started on 13 March 2020). Within the framework of the measures taken by KU Leuven, it was not possible to complete the data collection for this master's thesis and the processing therefore had to be based on limited results. This aspect needs to be taken into account when consulting this document.

Thank you for the adjustments and clarifications concerning your research dossier entitled: "Psychophysiological effects of EEG-Neurofeedback".

Your revised protocol is now complete and meets the expected ethical standards regarding the voluntary involvement of human participants in scientific research. The SMEC board gives you final approval.

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Preface

After five years of studying, I am glad to look back to my carrier and smile happy that I succeeded in finishing my master in the Biomedical Sciences. Although, I must be honest it was not an easy path, I advanced while avoiding the obstacles that were thrown during this journey. I am glad to say that after five years I became the scientist I always wanted to be and thus became the role model I dreamed for. Of course, this could not have been possible without the help of people that guided me along the road: supervisors, family, friends, and meaningful others. First, I would like to thank my promotor and supervisor Prof. Dr. Kaat Alaerts and PhD-candidate Julio Rodriguez Larios for accepting me in as their master student. Also, I thank them for their patience to guide me through programming, the EEG-related literature, and writing the master thesis. I could not imagine another thesis lab where I could have felt as comfortable. Second, I would like to thank the enthusiastic student lab-team I did data collection with: Rachel van de Vorst, Marie Drion and Savina de Radiguès. I really loved work together with you! Third, I would like to thank my mother, sister, and stepfather for their continuous support throughout the years. With your support and kindness, I came closer to achieving my academic goals. Also, I want to thank them since they were whenever I needed some extra support from their side. Fourth, I would like to thank the friends that let me ventilate when things were not turning as I wanted and to be there when I needed to talk (with or without coffee) and specially Aymara Taillieu. I really appreciated your company and loved your altruistic personality. Thank you for the funny coffee breaks and the jokes. At last, I would like to thank everyone that help me along the road and that let me develop further academically and personally.

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1. List of Abbreviations

ASR: Artifact surface reconstruction

BCI: Brain-Computer Interface

BVP: Blood volume pressure

ECG: Electrocardiogram

EEG: Electroencephalogram

EEG-NFT: Electroencephalogram-Neurofeedback training

EOG: Electro-oculogram

ERD: Event-Related desynchronization

ERP: Event-related potential

ERS: Event-Related synchronization

FA: Focus Attention

FDR: False Discovery Rate

FFT: Fast fourier transformation

LFP: Local field potential

NFT: Neurofeedback training

MAAS: Mindfulness Attention Awareness Scale

MBSR: Mindfulness-based stress regulation

MRI: Magnetic resonance imaging

MEG: Magneto encephalogram

OM: Open Monitoring

PCA: Principal component analysis

POMS: Profile of Mood scale

SC: Skin conductance

stFFT: short-term Fast Fourier Transformation

2. Abstract

Meditation practice has become widely used which mainly aims to enhance relaxation and has been linked with health benefits. One example of such technique is breath focus. During a breath focus session, the attention of a subject fluctuates between two episodes: breath focus and mind wandering. Both states have been associated to changes in brain oscillations as measured through electroencephalography (EEG). Although tracking and recognizing mind wandering episodes may turn-out to be challenging and even impossible for novices. Neurofeedback training is a potential tool to facilitate meditation practice which delivers real-time feedback based on an EEG-correlate of meditation. However, the EEG-correlates of meditation practice and mind wandering have not been completely clarified yet. In this study we explore the EEG-correlates of mind wandering during meditation practice during a breath focus task in non-experienced meditators by using a probe-caught experimental paradigm. Participants were instructed to focus on the sensation of breathing while EEG was recorded. At pseudo randomly time points (20-60 seconds), the subjects were asked whether they were mind wandering or focusing on their breath. We show that $\alpha_{8-12\text{ Hz}}$ was decreased during mind wandering episodes. Opposite, we found that $\theta_{4-7\text{ Hz}}$ and theta/beta ratio were increased during the mind wandering episodes relative to breath focus. Based on these results, we developed a neurofeedback protocol aimed to facilitate meditation practice by the reduction of the theta/beta ratio. In conclusion, we found that mind wandering and breath focus episodes are characterized by EEG-features that can be potentially translated into a neurofeedback protocol.

3. Introductory Literature overview

The brain is without doubt one of the most intriguing organs being investigated to date. From falling in love to focussing on the road while driving, our brain steers our cognition and determines for a major part how we interact with our environment and with other people. Different brain regions communicate constantly, depending on the context, resulting in changes in activity related to the event. Such activities are reflected in the form of electrical fluctuations that can be measured through electroencephalogram (EEG). For example, meditation is an activity that is reflected in the EEG-signal and that is related to beneficial health outcomes. Moreover, during meditation practice there are two main different consciousness states that are reflected in the EEG: 'focus on the task' and 'mind wandering'. However, little is known about the EEG-correlates of mind wandering. Also, learning to practice meditation might prove challenging for novice practitioners. Thus, the main objective of this study is to analyze the 'focussed on the task' and 'mind wandering' episodes in subjects that are not experienced in meditation and to develop a potential protocol to extract the EEG-correlate to facilitate meditation. In order to understand how meditation is correlated to EEG and how meditation can be facilitated, we will review first the basics of EEG and oscillatory brain activity, linking the brain waves with meditation practice and mind wandering. Furthermore, we will elaborate that the neuromodulatory tool, neurofeedback training (NFT), might help facilitate meditation practice in novices.

3.1 Functional relevance of the electroencephalogram

3.1.1 Electro-encephalogram: Basics and Analytical considerations

Nearly all human cognition processes have been correlated to brain activity which is measured through electroencephalogram (EEG). Specifically, EEG is a non-invasive technique used to detect cognitive and pathological neurophysiological biomarkers.^{1,2} This approach detects electrical fluctuations through electrodes attached to the human scalp.^{1,2} These currents are originated mainly from pyramidal cells in cortical areas that are detected as local field potentials (LFPs).² This means that EEG reflects neuronal population activity rather than single neuronal activity. Besides, the main advantage of EEG is its high precise temporal resolution which is in contrast with its low spatial resolution.^{1,3}

EEG-signals are generally dissected into brain waves. From an analytical point of view, brain waves can be simplified as oscillators.⁴ When we use the word 'oscillator', we refer to a movement with a specific phase, amplitude, and frequency. For example, an electrical brain fluctuation that moves in the time-

domain has a certain frequency (Hz). Also, it reaches a deflection (μV) and it moves from in phase (θ) relative to another wave.⁴ A time-domain series wave, like EEG-data, can be decomposed in different frequencies through a Fast-Fourier Transformation (FFT).⁴ The result of such transformation is the power of the frequency you are interested in, expressed in μV^2 . Also, brain rhythms are assumed to be rhythmical periodical movements. Such analytical framework is useful when we analyze systems that are assumed to behave like oscillators.⁵ Each brain oscillation has different temporal and spatial characteristics. In addition, oscillatory power is inversely correlated with its frequency, meaning that high frequencies are found in a smaller networks, thus the amplitude is attenuated.⁶

3.1.2 Underlying neuronal mechanisms of EEG

Several microscopic and macroscopic factors influence the EEG-signal characteristics. From a microscale point of view, electrical fluctuations are originated in neuronal micro-circuits.^{7,8} The summation of electrical activity of neurons generates LFPs.^{3,8,9} In particular, LFPs originate as the result of electrical transmission that derive from multiple single neuronal inputs.^{3,9} This generates a current which occur mainly as result of synaptic activity between two neurons. One example that contributes to the generation of LFPs can be found between neuron to neuron communication. Through the activation of channels by neurotransmitters, currents of Ca^{2+} or Na^{2+} flow into the cell.³ This is continued by generating extracellularly current sink and intracellularly depolarization.³ In other words, the fluctuations of excitatory and inhibitory input lead to generation of LFP oscillations, which can be modulated by external variants.^{3,7} Also, there are more complex examples that explain temporal filtering of frequencies from a cellular perspective.^{3,7} Although we described a common neuronal mechanism for every EEG-signal, it is important to highlight that this signal does not always have a common underlying neuronal mechanism. Thus, LFPs reflect changes in neuronal activity which contribute neuron to neuron, region to region communication. However, EEG only measures population activity rather than single neuronal activity. Therefore, macroscopic factors will largely determine how the EEG-signal behaves.

Zooming out to the macroscopic scale, the EEG-electrodes measure synchronous pyramidal activity with different polarizations charges across the neurons.^{3,10} More specifically, neurons create dipoles after excitation which means that one end of the neuron is the 'source' and the other one the 'sink'.¹⁰ The former term is translated into a positive deflection in the EEG whereas the latter reflects a negative current.¹⁰ For example, in the extreme case that all the pyramidal ending to the scalp generate a sink, the sum of this activity will be translated into the EEG as a negative deflection.¹⁰ Another example is

where the negative and positive charged dendrites cancel each other out, which is detected in the EEG electrode as no deflection.¹⁰ Also, dipoles propagate through the dendrites, neurons, and extracellular fluid, influencing the electrical transmission.¹⁰ In short, the location where the dipole generates, determines the different types of deflection measured by the electrodes which is influenced by internal and external factors.

3.1.3 Brain Oscillations and their cognitive processing

In 1929 the German psychiatrist, Hans Berger, discovered scalp rhythms coming from the human brain using scalp electrodes. Shortly after, he called the discovery 'alpha' rhythms.¹¹ However, the new EEG-signals were denoted as 'noisy' background by the scientific community; considering only certain events as scientifically relevant.⁹ It was not until the early 70s that the interest in EEG-signals revived.¹¹ Nowadays, human neuronal oscillations are divided within specific frequency ranges: delta (\approx 1-5 Hz), theta (\approx 4 – 8 Hz), alpha (\approx 8-12 Hz), beta (\approx 15 – 30 Hz) and gamma (\approx 30 – 90 Hz).¹¹ The range division of these frequency bands were drawn arbitrarily, and they were named after its discovery e.g. alpha band was first discovered, then beta etc.⁹ Thus, there is growing evidence that each frequency band contributes to neurocognition.

3.1.3.1 Delta rhythms

Delta rhythms are associated with motivational processing, reward-driven system and brain homeostasis.¹¹⁻¹³ One example of such functionality is the evidence that demonstrates that delta power tend to increase when animals suffer from starvation or hypoglycaemia, suggesting its role in motivational processing.^{12,13} Another example is that delta is prevalent in drug-craving behaviour, where delta increases during the craving state.^{12,13} The exact location of delta is still disputed, however delta waves have been associated to the medial prefrontal cortex, orbitofrontal cortex and anterior cingulate cortex.¹²

3.1.3.2 Theta rhythms

Theta rhythms are mainly associated with memory, executive control and information transfer.¹⁴ In addition, theta activity has been reported to be present during Rapid-Eye-Movement (REM) sleep, which suggests its involvement in memory consolidation.¹⁴ Possible origins of theta rhythms are: medial septum, limbic system and hippocampus.¹²

3.1.3.3 Alpha rhythms

Alpha rhythms have been mainly suggested to work as an inhibitory signal that regulates attentional control.¹⁵ Also, alpha activity has been inversely correlated with cognitive processing.¹¹ Current evidence leans towards the hypothesis that alpha frequency acts as an inhibitory oscillation during cortical suppression. For instance, during attentional focus, inhibition will be enhanced and this is reflected as alpha, which will be increased in task-irrelevant areas.¹⁶ Alpha rhythms are prevalent in different brain regions such as occipital lobe, hippocampus and thalamus, although these rhythms have been hypothesized to have a general distribution in the brain.¹⁷

3.1.3.4 Beta rhythms

Beta rhythms are associated with motoric control and auditory processing. In particular, they appear to be inhibited during motor imaginary.¹⁸ Also, there seem to be increasing evidence pointing to a relationship between beta and attention, however its role is still discussed. There have been some suggestions that beta oscillations are correlated with the dopaminergic pathway.¹⁸

3.2 Relationship of Meditation practice with attentional focus

3.2.1 Meditation practice and the focussed mind

Meditation is found in different religions and cultures across the world where the practice itself varies even within the same cultural context. Although the meaning of meditation differs from the cultural point of view, the definition can be simplified as: “techniques that aim self-regulation of emotion, consciousness and/or attention, with the main goal to achieve different transcendental states, relaxation or enhanced concentration focus”.¹⁹ Notice that ‘meditation’ and ‘meditation practice’ differ terminologically from each other. ‘Meditation’ involves the cultural traditions and the practice itself, whereas ‘meditation practice’ entails only the techniques and mental strategies that are used during meditation.²⁰ Examples of this artificial division are: Christian traditions where the use of contemplative prayer is common or Buddhist traditions where recitation of mantra is a common technique in certain contexts.²¹ These techniques are interesting tools to analyze their influence on the mind and how they facilitate relaxation. A theoretical framework on meditation practices facilitates the understanding and comparison between them. Dahl *et al* proposed three main categories of meditation practice based on their cognitive similarity: attentional, constructive, and deconstructive family.²² However, only the attentional family will further be discussed.

The attentional family refers to meditation practices that have as common ground self-regulation of attention and meta-awareness.²² The latter term is described as: “the cognitive function of being aware the processes of consciousness” by Lutz *et al* 2015.^{20,22} In other words, if meta-awareness appears to be low or absent, the subject fuses with sensations that he is experiencing. Thus, the attentional family refers to the monitoring, experiencing, and guiding of attentional focus. Furthermore, this category is subdivided into two main classes: focused attention (FA) and open monitoring (OM) meditation.²⁰ FA reflects practices that focus on a single object and where the process of attentional drift is detected.^{20,22} For example, in a session where the subjects are focusing on breathing, their attention will be directed on their abdomen, nostrils, etc. During this session, there will be time points where they will not pay attention on their breath, also defined as ‘mind wandering’. Thus, FA meditation is the practice that allows the practitioner to sustain their attention to a certain object and detect the drifts of attention.^{20,22} OM meditation is conceptually similar to FA meditation; however both subclasses differ fundamentally in some aspects.^{20,22} In OM meditation the subjects sustain their attention to meta-awareness rather than the focus on their breath, for example.^{20,22} In other words, the subjects will focus on what they are experiencing as a whole rather than to focus on a specific object. Summarizing, the key message is that each type of meditation offers a range of techniques to detect differences within consciousness states.

As insinuated in the previous paragraph, each ‘meditation family’²² is determined by practices that aim to increase ‘self-reflection’ or ‘meta-awareness’, which are translated in changes of self-awareness states and/or relaxation. In the case of the ‘attentional family’, these consciousness changes are generally reflected as ‘object-oriented focus’ or ‘mind wandering’.²⁰ Take for example a session where the subjects are instructed to focus on their breathing using the strategy they want. To focus on your breath means that the object of attention may be different depending on the participants subjective choice for strategies. To clarify, the subject may focus on the respiratory flow going through the nostrils or abdominal movement. If the attentional focus is sustained on their breath, we define this consciousness state as ‘breath focus episode’. When the subjects focus on their breath, their attention may drift.^{19,21} This is what we refer as ‘mind wandering’ episodes”. Thus, mind wandering is intrinsic to meditation practice. Notice that breath focus is not the only meditation technique available to sustain attention. For example, mantra recitation used in some Buddhist traditions can also serve as the subject’s object of attentional focus.²³ Finally, during meditation the attention of the subject may find itself in a drift or ‘focussed on the task’ mental state. Also, the

Buddhist traditions offer a wide range of meditation techniques that may be translated as potential therapeutical tools.

Deriving mainly from Buddhist traditions, meditation practice has been recently translated into the clinic mainly under the name of mindfulness interventions. Commonly, these interventions are also understood as ‘mindfulness-meditation’.²⁴ One of their main goal is to generate awareness on what is happening in the present. As pointed out before, this can be achieved by focusing on breathing, but can also take other forms as long as the focus is on the ‘present’ or ‘now’ perception. Besides, the choice of technique depends on the content of the therapy, for instance: targeting non-adaptive thoughts.²⁴ One example of such intervention is mindfulness-based stress reduction (MBSR) therapy.^{24,25} This program is guided by a professional on a weekly basis for eight weeks long. The main aim is to teach how to be mindful using different techniques. In addition, MBSR reduces mind wandering episodes and helps the individuals to determine when these episodes are happening so they can redirect their attention.²⁶ Such therapies have been applied in a wide range of psychopathologies: Post-traumatic stress disorder (PTSD), depression, anxiety, etc.^{24,25,27} Health related outcomes of MBSR programs are for example decrease in depression relapses, reduction in anxiety, impact on drug-craving behaviour.²⁴ In summary, meditation has been proven to be a powerful tool to enhance relaxation by increasing the awareness of the ‘now’ and reducing non-adaptive mind wandering episodes.

3.2.2 Mind wandering in daily life and in meditation practice

Mind wandering has been defined as ‘stimulus-independent thought’ or ‘self-generated thought’ unrelated to the task’.^{28,29} This means that there is a certain subdivision within the mind wandering thought. For instance, mind wandering happens when the experiment you are performing is troubling you and you think about this experimental setting. This is what is called as a ‘task-dependent thought’.²⁶ In this case, mind wandering is a thought dependent from the task which may help in problem solving.²⁶ For the sake of clarity, we will further define mind wandering as ‘not focussed on the task on hand’, without making a subdivision in dependent nor independent from the task. Moreover, mind wandering involves two main aspects: disengagement from our external attentional focus and its origin is ‘self-generated’.²⁶ An example of such thought is recalling autobiographical events or future appointments. Also, it has been insinuated that mind wandering is involved in attention selection. Specifically, while a subject is engaged during an external stimulus, mind wandering episode occurs as a distractor coming in the form of internal input. In this case, the

attentional selection is attenuated.²⁹ Thus, mind wandering has been identified to have different contents, where its function changes depending on the situation.

The content of a mind wandering thought varies depending on the context and has been correlated with a wide range of functions as well. Mind wandering episodes have been majorly considered as negative thoughts and furthermore it can possibly contribute to anxiety.²⁸ In addition, mind wandering has been hypothesized to lead to poor task performance²⁶ and it have been even considered as 'failure to self-cognitive control'.^{26,29,30} Contrarily, mind wandering is positively correlated to problem solving and creativity. Both disputing functions lead to the suggestion that depending to the mind wandering content and situation, the episode may be experienced in a different way depending on the emotion attributed to it. In line with this vision and contradictory mechanisms, there are two main key aspects that conceptualize the complexity of mind wandering: the context and content regulation.²⁶ The former refers to the fact that mind wandering is related to the situation where the subject is, whether it is operating a patient or just reading a scientific paper.²⁶ In other words, mind wandering might occur depending on the situation. Thus, mind wandering happens in tedious or important tasks. In case that mind wandering occurs in important tasks, it may lead to poor task performance such as not remembering the lines you read in a scientific paper. In case you are doing a tedious, monotonous task, mind wandering might serve as a coping mechanism. The latter, the content regulation aspect, denotes to what the mind wandering thought exactly is.²⁶ Consequently, context and content are crucial to analyze the nature of mind wandering episodes.

In a general context, mind wandering occurs in 50 % of our waking time.²⁸ Following this current notion, mind wandering has major benefits and costs. On the one hand, mind wandering might reduce texts comprehension and impede detecting mistakes.³⁰ Additionally, excessive mind wandering has also been defined as the result of an 'unhappy mind'.²⁸ Namely, the individual's mood is often influenced by the mind wandering thought.²⁸ As an example of the costs, subjects that were reading a detective novel and experienced mind wandering episodes had more difficulties in solving the crime than their peers that were focussed on the task.²⁶ On the other hand, benefits of mind wandering include problem solving or coping with boredom. For instance, mind wandering protected subjects that were performing a tedious task from mood reduction, such as fax operator.³⁰ Besides, external factors can influence the frequency of mind wandering episodes e.g alcohol or craving for a cigarette.²⁶ Overall, the perception of the ongoing experience and decoupling from it, influences whether we perform mistakes and how we cope with a given situation.

3.3 EEG correlates of meditation practice

EEG studies aim to characterize correlations between the EEG-signal and consciousness states. Since meditation influences attentional directivity involving the respective neuronal networks, one might suspect that this is reflected in the brain electrophysiology. In order to characterize the EEG-correlates of meditation, the oscillatory activity is analyzed from the frequency bands: delta, theta, alpha and beta. Moreover, EEG-correlates of meditation practice are assessed by comparing the EEG-signal of rest and meditation. Rest is more specifically a state where the researcher tells the participant to relax and not to fall in sleep.^{23,31} In other words, rest is assumed to be a state where the subject is 'not thinking' anything in particular. In brief, meditation states are correlated with spectral changes in the EEG-signal and defined as changes in the brain waves. To argument further on the EEG-correlates of meditation practice, we will depart mainly from the systematic review of Lomas *et al* (2015)³² which is the only systematic review that quantifies oscillatory activity within mindfulness meditation to the knowledge of the author.

3.3.1 Delta band and meditation

Delta band (1 – 4 Hz) has not been consistently reported to change during meditation compared to rest.³² In the systematic review of Lomas *et al*, five studies (n= 5) were included from which one (n = 1)³³ reported greater amplitude in meditation versus rest in frontal electrodes³³, three (n = 3)^{34–36} did not demonstrate difference between meditation and rest and one (n = 1) showed lower delta amplitude between meditation and rest.³⁷ Also, it has been suggested that delta band power increases during cognitive-demanding tasks while during meditation it decreases.³² This leads to the suggestion that delta wave plays a role in attentional disengagement.³⁸ To date, only a handful of studies reported changes in the delta band in experienced and novice practitioners.^{32,38}

3.3.2 Theta band and meditation

In the theta band (4 – 7 Hz) power has been shown to be enhanced or decreased depending on the meditation experience.³² Lomas *et al* examined 19 studies that reported theta amplitude changes. In short, many studies (n = 11)^{33,35,39–47} showed evidence that amplitude in theta band was enhanced during meditation compared to rest. However, only a few studies (n = 3) showed theta increase during meditation compared to rest in novices. On the contrary, few reported lower amplitude during meditation compared to rest in the theta band (n = 3)^{37,48,49}, where two of these studies included

novices. The rest of the studies reported no difference in amplitude changes compared to rest. Note however that also a limited number of studies reported enhanced theta in novice practitioners.³² In addition, enhanced theta power has been correlated with the amount of training experienced.³⁸ Finally, current evidence indicates that theta amplitude is only enhanced during meditation in experienced meditators while theta amplitude has been suggested to be decreased in novice practitioners compared to rest.

3.3.3 Alpha band and meditation

Alpha band (8 Hz – 12 Hz) has been demonstrated to be changed during meditation compared to rest.³² Majorly in the review of Lomas *et al*, several studies show that alpha amplitude increases during meditation compared to rest (n = 12)^{33,35,36,40,41,43,47–52}. While few papers report lower amplitude during meditation versus rest (n = 1)^{34,32}. Further, studies comparing resting state and meditative state showed that the frequency of the alpha band decelerated while its power increased.^{32,38} In addition, the level of experience in meditation practice has been suggested to be correlated with a higher alpha amplitude.^{32,38} This leads to the discussion whether the cortical brain structures led to a ‘deactivation’ state or a different attentional distribution.³² Thus, 67% of the papers analyzed by Lomas *et al* found consistent increase in the alpha amplitude.³²

3.3.4 Beta band and meditation

Outcomes on the beta band (13 – 30 Hz) activity are mixed.³² Lomas *et al* included 12 studies where a few reported greater amplitude (n = 3)^{35,39,41}, lower amplitude (n = 1)³⁴ and the majority did not find differences between rest and meditation (n = 5)^{33,35,36,45,49,51}. To date, there is contradictory evidence on the role of beta band during meditation.³⁸

3.3.4 Summary: Meditation and EEG-correlates

Current evidence points to a consistent increase in relative alpha and a decrease in relative theta power during the meditative states in novice practitioners while to date literature is inconclusive for delta. Also, theta has been suggested to be increased in experienced subjects while in novices it has been suggested that theta is decreases when comparing meditation and rest (Table 1).

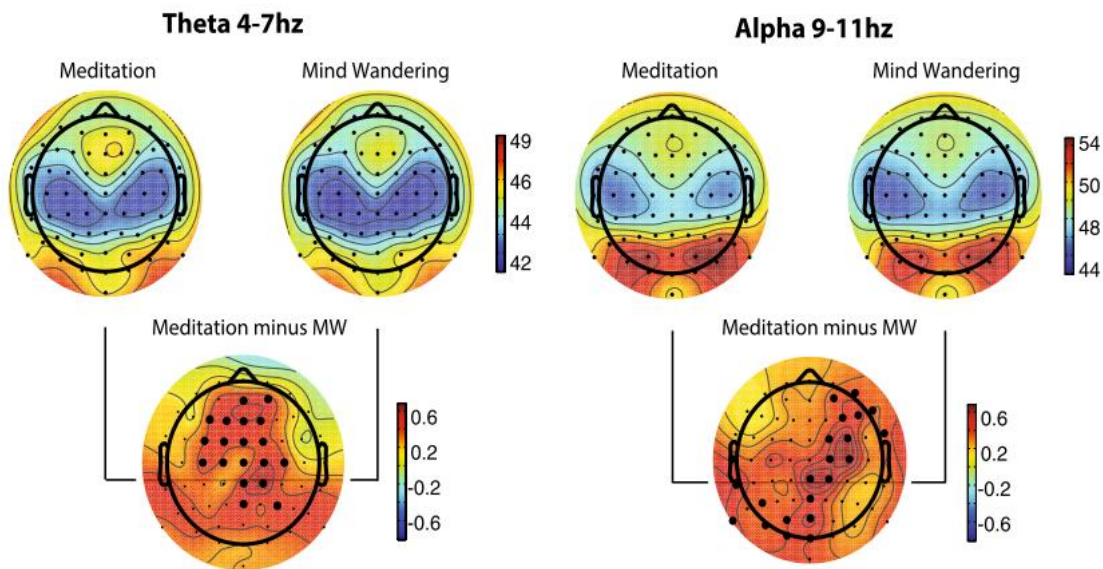


Figure. 1 Event-related spectral perturbation (ERSP) plots, and differential plots of significance in theta (4–7 Hz) and alpha (9–11 Hz) band activity for expert meditation practitioners. Power scale is expressed in $\mu\text{V}^2/\text{Hz}$. Black dots on the difference plots indicate electrodes significant at $p < 0.02$ after cluster correction for multiple comparisons. From Brandmeyer and Delorme *et al* (2018).²³

3.4 EEG-correlates of Mind wandering

Like meditation states, mind wandering episodes can be reflected into transient EEG changes although few studies have focussed on this issue within the context of meditation practice. Mind wandering episodes during breath focus meditation can be identified by interrupting the subjects at random time intervals throughout self-caught or probe-caught experience sampling paradigm. The former approach means that during the experimental setting the subjects need to realize that they are mind wandering. Distinctly, the latter approach refers to the paradigm where at pseudo-random timepoints the subjects are asked whether they were mind wandering or not. Using the probe-caught approach, Brandmeyer *et al* explored the difference between mind wandering episodes of experienced and novice Himalayan Yoga meditators (Figure 1).²³ The authors instructed the participants to focus on a continuous state to recite the mantra as their focus object. During the experiment, their depth of meditation, mind wandering, and tiredness were assessed.²³ This study resulted in the conclusion that expert practitioners experienced less mind wandering episodes compared to novices. From a spectral point of view, the expert subjects displayed an increase in theta power in the frontal cortex as well as an increase in alpha power in the parietal zones when comparing meditation with mind wandering. However, they did not observe in novices between meditation and mind wandering any significant

differences.²³ An example of self-caught mind wandering episodes, is the paper of Braboszcz *et al* where self-caught mind wandering episodes were investigated in novice practitioners (Figure 2).³¹ Subjects were instructed to count their breath until ten and press a button whenever they noticed they were not longer focussing on their breath and thus mind wandering. They concluded that delta and theta power were increased during mind wandering episodes while alpha power decreased, suggesting a lack of alertness.³¹ In another research paper, Dana van Son *et al* reproduced the experimental paradigm and findings of Braboszcz *et al*.⁵³ In addition, they found out that during mind wandering episodes, the theta/beta ratio was increased in the frontal electrodes. Also, delta power increased during mind wandering episodes. On the contrary, alpha power is increased during breath focus episodes.⁵³ **To summarize**, in previous literature mind wandering episodes have been linked to an increase in delta, theta power and theta/beta ratio, and a decrease in alpha power (Table 1).^{23,31,53}

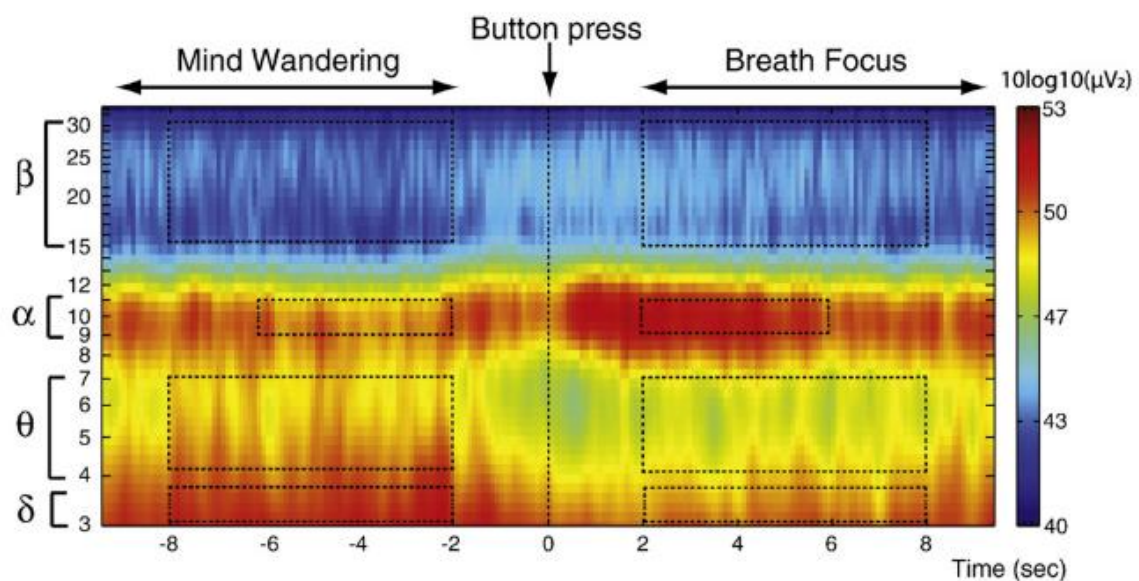


Figure. 2. Time frequency decomposition of transition from mind wandering to breath focus at electrode site **Oz**. Mind wandering was defined as the period preceding the meta-conscious event (button press) and breath focus was defined as the period following the meta-conscious event. Topographic maps of power difference are shown for the 2–3.5 Hz (δ), 4–7Hz (θ), 15–30 Hz (β) frequency bands from –8 to –2 s before and from 2 to 8 s after the button press. Adapted from Braboszcz and Delorme (2011).³¹

3.5 Guided self-relaxation: Neurofeedback training and meditation practice

Electroencephalogram-neurofeedback training (EEG-NFT) is a brain-computer interface (BCI) protocol which is based on self-regulation of a contingent EEG-feature activity. The main goal of NFT-EEG is to achieve EEG-signal modulation. Namely, modulating a certain brain wave is related to different outcomes, which are specific to the electrophysiological signal.⁵⁴ To achieve self-regulation of an EEG-feature, feedback is delivered to the subject as an auditory, visual or tactile modalities.⁵⁵ Also, NFT has been proven as a powerful tool for treatment in different pathologies such as epilepsy, attentional deficit hyperactivity disorder (ADHD), insomnia, stroke and PTSD.⁵⁶⁻⁵⁸ Overall, the EEG-feature that is aimed to be modulated need to be extracted real-time.

The extraction of EEG-NFT parameters has two key aspects that needs to be taken into consideration: the correct pre-processing of the data and choosing the right parameters the feedback is based on.⁵⁹ The first aspect refers on how the data is cleaned on a real-time basis which is influenced by eye, muscular, electrode or electrical artifacts.⁵⁹ This can be achieved by filtering out artifacts from the EEG signal using bandpass/stop filtering and correcting on a real-time basis the artifacts. Also, the main EEG-feature extraction is extracted from the interested signal is filtered out from the cleaned signal.⁵⁹ The second aspect refers on the brain signal the feedback is based on. For example, the experimenter in matter may be interested in filtering out the alpha signal of Cz using a FFT. This extracted feature is based on a cognitive relevant feature. At last the feedback is translated from an EEG-feature to a stimulus, or feedback.⁵⁹ This feedback may be delivered constantly or intermittently.⁵⁹ In short, the extraction of the EEG-features is translated into NFT protocols.

There is a wide-range of NFTs-protocols that have been applied in different settings. Such protocols are for example based on alpha enhancement, theta enhancement, beta enhancement, theta/beta ratio reduction.⁶⁰ Also, each NFT protocols is linked to a certain health outcomes. For example, protocols aiming to increase alpha mainly aim to enhanced cognitive performance, although most studies used a sample size was too small to make general claims.⁶⁰⁻⁶³ On the other hand, theta waves have been majorly attributed to memory related processes⁶⁴, thus theta protocols mainly aim to enhance cognition and memory.⁶⁰ Also, beta_{15 - 18 Hz} enhancement and theta/beta ratio reduction training have been reported to increase sustained attention in healthy participants and in ADHD.⁶⁰ Thus, NFT offers the possibility to deliver feedback to subjects while they are trying to achieve a certain mental state.

NFT and meditation practice might be combined to enhance the meditation experience of the practitioners.⁶⁵ Take again the example of breath focus during a mindfulness session. During this breath focus session, the subject will use breath as their attentional focus. Also, the subjects will experience intercalated meditation and mind wandering episodes. The feedback would be hypothetically delivered depending on the spectral changes during these episodes. However, there are two main issues related to this during this hypothetical NFT. The first question is which specific neuronal correlate is the feedback based on. Before training an EEG-feature the researcher needs to argue why this feature is extracted and provide at least some previous evidence that the EEG signal is modulated accordingly to breath focus. The second issue is that during meditation practice, there are two main focussed states: mind wandering and breath focus. However, these episodes intercalate between each other which means that both episodes need to be identified and differentiated from each other. Differentiating between both episodes is essential to extract the correct feature and deliver accurate feedback. Thus, there might be a certain change in the EEG-signal where the BCI can deliver feedback to the subject. However, the difference between mind wandering and breath focus episodes are unclarified. For that purpose, knowing the EEG-correlates of breath focus and mind wandering is critical to develop an NFT protocol in order to facilitate meditation.⁶⁵ Interestingly, neurofeedback protocols aim to train similar electrophysiological signals that are modulated during meditation practice as well like alpha, theta and theta/beta ratio. Departing from this thought, training EEG-features modulated by meditation using neurofeedback might offer new insights in contingent EEG-correlates

3.6 Conclusion

Brain rhythms play a pivotal role in neuronal integration and cognitive processing where each brain rhythm has been attributed to a cognitive role. These rhythms modulate during meditative states in experienced and in novice practitioners. Although the rhythms δ_{1-3} Hz, θ_{4-7} Hz, α_{8-12} Hz, β_{13-30} Hz have been explored, only α_{8-12} Hz and θ_{4-7} Hz frequencies change consistently through literature between two conditions (Table 1). It has been proposed that EEG could be used to facilitate meditation through EEG neurofeedback by helping the participants to identify mind wandering episodes based on their neural oscillations.⁶⁵ By knowing the EEG correlates of these two states, we can facilitate meditation practice in non-experience meditators by detecting whether the subject is mind wandering. Therefore, neurofeedback training can be used as a tool to facilitate meditation. For that reason, there is an urge to differentiate in the EEG mind wandering and meditative

states. However, until now there have been few studies differentiating these states within meditation practice.

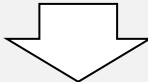


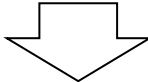


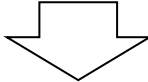
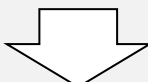
EEG-correlate	Meditation vs rest	Meditation vs Mind wandering
Delta (1 – 4 Hz)		 31,53
Theta (4 – 7 Hz)	a)  33,35,39-47 b)  37,48,49	 31,53
Alpha (7 – 12 Hz)	 33,35,36,40,41,43,47-52	 23,31,53
Beta (13 – 30 Hz)		 23,31,53
Theta/beta ratio		 53

Table. 1. Summary of spectral changes during meditation and mind wandering of delta (0.5 – 4 Hz), theta (4 – 7 Hz), alpha (8 – 12 Hz), beta (13 – 30 Hz) and theta/beta ratio versus meditation. Up-arrows indicate an increase of the respective EEG-correlate whereas the lower arrow symbolized a decrease in the respective EEG-correlate compared to either rest or mind wandering. Crossed cells denote inconclusive or contradictory findings. a) Increased Theta is correlated with meditation experience and thus increased in experienced practitioners. b) On the contrary, Theta have been suggested to be reduced during meditation compared to rest in novice practitioners.^{23,32,38}

4. Objectives

4.1 Identifying EEG-correlates of mind wandering and meditation

In this study we investigate the EEG-correlates of mind wandering and breath focus episodes during meditation practice in inexperienced meditators by using a probe-caught paradigm. Until now, recent studies on mind wandering and meditation practice explored self-caught mind wandering episodes during breath focus tasks in inexperienced subjects.^{31,53} Only one study investigated probe-caught mind wandering episodes.²³ However, the probe caught paradigm focussed on mantra recitation as the meditation object in expert and moderate meditators. In other words, little is known about the influence of breath focus in inexperienced subjects in the EEG-signal. Thus, this study aims to replicate the findings of previous literature by analysing the EEG-correlates of mind wandering episodes during a breath focus task in inexperienced practitioners. Given the evidence in previous literature, it is hypothesized that:

- **Hypothesis 1.** Delta Power increases during mind wandering episodes compared to breath focus.
- **Hypothesis 2.** Theta increases during mind wandering episodes compared to breath focus
- **Hypothesis 3.** Alpha reduces during mind wandering episodes compared to breath focus.
- **Hypothesis 4.** Theta/Beta Ratio increases during mind wandering episodes compared to breath focus.
 - Frontal electrodes are specific for mind wandering episodes and show higher theta/beta ratio.

4.2 Development of neurofeedback protocol

Differentiating between mind wandering and meditation practice might prove challenging for inexperienced meditators. Identifying whether the subjects are focusing on their breath or their attention is drifting, might facilitate the meditation experience in inexperienced subjects. Thus, after identifying the EEG-correlates of mind wandering during meditation, we will develop a neurofeedback protocol in order to facilitate meditation practice for inexperienced meditators which might be applied in future studies.

5. Materials and Methods

5.1 Participants

In total we recruited 28 participants (15 women) from 18 to 30 years old through social media, flyers, and posters. We excluded participants that had more than one-month meditation experience, had a psychiatric diagnosis and used psychotropic medication (anxiolytics, antidepressants, antipsychotics, etc) within the two years of participation. From the 28 enrolled participants, we included 25 participants with a mean age of 23.48 ± 2.51 years in our data analysis. Two participants were excluded due to technical difficulties during the recordings and one participant was excluded due to noisy EEG-data. The mother tongue of the participants was respectively, Dutch (n=10), French (n = 10), Serbian (n = 1), Bulgarian (n = 1), Polish (n = 1), Arabic (n = 1) and Spanish (n = 1). Twenty-two participants were right-handed, two were left-handed and one was ambidextrous. Seven participants self-reported to have tried meditation practice, but no longer than one month. All the participants signed the informed consent approved by the local ethic committee of the 'Social Maatschappelijke Ethische Commissie' (SMEC) and received 8€ per participated hour. After signing the informed consent, the participants were asked to fill-in the profile of mood state (POMS) questionnaire and mindful attention awareness scale (MAAS) questionnaire (see Appendix I).^{66,67} The study was conducted accordingly with the declaration of Helsinki.

5.2 EEG recordings

The EEG recordings were taken with the Nexus-32 amplifier (MindMedia), using a 21- EEG cap ('FP1', 'FP2', 'F7', 'F3', 'Fz', 'F4', 'F8', 'T3', 'C3', 'Cz', 'C4', 'T4', 'T5', 'P3', 'PZ', 'P4', 'T6', 'O1', 'O2', 'A1', 'A2') (Neurosky) with a sampling rate of 512 Hz. Biotrace+ software (MindMedia) was used to record EEG and physiological parameters. For offline artifact correction, left-eye vertical and horizontal electrooculogram (EOG) were recorded. Other physiological parameters were collected such as respiration rate, skin conductance (SC), electrocardiogram (ECG), blood volume pressure (BVP) and temperature with a sampling rate of 32 but these assessments will not be discussed further in the current report (see Appendix II for experimental preparation).

5.3 Experimental Paradigm

To identify mind wandering episodes, we used a probe-caught experimental paradigm to differentiate between 'breath focus' and mind wandering, named further as the breath focus task. During the breath

focus task participants were instructed to close their eyes, focus on their breath, and try not to fall asleep. The task lasted for approximately 30 to 40 minutes. The subjects were told they could use the strategy they seemed fit: attentional focus on their nostrils, abdomen, etc. The participants started with one test trial of the breath focus condition and had the opportunity to ask questions in case the test trial was not clear. At pseudorandom time points (20 seconds - 60 seconds), a bell sound was displayed, and the participants were instructed to open their eyes after hearing the sound. The screen display assessed whether the participants were thinking about something else, also called 'mind wandering' (MW) or if they were focusing on their breath, 'breath focus' (BF). Afterwards the participant's confidence on their previous answer was recorded using a scale from 1 to 7 (see Appendix I).^{66,67} As following, the participant's feeling was asked through a non-validated questionnaire asking if they were feeling either calm or excited on a scale from 1 to 9 (see Appendix I).⁶⁸ In total, 40 trials were fulfilled by each participant. For the question's presentation and sound display, we used the E-prime[®] software (Psychology Software Tools, Inc). The breath focus task was part of a larger experimental setting which description can be found in supplementary attachments (see Appendix I). All the instructions were provided in English.

5.4 EEG data pre-processing

The EEG data was pre-processed offline in MATLAB2019a[®] with EEGLab v7.0 toolbox.⁶⁹ A high- and low-pass filter of 40 Hz and 0.5 Hz were applied to the EEG-signal. EEG-data was screened for flat EEG-channels and artifacts using clean_rawdata plugin.⁷⁰ Artifacts were removed using artifact subspace reconstruction (ASR), $k = 5$. This artifact rejection method identifies first clean EEG-data segment, where it rejects afterwards corrupt components leaving clean data as output using principal component analysis (PCA). After rejecting artifacts, EEG data was referred to 'common average' and bad channels were interpolated spherically. EEG-amplitudes higher than 100 μV were removed to control for major artifacts. For each experimental trial, the two seconds prior to the bell sound were analyzed. Two-second epochs were categorized into breath focus ('BF') or mind wandering ('MW') episodes depending on the subject's answer. The first test trial was excluded from the analysis, leaving in total 40 MW or BF episodes. The two-second epoched time-series data was then transformed to spectral data using a short-term Fast Fourier transformation (stFFT) extracting frequencies from 1 Hz to 35 Hz with a sliding window of 512 samples (1 second) and overlap of 461 samples (~90%). Amplitude data was calculated for delta $1-3$ Hz, theta $4-7$ Hz, alpha $8-12$ Hz, and beta $13-30$ Hz as specified in the paper of Dana van Son *et al.*⁵³ Theta/Beta ratios were calculated by taking the ratio of theta and

beta power for each electrode independently. See supplemental materials for the pre-processing MATLAB script (Appendix I).

5.5 Neurofeedback protocol development

The neurofeedback protocol was developed using the open-source software OpenVibe developed by Inria technologies which lets the experimenter extract specific EEG features.⁷¹ OpenVibe software has two main applications: acquisition and designer. The former application extracts the EEG-signal from the EEG-amplifier whereas the latter application translates the acquired signal into a visible time-series signal. The neurofeedback EEG-feature extraction pipeline was developed using the designer software (see Appendix III).

5.6 Statistical analysis

Statistical analyses were performed with the software IBM® SPSS® Statistics for Windows, version 26. In order to assess whether amplitude at any frequency band and electrode differed between conditions we first ran an omnibus repeated measures ANOVA with frequency band (delta $1-3$ Hz, theta $4-7$ Hz, alpha $8-12$ Hz, beta $13-30$ Hz), conditions (BF, MW), and electrodes (21 electrodes) as factors. Also, to test whether there was an amplitude difference at each frequency band between condition (BF, MW), we used repeated measures ANOVA with conditions (BF, MW) and electrodes (21 electrodes) as factors. Before we calculated the main repeated measures ANOVA, we ran a repeated measures ANOVA for theta/beta ratio with condition (BF, MW) and electrodes (21 electrodes) as factors. P-values from the repeated measures ANOVA are reported using the Greenhouse-Geisser value. Post-hoc multi-comparisons were corrected using the Benjamini-Hochberg false discovery rate (FDR) correction method.

6. Results

6.1 Behavioural results

No significant differences were found using a paired samples t-test between the % of epochs in which participants reported to be focussing on their breath or mind wandering, $t_{24} = -1.64$ ($p = 0.11$). Also, no significant differences were found in the participant's confidence ratings between MW and BF, $t_{24} = 1.23$, ($p = 0.23$). Besides, no significant answer differences between MW and BF were found in the participant's arousal, $t_{28} = -0.95$ ($p = 0.35$). This data suggests that subjects without previous experience had an equal amount of mind wandering states as breath focus states.

6.2 EEG results

We ran *a priori* a repeated measures ANOVA for theta/beta ratio with 'condition' and 'electrode' as factors which demonstrated significant condition effects ($F_{1,24} = 10.00$; $p = 0.01$). Repeated measures ANOVA analyses revealed a significant two-way interaction between 'condition' * 'frequency band' ($F_{4,24} = 7.62$; $p = 0.01$), as well as a three way interaction between the factors 'condition' * band' * 'electrode' ($F_{4,24} = 2.45$; $p = 0.02$). To explore this three-way interaction further, we performed repeated measures ANOVA separately for each frequency band. Significant main conditions effects were found for the alpha_{8-12 Hz} band ($F_{1,24} = 7.77$; $p = 0.01$), indicating a decrease in alpha_{8-12 Hz} power during MW, compared to BF episodes (see Figure 3). Also, significant effects of condition were evident for the theta_{4-7 Hz} ($F_{1,24} = 6.07$; $p = 0.02$). No significant main condition differences were found in delta ($F_{1,24} = 0.16$; $p = 0.69$) and beta_{13-30 Hz} ($F_{1,24} = 4.46$; $p = 0.05$) (Figure 3). Significant main condition effects were found after correcting for FDR in theta_{4-7 Hz} ($F_{1,24} = 6.07$; $p = 0.03$); alpha_{8-12 Hz} band ($F_{1,24} = 7.77$; $p = 0.04$) and theta/beta ratio ($F_{1,24} = 10.00$; $p = 0.02$). Only alpha showed significant 'condition' * 'electrode' interaction ($F_{18,24} = 3.48$; $p = 0.02$). No significant 'condition' * 'electrode' interactions were found in delta_{1-3 Hz} ($F_{1,18} = 1.58$; $p = 0.145$), theta_{4-7 Hz} ($F_{1,18} = 1.22$; $p = 0.30$), beta_{13-30 Hz} ($F_{1,18} = 0.465$; $p = 0.85$) and theta/beta ($F_{1,18} = 1.34$; $p = 0.23$). Thus, alpha_{8-12 Hz} is decreased during 'MW' episodes while theta_{4-7 Hz} and theta/beta ratios are increased during 'MW' episodes. For those bands showing electrode*condition interaction, Benjamini-Hochberg FDR corrected paired-samples t-tests revealed significant condition-dependent differences in alpha power (Figure 4). Alpha power was significantly lower in MW compared to BF in the 'F7', 'F3', 'Fz', 'F4', 'F8', 'T3', 'C3', 'Cz', 'C4', 'T4', 'T5', 'P3', 'PZ', 'P4', 'T6', 'O1', 'O2', 'A1', 'A2' electrodes. See Appendix I for t-values, corrected and uncorrected p-values.

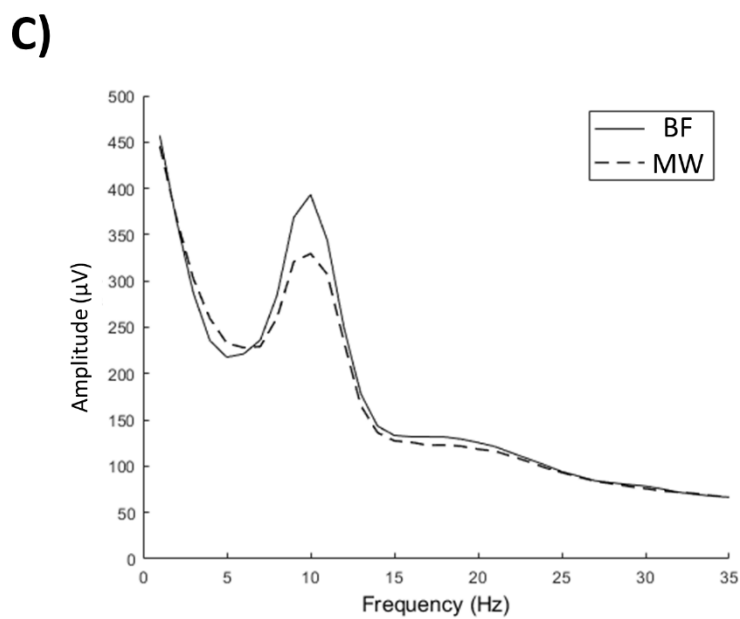
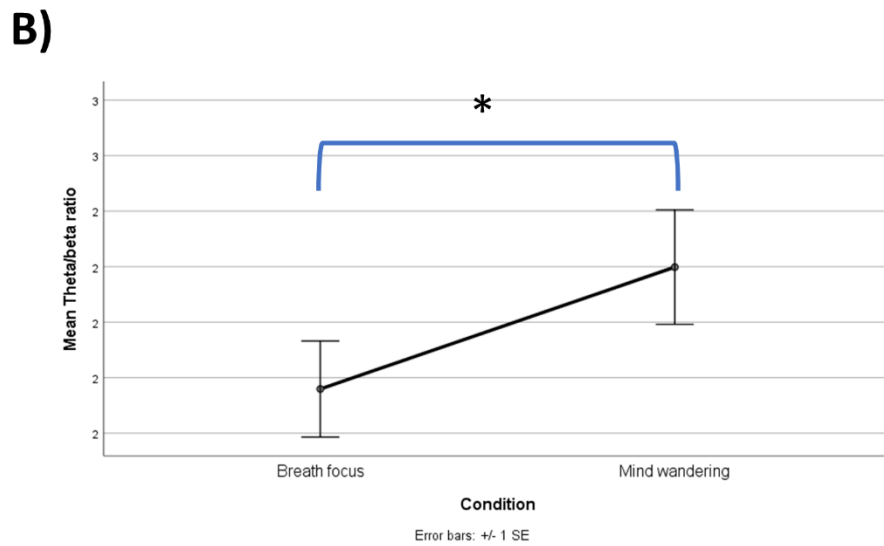
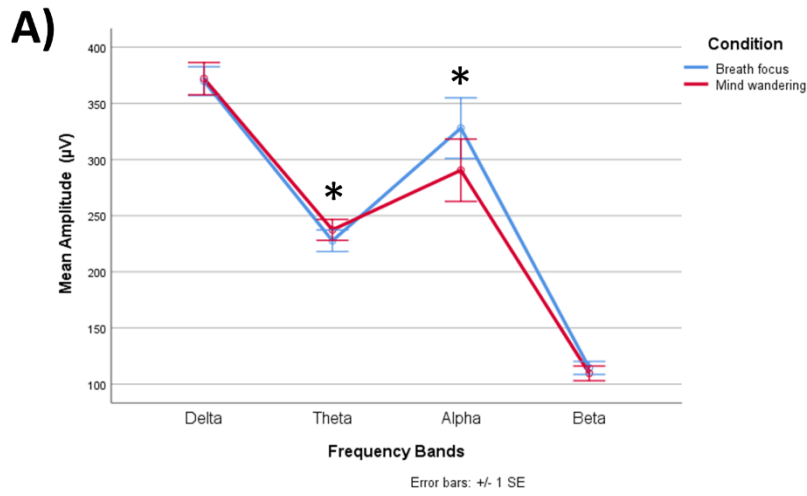


Figure 3. Amplitude changes across the electrodes during mind wandering and breath focus episodes. Amplitude changes between Mind wandering (MW) and breath focus (BF) for each frequency band. **A)** Estimated mean amplitude (μV) for band $\delta_{1-3\text{Hz}}$, $\theta_{4-7\text{Hz}}$, $\alpha_{8-12\text{Hz}}$, $\beta_{13-30\text{Hz}}$ and **B)** theta/beta ratio for MW and BF condition. **C)** Grand amplitude average across the electrodes for MW (straight lines) and MW (dashed lines). Statistical significance: * $p < 0.05$.

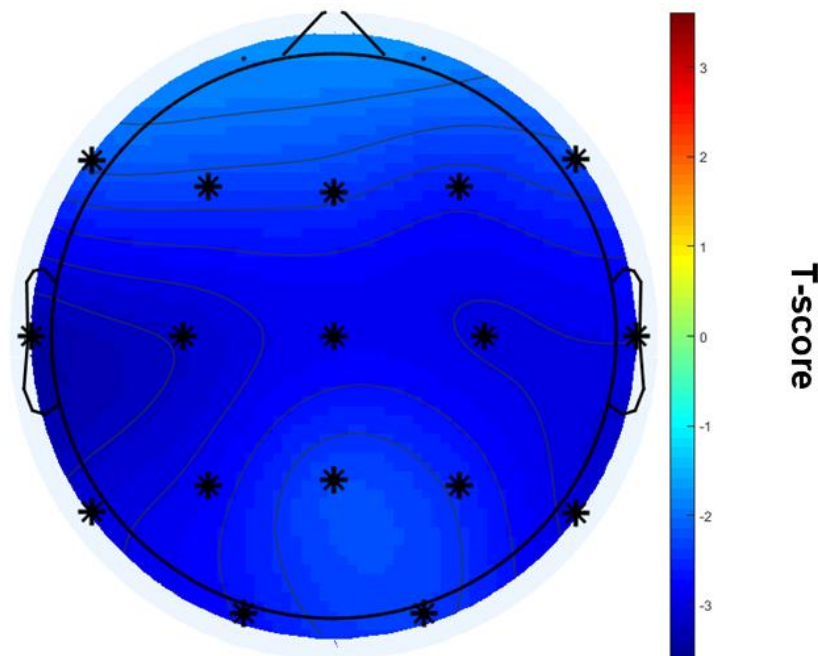


Figure 4. Topographical power changes in Mind wandering versus Breath focus in Alpha frequency. Mind wandering (MW) and breath focus (BF) episodes were measured using a probe-caught paradigm. Spectral electrodes T-values of $\alpha_{8-12\text{Hz}}$ MW versus BF corrected for Bonferroni multiple comparison. Alpha power decreases during MW and specifically in 'F7', 'F3', 'Fz', 'F4', 'F8', 'T3', 'C3', 'Cz', 'C4', 'T4', 'T5', 'P3', 'Pz', 'P4', 'T6', 'O1', 'O2' electrodes. Asterisks represent statistical significance ($p < 0.05$), corrected for multiple comparison.

6.3 Implementation of Neurofeedback protocol

Consistently with previous literature, we identified an increase in theta^{31,53}, theta/beta ratio⁵³ during mind wandering episodes and a decrease in alpha during breath focus episodes.^{23,31,53} Taking into consideration our previous findings, we propose a neurofeedback protocol to detect mind wandering episodes in novices during meditation practice. To translate our previous findings into a NFT paradigm, we used the open-source software OpenVibe which allows experimenters to develop accurate BCI protocols.⁷¹ Our protocol is divided into four main sections: the first extracts the signal from the EEG-amplifier and filters out one channel, the second reflects the signal pre-processing steps, the third extracts the EEG-feature from the spectral signal and the fourth translates the signal into an auditory feedback (Figure 5). The first section of the protocol extracts the data from the EEG amplifier to the OpenVibe software and filters out the 'Cz' channel. The second section consists of the extraction of the EEG-feature which follows our pre-processing guidelines. First, Butterworth bandpass filter between 0.5 and 40 Hz is used to filter out general noise sources. Second, the data is epoched in 2 seconds each 0.25 seconds in order to have a real-time continuous data delivery to the subject. Third, EEG-signal higher than 100 μV is capped which filters out major artifacts. Fourth, the power of the signal is extracted using FFT. Fifth, the average of the two seconds is calculated resulting in data equal to the frequency dimension. The third section extracts the EEG-feature. Theta_{4-7 Hz} and beta_{15-25 Hz} powers are extracted from the spectral data which are averaged across the discrete frequencies and their theta/beta ratio is calculated. The fourth section translates the EEG-feature into auditory feedback. First, incoming data is filtered based on a threshold which is determined on baseline, e.g EEG-rest state. Second, values above or under a certain threshold are translated into sign change values. For example, if the data is higher than 2, 1 will be send 'to the sign detector'. On the other hand, if the data is lower than 2, -1 will be send to the sign detector. Changes between 1 or -1 values is translated into feedback. 1 values coming from the sign change box delivers stimulations to the sound player. In other words when the theta/beta ratio is higher than 2, the sign-change box 'activates' the sound by sending incoming stimuli. On the contrary, when theta/beta ratio is lower than 2, the sound is 'deactivated'.

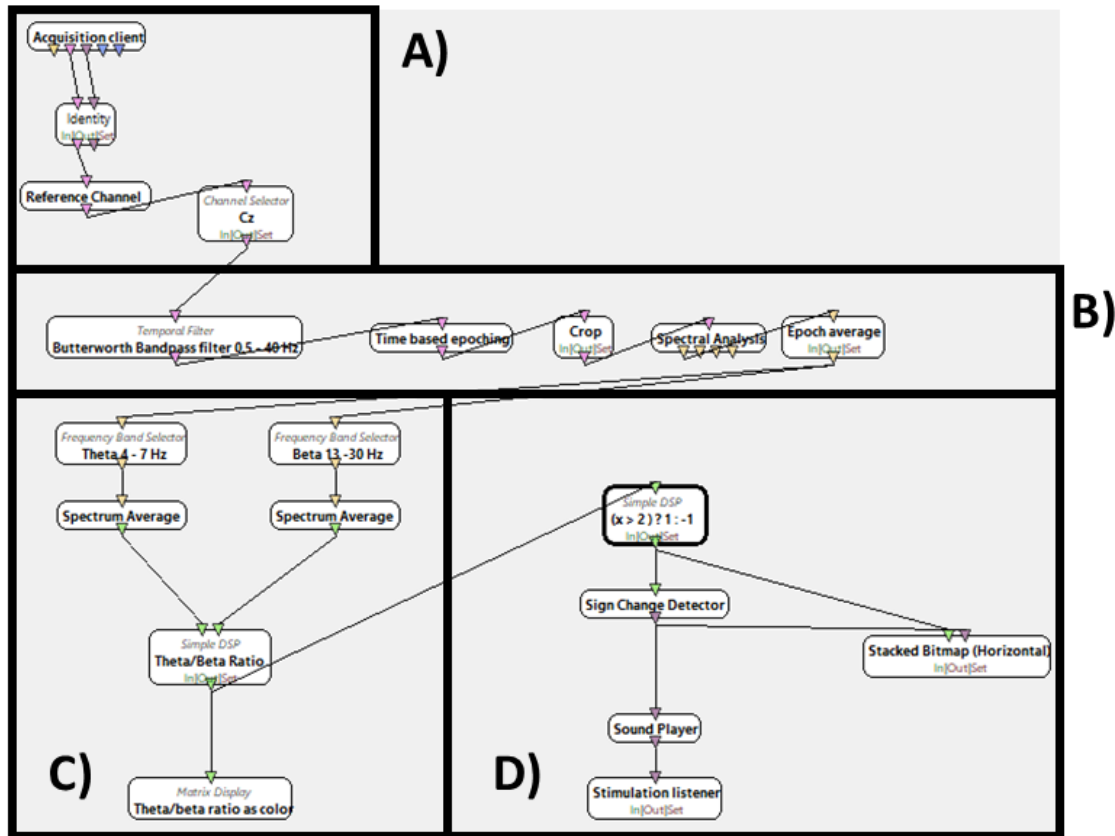


Figure 5. Neurofeedback protocol based on theta/beta ratio. OpenVibe Designer screen that extract, filters and translate raw EEG-data into auditory feedback. Every box represents an action where every line represents the flow of information. **A)** Connection between the BCI-EEG amplifier. EEG-data is extracted from the EEG-amplifier and the 'Cz' channel is filtered out afterwards, **B)** EEG-data pre-processing, the raw EEG-signal is filtered using a bandpass filter and epoched each 0.25 seconds for 2 seconds long. Also, data above 100 μ V is capped and decomposed into spectral components and the epoch average is calculated. **C)** EEG-feature extraction. Theta/beta ratios are calculated and plotted. **D)** Feedback delivery. Ratios above a threshold of 2 deliver auditory feedback to the participant where feedback lower than 2 deliver no feedback.

4. General discussion and conclusion

In this study we explored the EEG correlates of mind wandering during meditation practice in nonexperience subjects. For that purpose, we used an experience sampling probe-caught method where we assessed at pseudo-random time points whether the participants were mind wandering or focusing on their breath. Compared to breath focus, mind wandering is characterized with increase in $\theta_{4-7\text{Hz}}$ amplitude and theta/beta ratio. On the contrary, we found that breath focus leads to an increase in $\alpha_{8-12\text{Hz}}$ amplitude. In addition, alpha power was increased in parietal and occipital electrodes. Thus, our results further support partially the existing evidence that mind wandering episodes are characterized by high theta, theta/beta low alpha although we failed to demonstrated delta amplitude changes. Departing from these results, we developed an EEG based neurofeedback software using the open-source program OpenVibe.

We made our hypothesis departing from experimental settings with similar goals such as conducted by Dana van Son *et al.*,⁵³ Braboszcz *et al.*³¹ and Brandemeyer *et al.*²³ Our experimental setting is similar to the latter study. Although, some major differences between our study and these proof-of-concept studies that are worth mentioning. The experimental setting of Van Son *et al* and Braboszcz *et al* assess mind wandering episodes through a button press task. Specifically, the participants were asked to count until ten and press a button in case they were distracted or lost count of their breath. Thus, both studies assessed self-caught mind wandering episodes, relying on the subject's introspection availability. Whereas, we investigated probe-caught mind wandering episodes that the participants might not have been noticed, similar to the experimental setting of Brandemeyer *et al.* This underlies different approaches to investigate self-generated thoughts during experimental sampling paradigm. The main disadvantage of a self-caught paradigm is that the subjects need to be aware of the emergence of mind wandering episodes in order to analyse the difference between these episodes. Many participants were excluded since they did not have enough self-reported mind wandering epochs. Though, the probe-caught paradigm has as disadvantage that breath focus depth is difficult to achieve since the focus period is short. In other words, the 'meditation experience' could tend to be less immersive than with a self-caught paradigm. Statistical differences between our study and theirs could be explained by the difference method to assess mind wandering episodes.

Our first hypothesis stated that $\delta_{1-3\text{Hz}}$ power would be increased during mind wandering episodes. However, we failed to demonstrate statistical condition-related effect in the delta band. Delta has

been postulated to be enhanced during motivational processing and reward-driven systems.¹³ However, the role of delta remains disputed within meditation.³² Slow delta rhythms are predominant during non-rapid-eye-movement (REM) sleep, on the other hand increased delta has been correlated with decrease in alertness.^{31,53} Another explanation on failing to demonstrate delta power changes, may be explained by the difference in pre-processing pipelines which may affect the direct comparison of our results with theirs.

As stated in our second hypothesis, we found that $\theta_{4-7\text{Hz}}$ power was enhanced during mind wandering episodes relative to breath focus. Theta has been shown in previous studies to be prominent during mind wandering episodes compared to breath focus.^{31,53} However, Brandmeyer *et al* reported to find higher theta during focused attention episodes.²³ This discrepancy could be explained by two main experimental differences. The first difference is that in our study the participants use breath focus as their attentional object, while in the paper of Brandmeyer *et al* their subjects use mantra recitation as their meditation object. This further emphasizes that meditation practice may differ essentially from each other. Also, these differences suggest that meditation practice cannot be merely oversimplified with theoretical frameworks. Future studies should assess spectral differences between breath focus and other meditation practices. The second explanation is that Brandmeyer *et al* uses experienced meditators while we use non-experienced meditators. Long-term effects of meditation practice have not been properly addressed by the literature. However, there is slight suggestion that theta is increased in experienced meditators whereas in novice practitioners it is reduced compared to rest.³² This seems rather plausible taking into consideration that our results are in line with previous findings on novice practitioners^{31,53} but not in experienced meditation practitioners.²³ Thus, this further suggest that theta is enhanced during meditation practice in experienced practitioners while theta is reduced during meditation practice in novices, compared to mind wandering or rest. Also, it has been suggested that meditation practice enhanced memory related processes, which might offer an explanation why in experienced meditators theta is enhanced.^{12,38,64,72}

In line with our third hypothesis, $\alpha_{8-12\text{Hz}}$ power was diminished during mind wandering episodes compared to breath focus. Our findings further support the evidence that alpha amplitude is predominant during breath focus states, more specifically in non-experienced meditators. More specifically, we found that alpha power was enhanced in the parietal areas and occipital areas. These findings may be explained by previous findings which reported that alpha was located in the

somatosensory cortex of experienced-meditators.²³ Furthermore, alpha has been suggested to be topographically non-specific.⁷² Putative mechanisms of alpha can be interpreted in the light of Klimesh's hypothesis: alpha activity has been presumed to act as an inhibitor of 'non-task' relevant input and selective in attention focus. This is reflected when the subject closes its eyes, alpha increases reflecting a cortical inhibition.⁷² Thus, when the subjects are mind wandering, they are disengaged of their internal focus such as breath focusing. When the participants meditate, they are engaged in internal focus and 'non-relevant' internal input will be inhibited. Generally, alpha have been postulated to act as a neuronal correlate for sustained internal and external attention control.¹⁵ Together with previous consistent findings, our results further support indirectly that alpha acts as a directed attentional control mechanism. Future studies would have to delineate whether alpha may differ between novice and experienced meditators.¹⁵ Departing from the theory that alpha is enhanced during breath focus, one might actually argue that alpha is influenced by activities that require sustained attention such as sport or music. Thus, future studies should take into consideration controlling for these underlying cofounders.

Theta/beta ratio was enhanced during mind wandering, supporting partially our fourth hypothesis. On the contrary we did not find any electrode specificity in theta/beta ratio as first hypothesized. Our failure to demonstrate a major difference in theta/beta ratio may be reflected in the different pre-processing and analytical comparisons. While Van son *et al* compared epochs pre-post button press, we analyzed epochs before button press. Nevertheless, we further support the current evidence that theta/beta ratio is specific for mind wandering in adults during eye-closed meditation. Theta/beta ratio has been associated many times with attentional control which has been hypothesized to reflect cortical inhibition to subcortical areas which indicates attentional control in the prefrontal cortex (PFC).^{37,53,73,74} Different studies found that theta/beta ratio is negative correlated with the attentional control score (ACS), a reliable score testing the participant's control on their attention.^{73,74} This is translated into clinical populations, namely ADHD-patients. Specifically, theta/beta ratio has been confirmed to be negative predictor for ADHD-attention, making this a suitable parameter to detect distracted thoughts in healthy and pathological populations. Also, medication targeting the PFC and specific for ADHD has been shown to normalize theta/beta ratio.⁷⁵ Remarkably, theta/beta ratio has been reported to be modulated during meditation practice⁵³ which suggests that distracted thoughts during meditation have a similar underlying mechanism as ADHD. Taking into consideration the healthy and pathological brain biomarker, theta/beta ratio is a relevant candidate to identify mind wandering episodes in novice practitioners.

Exploratively, we tested $\beta_{13-30\text{ Hz}}$ to see whether it was specific for mind wandering episodes. However, we failed to prove that this band was modulated during mind wandering and breath focus episodes. Previous findings showed that $\beta_{20-35\text{ Hz}}$ was not dependent of breath focus nor mind wandering episodes.³¹ These observations in different beta band definitions might reflect that beta oscillations might be independent from mind wandering and breath focus episodes and thus this neuronal marker might be used as a control rhythm for future studies. Beta rhythms have been suggested to work through top-down attentional processes which similar to alpha's role. This is further suggested by neurofeedback training based on $\beta_{15-25\text{ Hz}}$. Neurofeedback training focused to enhance $\beta_{15-25\text{ Hz}}$ band has been reported to be enhanced together in alpha band in focus attention tasks.⁷⁶ This provides some suggestions that $\beta_{15-25\text{ Hz}}$ and alpha have a similar function in the brain.

Our findings support further novel evidence to the suggestion that NFT could serve to facilitate meditation practice in novices. One of the difficulties for starting meditation practice without formal training, is the lack of ability to detect mind wandering episodes. Experienced meditation practitioners are trained to redirect their direction to the focus when their attention drifts from their breath. On the contrary, novices that do not follow formal meditational practice training might not be able to detect mind-wandering that easily. Thus, to facilitate meditation practice in non-experienced subjects means that one must be able to guide novices into redirecting their attention. The aim of NFT-meditation would be to train novices to detect mind wandering episodes and redirect their attention to the object of meditation. These nuances that meditation practice does not *per se* entail a reduction in mind wandering episodes but rather the ability to detect such episodes. For example, feedback could be delivered in a way that a sound is displayed when the subject is not focussed on the task. One of the perks of neurofeedback is that it is a real-time feedback based on the EEG-signal. Another advantage is that this feedback allows people to use it with mobile technology and it may become portable which may help people to follow-up their evolution in meditation experience.⁶⁵ Following this rationale, NFT facilitating meditation practice may be translated into the clinic where mindfulness-stress based therapy interventions are exponentially increasing.⁷⁷

Furthermore, we propose a NFT protocol based on theta/beta ratio to facilitate meditation practice by detecting mind wandering episodes. We propose this parameter due to its novel involvement in meditation practice, demonstrated by previous findings⁵³ and our results. This is reaffirmed by findings in ADHD literature.^{73,74} In short, the desired parameter is extracted, and feedback is delivered when theta/beta ratio is higher than a certain threshold. The threshold is computed per subject on the

average of a baseline measurement, for example eyes-closed rest of five minutes. Note that theta/beta ratio and mind wandering should have a certain contingency. In other words, if the subject's attention drifts, theta/beta ratio should be increased as well. Nevertheless, future studies should focus on validating reliable NFT parameters that can be applied in meditation practice. Although we propose theta/beta ratio as our main parameter, theta, or alpha are also perfect candidates that should be investigated as a possible target to facilitate breath focus meditation. In our implementation pipeline we used the open-source software OpenVibe that gives the experimenter freedom to determine the signal cleaning and feedback delivery. Piloting our neurofeedback pipeline should be covered by future studies with the main goal of solving technical issues. Proof-of-concept NFT trials should focus on exploring which EEG-correlate is the most suitable to train.

Limitations

There are some major limitations in our study concerning the analysis and experimental setting. In our analysis we used the Benjamini-Hochberg FDR correction for multi-comparisons. However, it has been reported that that cluster-based analysis on EEG-data using a 'Monte-Carlo' MCP correction to be a superior statistical approach when comparing multi-dimensional data like EEG.⁷⁸ Also, we included total of 25 participants in our data analysis, however we should consider increasing our sample size to increase our statistical power. Another issue is that non-experienced meditators might not differentiate between mind wandering and focus states. Experienced meditators are sensitive to know if they are mind wandering and the depth of it. In line with this view, we should include experienced meditators to control for this issue.

Conclusion

In conclusion, our findings support the idea that mind wandering during meditation practice in non-experienced practitioners is characterized by specific EEG-features. Such features are high $\theta_{4-7\text{ Hz}}$, theta/beta ratio and low $\alpha_{8-12\text{ Hz}}$ during mind wandering episodes. Furthermore, we suggest a neurofeedback protocol to help identify mind wandering episodes during meditation practice. This further supports that different EEG-parameters can be used with the aim to facilitate meditation. Our experimental findings open a new field for future study where neurofeedback training would further facilitate meditation in the experimental setting and, from a translational perspective, in the clinic.

5. Dutch Summary

Ons brein communiceert voortdurend met andere regio's. Interactie, communicatie en informatiestroom in de hersenen worden weerspiegeld als elektrofysiologische veranderingen in de hersenen, afhankelijk van de acties die we uitoefenen, zoals meditatie. Meditatie is een veelgebruikte techniek om ontspanningstoestanden te verbeteren die in verschillende culturen en tradities voorkomen. Er is echter wel een verschil tussen meditatie en meditatiebeoefening. Het woord 'meditatie' benadrukt de culturele en traditionele context, terwijl de term meditatiebeoefening technieken omvat die worden gebruikt om ontspanning te bereiken door de aandacht te richten op een welbepaald focusobject, zoals concentreren op de ademhaling. Tijdens een ademhalingsfocussessie zijn er twee belangrijke aandacht toestanden die duidelijk kunnen worden onderscheiden: gefocust op de ademhaling en 'het dwalen van gedachten'. Beide toestanden worden weerspiegeld in het EEG als voorbijgaande en/of aanhoudende veranderingen bij beginnende en ervaren meditatie beoefenaars. Het volgen en herkennen van deze concentratie toestanden kan echter een uitdaging blijken te zijn en zelfs onmogelijk voor beginners. Neurofeedbacktraining is een potentieel hulpmiddel om meditatiebeoefening te vergemakkelijken en levert feedback op basis van een gecorreleerde EEG-sigitaal, ook genaamd EEG-correlaat. De EEG-correlaten van meditatiebeoefening en 'het dwalen van gedachten' zijn echter nog niet volledig opgehelderd. In deze studie verkennen we de EEG-correlaten van dwalen van gedachten tijdens meditatiebeoefening tijdens een ademhalingsfocustaak bij niet-ervaren meditatie beoefenaars met behulp van een door een sonde gevangen experimenteel paradigma. Deelnemers kregen de instructie om zich te concentreren op hun ademhaling op eender welke manier, terwijl we 21 elektroden EEG-activiteit registreerden. Op pseudo-willekeurige tijdstippen van 20 - 90 seconden werd aan de proefpersonen gevraagd of ze met hun gedachten afdwaalden of zich met intervallen op hun ademhaling concentreerden. We tonen aan dat alpha (8 - 12 Hz) reduceert tijdens 'het gedacht dwalende' episodes. Aan de andere kant vonden we dat de theta (4 - 7 Hz) en theta/beta-verhouding tijdens de dwalende episodes waren toegenomen. Vertrekkend van de EEG-correlaten, ontwikkelden we een neurofeedback-protocol op basis van de theta/beta verhouding. We kunnen concluderen dat deze parameters kunnen worden gebruikt om meditatie te vergemakkelijken met gebruik van Neurofeedback-training door het identificeren van aandacht dwalende episodes bij niet-ervaren meditatie beoefenaars en kunnen ze worden toegepast in de kliniek.

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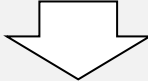


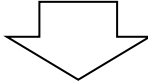


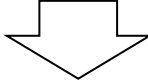
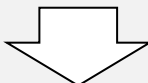
EEG-correlate	Meditation vs rest	Meditation vs Mind wandering
Delta (1 – 4 Hz)		 31,53
Theta (4 – 7 Hz)	a)  33,35,39-47 b)  37,48,49	 31,53
Alpha (7 – 12 Hz)	 33,35,36,40,41,43,47-52	 23,31,53
Beta (13 – 30 Hz)		 23,31,53
Theta/beta ratio		 53

Table 1. Summary of spectral changes during meditation and mind wandering of delta (0.5 – 4 Hz), theta (4 – 7 Hz), alpha (8 – 12 Hz), beta (13 – 30 Hz) and theta/beta ratio versus meditation. Up-arrows indicate an increase of the respective EEG-correlate whereas the lower arrow symbolized a decrease in the respective EEG-correlate compared to either rest or mind wandering. Crossed cells denote inconclusive or contradictory findings. a) Increased Theta is correlated with meditation experience and thus increased in experienced practitioners. b) On the contrary, Theta have been suggested to be reduced during meditation compared to rest in novice practitioners. ^{23,32,38}

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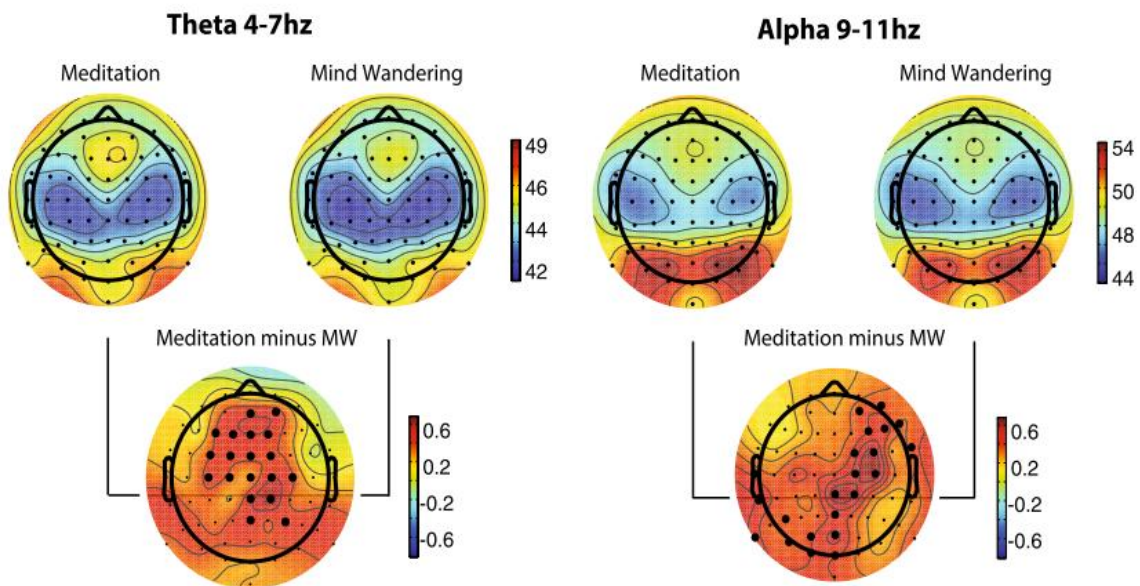


Figure. 1 Event-related spectral perturbation (ERSP) plots, and differential plots of significance in theta (4–7 Hz) and alpha (9–11 Hz) band activity for expert meditation practitioners. Power scale is expressed in $\mu\text{V}^2/\text{Hz}$. Black dots on the difference plots indicate electrodes significant at $p < 0.02$ after cluster correction for multiple comparisons. From Brandmeyer and Delorme *et al* (2018).²³

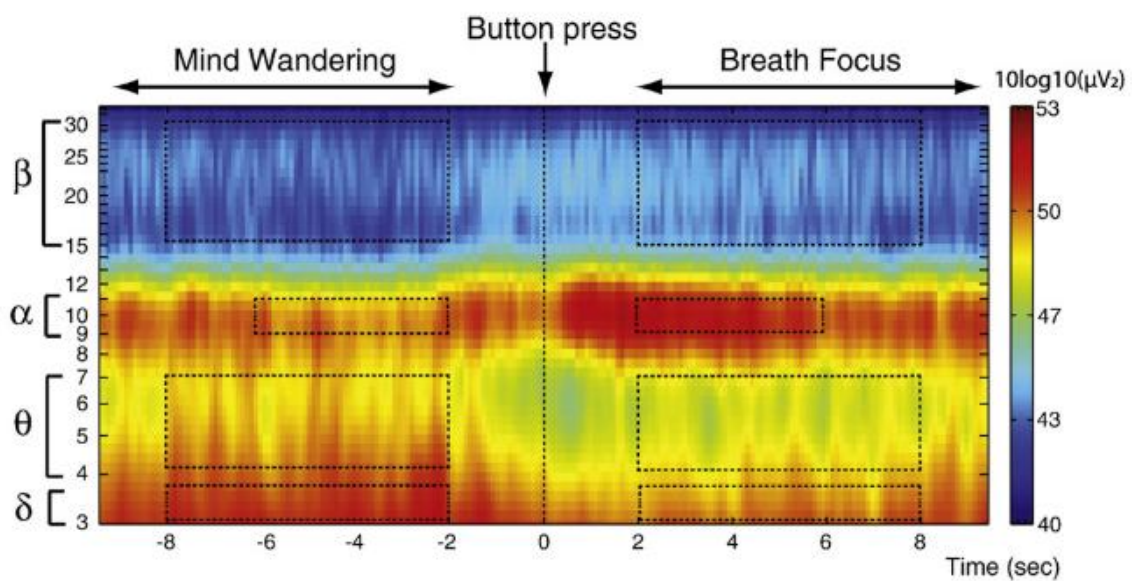


Figure. 2. Time frequency decomposition of transition from mind wandering to breath focus at electrode site Oz. Mind wandering was defined as the period preceding the meta-conscious event (button press) and breath

focus was defined as the period following the meta-conscious event. Topographic maps of power difference are shown for the 2–3.5 Hz (δ), 4–7Hz (θ), 15–30 Hz (β) frequency bands from –8 to –2 s before and from 2 to 8 s after the button press. Adapted from Braboszcz and Delorme (2011).³¹

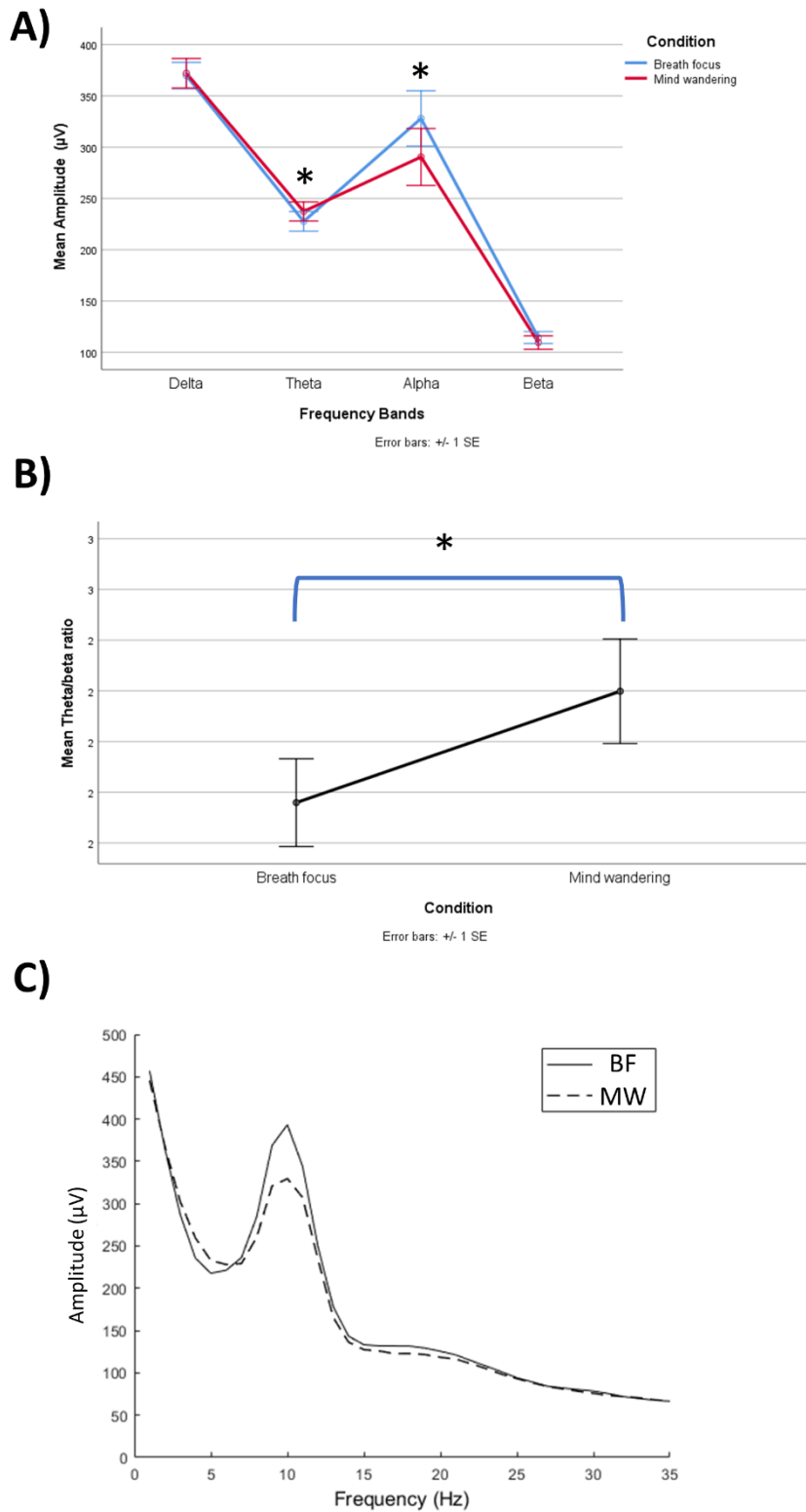


Figure 3. Amplitude changes across the electrodes during mind wandering and breath focus episodes. Amplitude changes between Mind wandering (MW) and breath focus (BF) for each frequency band. A) Estimated

mean amplitude (μV) for band $\text{delta}_{1-3\text{Hz}}$, $\text{theta}_{4-7\text{Hz}}$, $\text{alpha}_{8-12\text{Hz}}$, $\text{beta}_{13-30\text{Hz}}$ and **B)** theta/beta ratio for MW and BF condition. **C)** Grand amplitude average across the electrodes for MW (straight lines) and MW (dashed lines). Statistical significance: * $p < 0.05$.

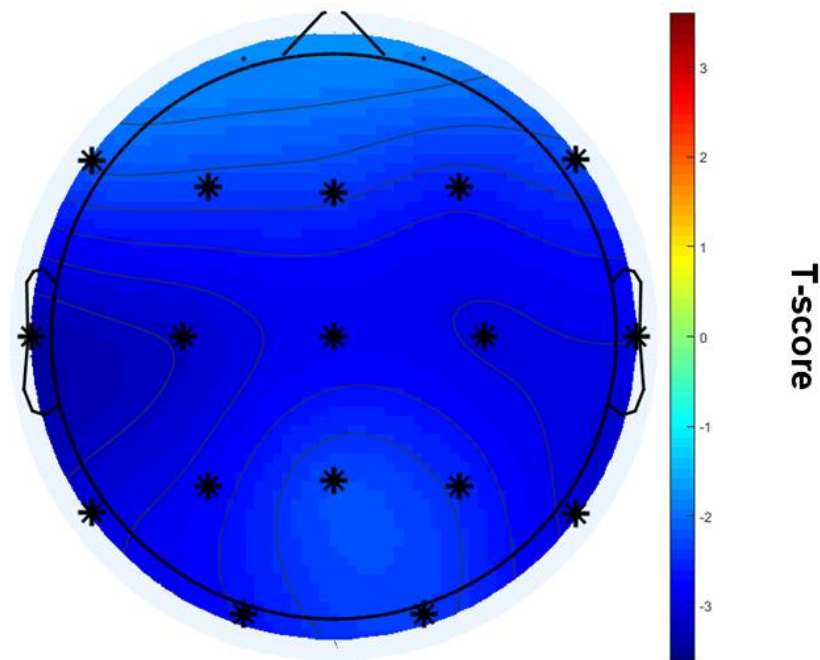


Figure 4. Topographical power changes in Mind wandering versus Breath focus in Alpha frequency. Mind wandering (MW) and breath focus (BF) episodes were measured using a probe-caught paradigm. Spectral electrodes T-values of $\text{alpha}_{8-12\text{Hz}}$ MW versus BF corrected for Bonferroni multiple comparison. Alpha power decreases during MW and specifically in 'F7', 'F3', 'Fz', 'F4', 'F8', 'T3', 'C3', 'Cz', 'C4', 'T4', 'T5', 'P3', 'Pz', 'P4', 'T6', 'O1', 'O2' electrodes. Asterisks represent statistical significance ($p < 0.05$), corrected for multiple comparison.

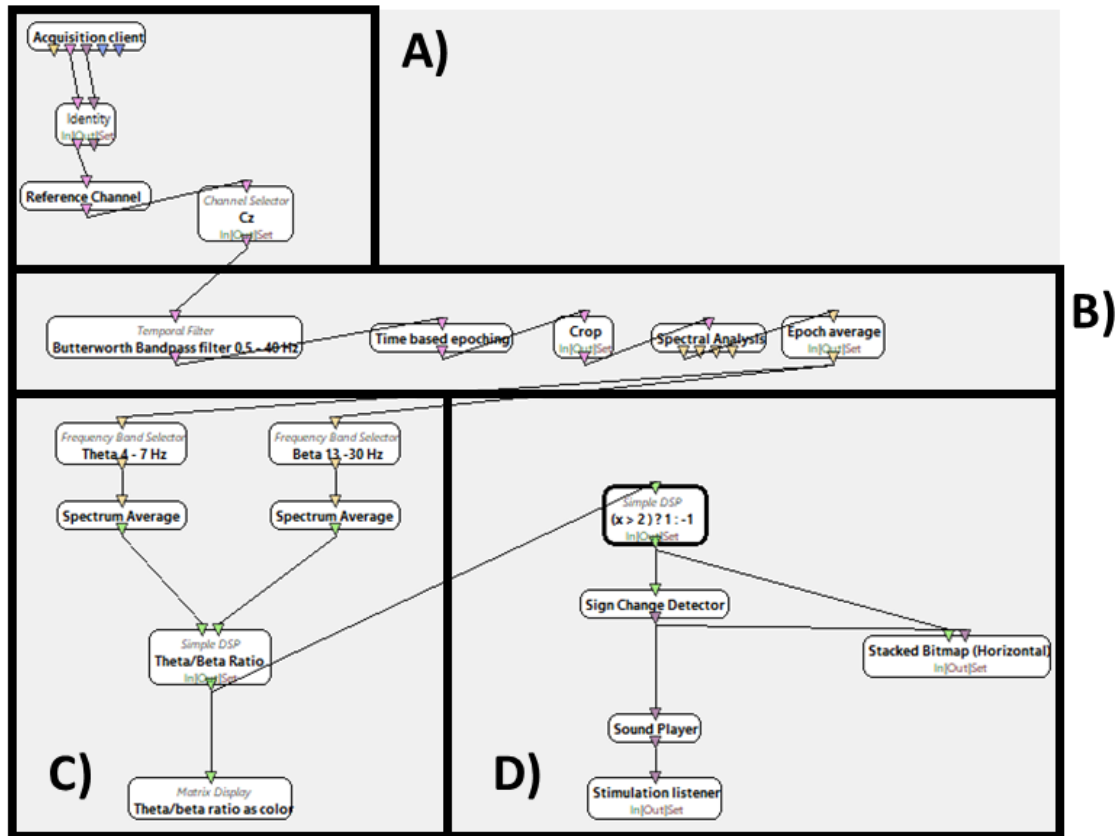


Figure 5. Neurofeedback protocol based on theta/beta ratio. OpenVibe Designer screen that extract, filters and translate raw EEG-data into auditory feedback. Every box represents an action where every line represents the flow of information. **A)** Connection between the BCI-EEG amplifier. EEG-data is extracted from the EEG-amplifier and the 'Cz' channel is filtered out afterwards, **B)** EEG-data pre-processing, the raw EEG-signal is filtered using a bandpass filter and epoched each 0.25 seconds for 2 seconds long. Also, data above 100 μV is capped and decomposed into spectral components and the epoch average is calculated. **C)** EEG-feature extraction. Theta/beta ratios are calculated and plotted. **D)** Feedback delivery. Ratios above a threshold of 2 deliver auditory feedback to the participant where feedback lower than 2 deliver no feedback.

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Appendix I: Supplementary Materials

I.A Extended experimental setting

Participants followed five different conditions: rest state, mind wandering condition, meditation condition, heartbeat counting condition and arithmetic condition. All the instructions were performed in English, unclear information was further clarified in French or in Dutch. The first condition lasted five minutes and was called “rest state”, the participants were told to “Close your eyes, try to relax and not to fall in sleep”. The second condition, mind wandering condition, had as main goal to detect mind wandering and breath concentration episodes in novice meditators. Participants were instructed to close their eyes, focus on their breath, and try not to fall in sleep, this lasted between 30 and 40 minutes. The participants started with one trial and went further. They were told they could use the strategy they seemed fit: attentional focus on their nostrils, abdomen, etc. At pseudorandom time points (20 seconds - 60 seconds), a bowl sound was displayed, and the participants were instructed to open their eyes after hearing the sound. The screen display assessed the participants if they were thinking about something else or if they were focusing on their breath. Afterwards the participant’s confidence on their previous answer was recorded in a scale from 1 to 7 (see supplementary figure). As following, the participant’s feeling was asked through a non-validated questionnaire asking if they were feeling either calm or excited on a scale from 1 to 9 (see supplementary material). In the third condition, meditation condition, the participants were instructed to do the same as they were doing before. This condition lasted 5 minutes. During the fourth condition, heartbeat counting condition, the participants were instructed to count their heartbeat without touching their pulse. After one trial, the subjects performed 4 times this task. The fifth condition was called as “arithmetic condition”. The participants were instructed to sum in a Fibonacci pattern starting from two numbers e.g $1 + 2 = 2$; $2 + 1 = 3$; $3 + 2 = 5$. After they surpassed 100, they were asked to tell the number to the investigator. This task was done with eyes closed and it had 5 trials. After the rest state, mind wandering condition, meditation condition and heartbeat counting condition the participants were asked to fill-in a paper version of a non-validated questionnaire asking them on how they were feeling after each condition. The EEG data of mind wandering condition is the data that will be further pre-processed and analysed.

I.B MAAS Questionnaire

The Mindful Attention Awareness Scale (MAAS)

The trait MAAS is a 15-item scale designed to assess a core characteristic of mindfulness, namely, a receptive state of mind in which attention, informed by a sensitive awareness of what is occurring in the present, simply observes what is taking place.

Brown, K.W. & Ryan, R.M. (2003). The benefits of being present: Mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology*, 84, 822-848.

Carlson, L.E. & Brown, K.W. (2005). Validation of the Mindful Attention Awareness Scale in a cancer population. *Journal of Psychosomatic Research*, 58, 29-33.

Instructions: Below is a collection of statements about your everyday experience. Using the 1-6 scale below, please indicate how frequently or infrequently you currently have each experience. Please answer according to what really reflects your experience rather than what you think your experience should be. Please treat each item separately from every other item.

almost very somewhat somewhat very almost never 1 2 3 4 5 6 always frequently frequently
infrequently infrequently

_____ 1. I could be experiencing some emotion and not be conscious of it until some time later.

_____ 2. I break or spill things because of carelessness, not paying attention, or thinking of something else.

_____ 3. I find it difficult to stay focused on what's happening in the present.

_____ 4. I tend to walk quickly to get where I'm going without paying attention to what I

experience along the way.

_____ 5. I tend not to notice feelings of physical tension or discomfort until they really grab

my attention.

_____ 6. I forget a person's name almost as soon as I've been told it for the first time.

_____ 7. It seems I am "running on automatic," without much awareness of what I'm doing.

_____ 8. I rush through activities without being really attentive to them.

_____ 9. I get so focused on the goal I want to achieve that I lose touch with what I'm doing

right now to get there.

_____ 10. I do jobs or tasks automatically, without being aware of what I'm doing.

_____ 11. I find myself listening to someone with one ear, doing something else at the same

time.

_____ 12. I drive places on 'automatic pilot' and then wonder why I went there.

_____ 13. I find myself preoccupied with the future or the past.

_____ 14. I find myself doing things without paying attention.

_____ 15. I snack without being aware that I'm eating.

Scoring: To score the scale, simply compute a mean (average) of the 15 items.

I.C POOMS Questionnaire

Below is a list of words that describe feelings people have. Please **CIRCLE THE NUMBER**

THAT BEST DESCRIBES HOW YOU FEEL RIGHT NOW.

	Not At All	A Little	Moderately	Quite a lot	Extremely
Tense	0	1	2	3	4
Angry	0	1	2	3	4
Worn Out	0	1	2	3	4
Unhappy	0	1	2	3	4
Proud	0	1	2	3	4
Lively	0	1	2	3	4
Confused	0	1	2	3	4
Sad	0	1	2	3	4
Active	0	1	2	3	4
On-edge	0	1	2	3	4
Grouchy	0	1	2	3	4
Ashamed	0	1	2	3	4
Energetic	0	1	2	3	4

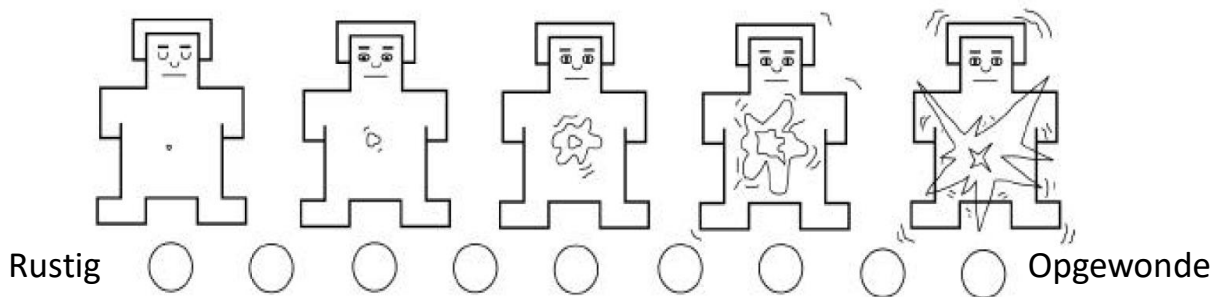
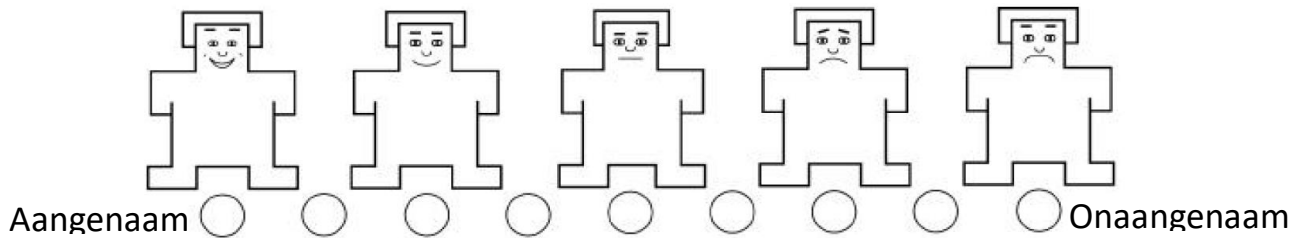
Hopeless	0	1	2	3	4
Uneasy	0	1	2	3	4
Restless	0	1	2	3	4
Unable to concentrate	0	1	2	3	4
Fatigued	0	1	2	3	4
Competent	0	1	2	3	4
Annoyed	0	1	2	3	4
Discouraged	0	1	2	3	4
Resentful	0	1	2	3	4
Nervous	0	1	2	3	4
Miserable	0	1	2	3	4

PLEASE CONTINUE WITH THE ITEMS ON THE NEXT PAGE

	Not At All	A Little	Moderately	Quite a lot	Extremely
Confident	0	1	2	3	4
Bitter	0	1	2	3	4
Exhausted	0	1	2	3	4
Anxious	0	1	2	3	4
Helpless	0	1	2	3	4
Weary	0	1	2	3	4

Satisfied	0	1	2	3	4
Bewildered	0	1	2	3	4
Furious	0	1	2	3	4
Full of Pep	0	1	2	3	4
Worthless	0	1	2	3	4
Forgetful	0	1	2	3	4
Vigorous	0	1	2	3	4
Uncertain about things	0	1	2	3	4
Bushed	0	1	2	3	4
Embarrassed	0	1	2	3	4

I.D Non-validated questionnaire



I.E MATLAB Script

```
clear all
clc

%% Section 1: Determination of EEG-parameters beforehand
%Determination of subject parameters beforehand
amount_of_subjects = 1:28;
amount_of_subjects(:,21) = [];
amount_of_subjects(:,6) = [];
amount_of_subjects(:,4) = [];

%Launching option file for reading EEG21locs file

option_text_EEG21 %option file for text EEG21locs
EEG_chan_var = table2struct(readtable('EEG21_tab.txt', opts));
clear opts

% EEG parameters
window_size = 512*2;
window = 512; %sliding window size; 1 second
noverlap = 461; %overlap between windows ~ 90 %
freq = 1:35; %frequencies I wanted to extract
fs = 512; %sampling rate
electrodes_array = ["FP1", "FP2", "F7", "F3", "Fz", "F4", "F8", ...
```

```

    "T3", "C3", "Cz", "C4", "T4", "T5", "P3", "PZ", "P4", "T6", "O1", "O2",
    "A1", "A2", "E_SC_GSR", "F_BVP", "G_RSP", "H_TEMP", "HR", "HRV_amp",
    "HRV_LF_Power", "HRV_HF_Power", "RR", "Events"];

%Trigger names

trig_name_sound = 'RS232 Trigger: 100';
trig_name_breath = 'RS232 Trigger: 101';
trig_name_mw = 'RS232 Trigger: 102';

%Options of inporting EEGdata
options_import_EEGdata %options for importing EEG_data + physio importation

%% Section 2: EEG DATA CLEANING & Importing text files

for i = amount_of_subjects % for-loop for preprocessing purposes, clean it
and save it

    clearvars EEG %%Clear EEG before running eeglab
    disp('Starting Importing Subject data')

    % %%% Section 2.1: Import data from 1 subject & Variables%%%%%%%%%%

    filename = ['P_' int2str(i) '_MW' '.txt'] %Readfile 'P' 'number 'MW'
e.g readfile P_1_MW
    EEG_data = readtable(filename,opts);
    event = [EEG_data.Samples EEG_data.Events];
    samples = EEG_data.Samples;
    disp('Subject data successfully imported')

    % Trigger preprocessing
    tmp = (find(contains(EEG_data.Events, 'R'))); %find every event
containing 1 (everyone of them)
    trig_names = [EEG_data.Events(tmp)]; % %Save the trig_names in a matrix
    trig_times = [tmp] - 1; %samples start telling from 0, MATLAB index
starts telling from 1 therefore -1
    trig_name_time = table(trig_times, trig_names);

    trig_names([1:4],:) = [];
    trig_name_time([1:4],:) = [];%eliminate the first trigger (Trial)

%    %Save True/false values for every trigger will be used for epoching
    trig_name_time.TF_100 = contains(trig_names, 'RS232 Trigger: 100(');
    trig_name_time.TF_101 = contains(trig_names, 'RS232 Trigger: 101(');
    trig_name_time.TF_102 = contains(trig_names, 'RS232 Trigger: 102(');
    total_answers{i} = varfun(@sum, (trig_name_time(:,3:5)));

clearvars tmp

%Remove unnecessary values
EEG_data = removevars(EEG_data, {'Samples', 'Events',
'E_SC_GSR', 'F_BVP', 'G_RSP', ...
'H_TEMP', 'HR', 'HRV_amp', 'HRV_LF_Power', 'HRV_HF_Power', 'RR'});

```

```

% %Section 2.2 Launching EEGLAB and data cleaning
eeglab; % launch eeglab

EEG_data = [table2array(EEG_data)]'; %change EEG_data to array + rows
to arrows (only way EEG_data can be read)

%Import and change data parameters to correct data parameters
EEG = pop_importdata('data', EEG_data); % import data
EEG = pop_editset(EEG, 'srate', 512); %Editing sample-rate
EEG = pop_editset(EEG, 'nbchan', 21); %Edit number of channels
EEG = pop_editset(EEG, 'chanlocs', EEG_chan_var); %Edict channellocs

%Preprocessing Steps

disp('Starting Preprocessing')

EEG = pop_eegfiltnew(EEG, [], 0.5, [], true, [], 0); %low pass filter
EEG = pop_eegfiltnew(EEG, [], 40, [], false, [], 0); % high pass filter
signal = clean_flatlines(EEG); %the problem here is that you use the
electrode labels after removal
amount_flat_channel{i} = size(signal); %save a cellarray, by
determining the channel size helps determining the amount of falt channels
signal = clean_asr(signal, 20);
EEG = pop_interp(signal, EEG.chanlocs , 'spherical');

%save after preprocesing
save(['EEG_post_preprocessing_' int2str(i)], 'EEG', '-v7.3');

disp('Post preprocessed data has been saved, epoching....')

% % Section 2.2 Eventdata Preprocessing: Epoching %%%%%%%%%%
%Data has been save in a table format thus we do not need to
%eliminate two different variables trig_names and trig_time
%these variables can individually be saved if needed

disp('Deleting epochs.....')

for a = 1:size(trig_name_time.trig_times,1) - 1 %for each trial e.g
after trigger 100, 40 trials in total
    delete_epochs(a) = isempty(strfind(trig_name_time.trig_names{a},
'RS232 Trigger: 0(')) == 0;
end

trig_name_time(delete_epochs,:) = []; %deletion of rows == trigger 0
clearvars delete_epochs a x

%Trigger names and meaning
%epoching
%100 = question trigger
%101 = Breath focus answer
%102 = Mind wandering answer

disp('For-loop: Epochs and EEG-data ')

```



```

EEG_backup_data{i} = EEG;

for x = 1:size(trig_name_time.trig_names) -1 %loop trials over 1st
dimension
    if (strfind(trig_name_time.trig_names(x), 'RS232 Trigger: 100')
== 1) % use strfind to identify question marker (trigger 100) and answer
101 (breath focus)
        %answer will be in position trigger 100 + 1

        data1 = EEG.data(1:19, [trig_name_time.trig_times(x)-
window_size:trig_name_time.trig_times(x)-1]);
        [r,c] = find(data1 > 100); %extract the column indices where
the data1 > 100
        data1(:,c) = NaN; %from 1 to 19 channels replace to NaN if one
number is higher than 100 µV
        if (strfind(trig_name_time.trig_names(x+1), 'RS232
Trigger: 101') == 1) %is position x + 1 trigger 101?
            EEG_epochs_med{i,x} = data1;

            elseif (strfind(trig_name_time.trig_names(x+1), 'RS232
Trigger: 102') == 1) %is position x + 1 trigger 102?
                EEG_epochs_mw{i,x} = data1;
            end
        end
    end

clearvars x

for x = 1:size(trig_name_time.trig_names) -4
    if (strfind(trig_name_time.trig_names(x), 'RS232 Trigger: 100') == 1)
% use strfind to identify question marker (trigger 100) and answer 101
(breath focus)
        %Trigger 100 will be in position trigger 100 + 1
        %Answer Confidence is position x+2 and x + 3 is no-validated
        %questionnaire
        EEG_response_trigger{i,x} = {trig_name_time.trig_names(x+1);
trig_name_time.trig_names(x+2);...
trig_name_time.trig_names(x+3)};

    end
end

end

%% Section 3 Spectral analysis
%%Isfinite function checks whether a certain electrode has NaNs
%%spectrogram function checks online finite values e.g 1,2,3... 1000
% NaN's are thus ignored
%Downside of the next method is that I am not able to divide epochs of
%subject 1 or 2 or 3 or .... 28

%% %%% Section 3.1 Subject Average across Epochs and electrodes%%
%% %%%

```

```

for w = amount_of_subjects %Organize empty epochs to subjects
    EEG_subject_med{w} = EEG_epochs_med(w, :);
    EEG_subject_mw{w} = EEG_epochs_mw(w, :);
end

for c = amount_of_subjects
    a = EEG_subject_med{1,c}(1, :);
    b = EEG_subject_mw{1,c}(1, :);
    EEG_subject_med{c} = a(~cellfun(@isempty,a));
    EEG_subject_mw{c} = b(~cellfun(@isempty,b));
end %output: everycell contains the amount of mindwandering or meditation
epochs per participants, without empty epochs

clearvars a b c

%Now it is time to do spectrogram analysis per participant --> convert
%every channel of every epoch to a spectrogram, then average the spectrogram
%of all the channels through all the epochs

for subject = amount_of_subjects
    for epoch = 1:size(EEG_subject_med{1,subject},2)
        for electrode = 1:19
            if (isfinite(EEG_subject_med{1,subject}{1,epoch}(electrode,:))
== true)
                EEG_subject_med_spectrogram{electrode,epoch,subject} =
abs(spectrogram...

(EEG_subject_med{1,subject}{1,epoch}(electrode,:),window,noverlap, freq,
fs));
            end
        end
    end
end

for subject = amount_of_subjects %Spectrogram calculations 19x33x28
    for epoch = 1:size(EEG_subject_mw{1,subject},2)
        for electrode = 1:19
            if (isfinite(EEG_subject_mw{1,subject}{1,epoch}(electrode,:))
== true)
                EEG_subject_mw_spectrogram{electrode,epoch,subject} =
abs(spectrogram...

(EEG_subject_mw{1,subject}{1,epoch}(electrode,:),window,noverlap, freq,
fs));
            end
        end
    end
end

%output: 19x33x28 matrix, (:,:,1) --> 1 = number of subject, rows
%electrodes and culomms epochs

%% %% %% Section 3.2 Subject averaging across electrodes
for subject = amount_of_subjects
    k_med = EEG_subject_med_spectrogram(:,:,subject);
    k_mw = EEG_subject_mw_spectrogram(:,:,subject);

```

```

        for electrode = 1:19
            mean_of_epochs_med{subject,electrode} =
mean(cat(3,k_med{electrode,:}),3);
            mean_of_epochs_mw{subject,electrode} =
mean(cat(3,k_mw{electrode,:}),3);
        end
end %output: 28x19 cells, per participant average of epochs across all the
electrodes

clearvars subject electrodes

for subject = 1:28
    for electrode = 1:19
        mean_of_epochs_time_med{subject, electrode} =
mean(mean_of_epochs_med{subject,electrode},2);
        mean_of_epochs_time_mw{subject, electrode} =
mean(mean_of_epochs_mw{subject,electrode},2);
    end
end

for subject = amount_of_subjects
    for electrode = 1:19
        %average of power of parameters during Mindwandering episodes of
electrodes
        alpha_power_mw_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_mw{subject,electrode}(8:12,:))/5];
        delta_power_mw_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_mw{subject,electrode}(1:3,:))/3];
        beta_power_1_mw_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_mw{subject,electrode}(12:20,:))/9];
        beta_power_2_mw_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_mw{subject,electrode}(20:35,:))/16];
        theta_power_mw_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_mw{subject,electrode}(3:7,:))/5];

        theta_power_2_mw_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_mw{subject,electrode}(4:7,:))/4];
        beta_power_3_mw_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_mw{subject,electrode}(13:30,:))/18];

        %average of power of parameters during Meditation "episodes" of
electrodes
        alpha_power_med_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_med{subject,electrode}(8:12,:))/5];
        delta_power_med_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_med{subject,electrode}(1:3,:))/3];
        beta_power_1_med_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_med{subject,electrode}(12:20,:))/9];
        beta_power_2_med_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_med{subject,electrode}(20:35,:))/16];
        theta_power_med_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_med{subject,electrode}(3:7,:))/5];
    end
end

```

```

        theta_power_2_med_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_med{subject,electrode}(4:7,:))/4];
        beta_power_3_med_subject_per_el{subject, electrode} =
[sum(mean_of_epochs_time_med{subject,electrode}(13:30,:))/18];

    end
end

%mean for meditation (across time)
delta_med_mean_across_electrodes =
cell2table(cellfun(@mean,delta_power_med_subject_per_el, 'UniformOutput',
false));
alpha_med_mean_across_electrodes =
cell2table(cellfun(@mean,alpha_power_med_subject_per_el, 'UniformOutput',
false));
theta_med_mean_across_electrodes =
cell2table(cellfun(@mean,theta_power_med_subject_per_el, 'UniformOutput',
false));
theta_2_med_mean_across_electrodes =
cell2table(cellfun(@mean,theta_power_2_med_subject_per_el, 'UniformOutput',
false));

beta_1_med_mean_across_electrodes =
cell2table(cellfun(@mean,beta_power_1_med_subject_per_el, 'UniformOutput',
false));
beta_2_med_mean_across_electrodes =
cell2table(cellfun(@mean,beta_power_2_med_subject_per_el, 'UniformOutput',
false));
beta_3_med_mean_across_electrodes =
cell2table(cellfun(@mean,beta_power_3_med_subject_per_el, 'UniformOutput',
false));

%mean for mindwandering (across time)
delta_mw_mean_across_electrodes =
cell2table(cellfun(@mean,delta_power_mw_subject_per_el, 'UniformOutput',
false));
alpha_mw_mean_across_electrodes =
cell2table(cellfun(@mean,alpha_power_mw_subject_per_el, 'UniformOutput',
false));
theta_mw_mean_across_electrodes =
cell2table(cellfun(@mean,theta_power_mw_subject_per_el, 'UniformOutput',
false));
theta_2_mw_mean_across_electrodes =
cell2table(cellfun(@mean,theta_power_2_mw_subject_per_el, 'UniformOutput',
false));

beta_1_mw_mean_across_electrodes =
cell2table(cellfun(@mean,beta_power_1_mw_subject_per_el, 'UniformOutput',
false));
beta_2_mw_mean_across_electrodes =
cell2table(cellfun(@mean,beta_power_2_mw_subject_per_el, 'UniformOutput',
false));

```

```

beta_3_mw_mean_across_electrodes =
cell2table(cellfun(@mean,beta_power_3_mw_subject_per_el, 'UniformOutput',
false));

%alpha_theta ratio
alpha_theta_med =
array2table([table2array(alpha_med_mean_across_electrodes)]./[table2array(theta_med_mean_across_electrodes)]);
alpha_theta_mw =
array2table([table2array(alpha_mw_mean_across_electrodes)]./[table2array(theta_mw_mean_across_electrodes)]);

%theta_beta ratio
theta_2_beta_3_med =
array2table([table2array(theta_2_med_mean_across_electrodes)]./[table2array(beta_3_med_mean_across_electrodes)]);
theta_2_beta_3_mw =
array2table([table2array(theta_2_mw_mean_across_electrodes)]./[table2array(beta_3_mw_mean_across_electrodes)]);

theta_alpha_med =
array2table([table2array(theta_med_mean_across_electrodes)]./...
[table2array(alpha_med_mean_across_electrodes)]);

theta_alpha_mw =
array2table([table2array(theta_mw_mean_across_electrodes)]./...
[table2array(alpha_mw_mean_across_electrodes)]);

for electrodes = 1:19 %for loop assignment for correct names
    %basic frequencies
    table_name_alpha_med = join(['alpha', electrodes_array(electrodes)
'MED'], '_');
    table_name_alpha_mw = join(['alpha', electrodes_array(electrodes)
'MW'], '_');
    table_name_delta_med = join(['delta', electrodes_array(electrodes)
'MED'], '_');
    table_name_delta_mw = join(['delta', electrodes_array(electrodes)
'MW'], '_');
    table_name_theta_med = join(['theta', electrodes_array(electrodes)
'MED'], '_');
    table_name_theta_mw = join(['theta', electrodes_array(electrodes)
'MW'], '_');
    table_name_theta_2_med = join(['theta_2', electrodes_array(electrodes)
'MED'], '_');
    table_name_theta_2_mw = join(['theta_2', electrodes_array(electrodes)
'MW'], '_');
    table_name_beta_1_med = join(['beta_1', electrodes_array(electrodes)
'MED'], '_');
    table_name_beta_1_mw = join(['beta_1', electrodes_array(electrodes)
'MW'], '_');
    table_name_beta_2_med = join(['beta_2', electrodes_array(electrodes)
'MED'], '_');
    table_name_beta_2_mw = join(['beta_2', electrodes_array(electrodes)
'MW'], '_');

```

```

    table_name_beta_3_med = join(['beta_3', electrodes_array(electrodes)
'MED'], '_');
    table_name_beta_3_mw = join(['beta_3', electrodes_array(electrodes)
'MW'], '_');

    %ratios
    table_name_alpha_theta_ratio_med = join(['A_T',
electrodes_array(electrodes) 'MED'], '_');
    table_name_alpha_theta_ratio_mw = join(['A_T',
electrodes_array(electrodes) 'MW'], '_');
    table_name_theta_beta_ratio_med = join(['T2_B3',
electrodes_array(electrodes) 'MED'], '_');
    table_name_theta_beta_ratio_mw = join(['T2_B3',
electrodes_array(electrodes) 'MW'], '_');

    table_name_theta_alpha_ratio_med = join(['T_A',
electrodes_array(electrodes) 'MED'], '_');
    table_name_theta_alpha_ratio_mw = join(['T_A',
electrodes_array(electrodes) 'MW'], '_');

    alpha_med_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_alpha_med;
    alpha_mw_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_alpha_mw;

    delta_med_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_delta_med;
    delta_mw_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_delta_mw;

    theta_2_med_mean_across_electrodes.Properties.VariableNames(electrodes)
= table_name_theta_2_med;
    theta_2_mw_mean_across_electrodes.Properties.VariableNames(electrodes)
= table_name_theta_2_mw;

    theta_med_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_theta_med;
    theta_mw_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_theta_mw;

    beta_1_med_mean_across_electrodes.Properties.VariableNames(electrodes)
= table_name_beta_1_med;
    beta_1_mw_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_beta_1_mw;

    beta_2_med_mean_across_electrodes.Properties.VariableNames(electrodes)
= table_name_beta_2_med;
    beta_2_mw_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_beta_2_mw;

    beta_3_med_mean_across_electrodes.Properties.VariableNames(electrodes)
= table_name_beta_3_med;
    beta_3_mw_mean_across_electrodes.Properties.VariableNames(electrodes) =
table_name_beta_3_mw;

```

```

alpha_theta_med.Properties.VariableNames(electrodes) =
table_name_alpha_theta_ratio_med;
alpha_theta_mw.Properties.VariableNames(electrodes) =
table_name_alpha_theta_ratio_mw;

theta_2_beta_3_med.Properties.VariableNames(electrodes) =
table_name_theta_beta_ratio_med;
theta_2_beta_3_mw.Properties.VariableNames(electrodes) =
table_name_theta_beta_ratio_mw;

theta_alpha_med.Properties.VariableNames(electrodes) =
table_name_theta_alpha_ratio_med;
theta_alpha_mw.Properties.VariableNames(electrodes) =
table_name_theta_alpha_ratio_mw;
end

%% Table preparation for spss

whole_table_for_spss_export = [delta_med_mean_across_electrodes
delta_mw_mean_across_electrodes...
alpha_med_mean_across_electrodes alpha_mw_mean_across_electrodes...
theta_med_mean_across_electrodes theta_mw_mean_across_electrodes...
theta_2_med_mean_across_electrodes theta_2_mw_mean_across_electrodes...
beta_1_med_mean_across_electrodes beta_1_mw_mean_across_electrodes...
beta_2_med_mean_across_electrodes beta_2_mw_mean_across_electrodes...
beta_3_med_mean_across_electrodes beta_3_mw_mean_across_electrodes...
theta_2_beta_3_med theta_2_beta_3_mw];

whole_table_for_spss_export(21,:) = [];
whole_table_for_spss_export(6,:) = [];
whole_table_for_spss_export(4,:) = [];

writetable(whole_table_for_spss_export, 'Data_20_05_ASR20_2');

```

I.F Electrodes Significance List

Electrodes	T-values	Uncorreted P-values	Corrected P-values
FP1	-1.79	0.09	0.09
FP2	-1.82	0.08	0.09
F7	-2.14	0.04	0.05
F3	-2.31	0.03	0.04
Fz	-2.40	0.03	0.04
F4	-2.59	0.02	0.03
F8	-2.28	0.03	0.04

T3	-3.39	0.01	0.02
C3	-3.15	0.01	0.02
Cz	-2.86	0.01	0.02
C4	-2.97	0.01	0.02
T4	-2.93	0.01	0.02
T5	-3.04	0.01	0.02
P3	-2.82	0.01	0.02
Pz	-2.26	0.03	0.04
P4	-2.52	0.02	0.03
T6	-3.02	0.01	0.02
O1	-2.66	0.01	0.03
O2	-2.36	0.03	0.04

Table 2. Overview of statistical values of $\alpha_{8-12\text{ Hz}}$ band through the electrodes. T-values and p-values were acquired using paired-samples t-test. False discovery rate (FDR) corrected p-values were corrected using the Benjamini-Hochberg procedure.

Appendix II: Experimental preparation

Function check EEG equipment

1. Turn on all power sources
2. Turn on lab laptop
3. Turn on lab computer
4. Make sure that the Nexus Trigger Interface (NTI) is correctly connected to the Nexus:



5. Attach RS232 input to NTI and pc:



6. Switch the NTI on. The NTI can be switched on by pressing the button on top of the NTI for 3 seconds. When the status LED stays green the NTI is ready for operation. If the button is released to soon, the NTI will turn off again.
7. Turn on the switcher (white box) connected with the LC screen.

1. PREPARATION

PART I. EOG PREPARATION

1. Attach the Arbo self-adhesive ECG/sEMG electrodes based on Ag/AgCl (small ones) to the EXG sensors.
2. Prepare the skin above and below the left eye and to the side of the left and right eye by gently cleaning the skin with a cotton pad with some alcohol on it or NuPrep. Please notice that the skin below the eyes can be very sensitive. Make sure that the eyes of the participants are closed when you do this!
3. **Attach electro-oculographic electrodes (EOGs)** to monitor vertical (e.g., blinks) and horizontal eye movements. Remove the film right before placing the electrodes.

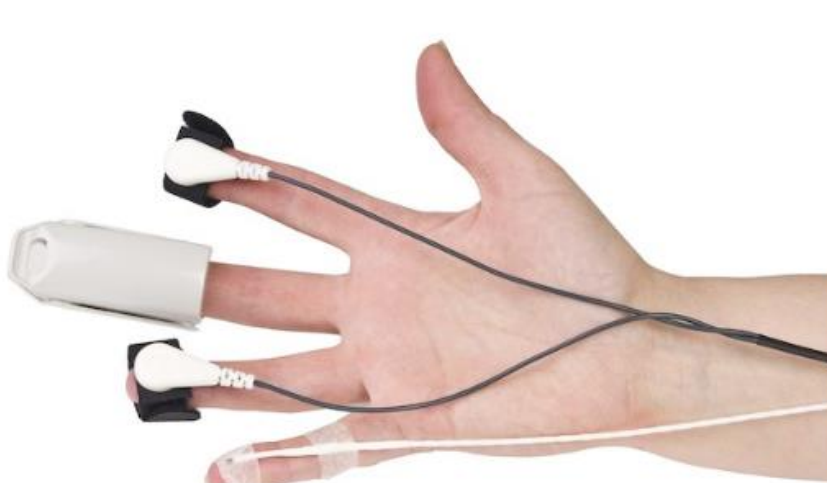


- a. **Vertical eye movements (VEOG):** place the red electrode of Pair 1 approximately 2 cm above the left eye. Place the black electrode of Pair 1 below the left eye.
- b. **Horizontal eye movements (HEOG):** place the red electrode of Pair 2 directly to the side of the left eye and the black electrode to the side of the right eye.

PART II. Skin conductance, bvp and temperature

Desinfect the fingers anular, middle and index finger of the non-dominant hand with a bit of alcohol.

See montage below:



For skin conductance:

1. **Apply conductive gel**
2. **Attach the sensors** on the palmar side of each fingertip, secure the Velcro strap. Make sure the sensor isn't too tight or too loose. If the Velcro is not sticky anymore replace it
3. Make sure the wires are not crossed. Attach wires to wrist with tape.
4. If necessary secure the wires in place with paper tape.

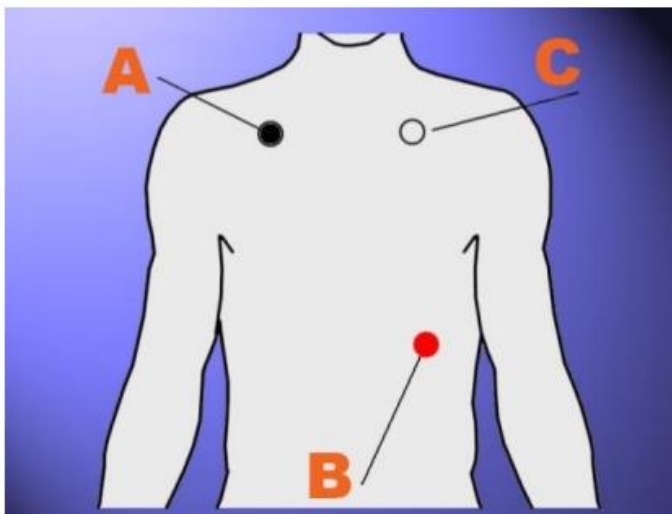
For BVP:

1. No conductive gel
2. The wire should rest on the back side of hand (see figure). Eventually, attach the wire to the hand with tape.
3. Make sure not to move the sensor too much since this will influence your signal and create artifacts/noise.

For temperature sensor, just attach the cable as depicted.

PART II. ECG

The montage of the ECG must be placed as depicted below:



You will ask the participants to clean the skin with an alcohol pad at all electrode positions before applying the electrodes. Only electrodes A and B are placed (electrode C is a reference that we already have in EEG). Show the picture to the participants and ask them to place the electrodes on their own. Optimally, the red (positive) electrode would be placed below the left rib cage (B) and the black (negative) electrode just below the right collarbone (A).PART III. EEG preparation

1. **Preparation** of the skin. Use NuPrep gel to clean forehead and skin behind ears. Rub it into the skin lightly (e.g. with a cue tip), after which you can clean any excess gel with a clean cotton pad.
2. **Select the correct cap size.** Measure the head circumference in cm (hat size) of the participant around the widest point on the head using a flexible tape measure:
 - 50 – 54 cm = cap size Small
 - 54 – 58 cm = cap size Medium
 - 58 – 62 cm = cap size Large

It is very important to ensure a cap is fitted correctly, as a cap that is too large may reduce quality of EEG recordings, or make preparation of electrodes and lowering of impedances much more difficult. To check the fit of the cap, ask participants to nod head up and down, and turn head side to side. Also, gently press down on one of the electrode adaptors towards the scalp. If the adaptor bounces back, there may be too much space between electrode adaptor and scalp, and a smaller cap size should be tried.

3. **Mount the cap on the participant.**
 - a. Measure the distance between the participants' nasion (bridge of the nose) and inion (bump on lower base of skull). The middle point should correspond to Cz.
 - b. When cap is positioned correctly, the frontopolar electrodes Fp1/Fp2 should lie directly above the eyebrows, and the inion electrode should lie directly on top of the inion. Also check that CZ is right-left centered as well, and that lateral electrode positions are symmetrical. Finally, make sure that the center line of electrodes is centered on the participant's head.
4. **Apply electrolyte gel** to minimize impedance of electrical connection between electrode and scalp. This gel conducts electrical activity from the scalp to the electrodes themselves.
 - a. Fill 2 syringes with mixture of EEG electrolyte gel.
 - b. Remove the hair under the electrode side by moving the blunt end of the needle in one direction until the skin is clearly visible.
 - c. Press with two fingers the electrode gently to the skin.
 - d. Gently scrub on the scalp through the electrode opening by twirling the blunt end.
 - e. Inject the electrode gel. Fill the electrode cavity completely such that the gel comes out of the opening when pressed to the scalp.
 - f. Remove excessive gel with a tissue. Make sure to fill all electrodes.

2. SIGNAL CHECK

1. In **Biotrace+**: press “L” > Julio’s screen> MW-EXP
2. Press the record button at the bottom of the screen. Choose any of the test participants.
3. The new session recording screen will appear. The computer starts connecting to the NeXus > ‘record’.

VEOG/HEOG

1. Ask participant first to look straight ahead and to fixate at a certain point.
2. Then ask participant to blink. You should now see a peak at the VEOG (top panel).
3. Ask participant to look from left to right and back. You should now see a peak at HEOG (bottom panel).

SKIN CONDUCTANCE

1. You should see a signal between 2 and 20 microSiemens.
2. Ask your participant to breathe in and out deeply, this should be visible in the SC stream. If so, you have a signal and can skip the following remarks.
3. Ask your participant hold their breath and 'clench' their toes, this should be visible in the SC stream.

EEG SIGNAL

1. **Check impedances.** Press the “signal check” bottom at the top of the screen. Make sure that for every electrode there is a green check mark and that the signal is NOT ZERO. You will get a green check (between 0 and 2.5 kOhm), an orange explanation mark (between 2.5 and 5 kOhm) and a red mark (above 5 kOhm).

To lower impedances:

- a. Continue to twist blunt needle on the scalp and try to move some hair away from the electrode. It may be necessary to apply more gel using. Do not use excessive pressure as it may cause abrasions.
- b. Prevent electrolyte gel from swelling underneath the adapter rim and bridging two adjacent electrodes.

Impedances for all electrodes are compared to both the **ground** and **reference electrodes** during data analysis. Therefore, if there are poor impedances on either of these electrodes, good impedances will not be possible on any other electrodes. Thus, the ground and reference electrodes should be prepared and checked first.

2. **Check resting signal.** If all impedances are okay, go back to the EEG screen. Observe the resting activity of all electrodes and make sure there are no “bad” channels; that is, electrodes that produce flat line signals, or show a lot of activity while the participant is resting. If any bad channels are suspected, it may be necessary to apply more electrode gel and scrub to minimize impedances.
3. **Also check the FFT signal on the right side.** If there are a few channels that have a peak that is more pronounced than in other channels, check those electrodes. A peak at 50 Hz in all channels indicate that there is a lot of noise from the environment.
4. If there is a bad signal and you are not able to fix it, write it down in your protocol.
5. Tell the participant to avoid eye blinks, and tensing muscles in their forehead or jaw, as this will introduce noise into the EEG data. Allow them to view a computer screen with the active EEG signals. Ask participants to blink eyes/raise eyebrows/clench jaw/tighten forehead muscles, and then observe the effect on EEG signal. Emphasize that these large changes in the signal make it hard to understand the information that is collected, and so it is important to avoid.

Once all the electrode signals look acceptable, begin the experiment.

Appendix III: OpenVibe Lab Guide

This guide was developed for start-up in Openvibe with Nexus-32, the majority of the information was taken from the [Openvibe website](#). OpenVibe Software has two main software's:

- OpenVibe 64-bit Acquisition : Acquires the EEG signal.
- OpenVibe 64-bit Designer: user friendly interface with algorithms for developing Neurofeedback and brain-machine interface algorithms.

Before starting to work with OpenVibe, you need to install the following programs:

- **Microsoft Visual Studio 2019 ([here](#))**: this program allows us to perform some developers tools, configuration files etc. from OpenVibe. It reads basically C++ language. This one is not necessary if you do not want to develop in C++.
- **Notepad++**: reads the configuration files of OpenVibe, highly recommended to download.
- **OpenVibe 2.0**.
- **MATLAB/ Python (optional)**: these programs will work as an external plugin in OpenVibe.
- **Ogre (optional)**: this program allows you to develop virtual reality scenarios for Neurofeedback training, motor imagery...
- **Lab stream layer (Optional)**: This program allows to lay down a communication path between the acquisition server and other software's, like MATLAB, without using OpenVibe.

2. Structure of OpenVibe

A. Introduction

Before we start developing scenarios with OpenVibe, we need to understand its folders, where to find the important files, how to change a configuration file and so on. Why? It's simple, there will be always a chance that OpenVibe start bugging. In this section, I will elaborate on:

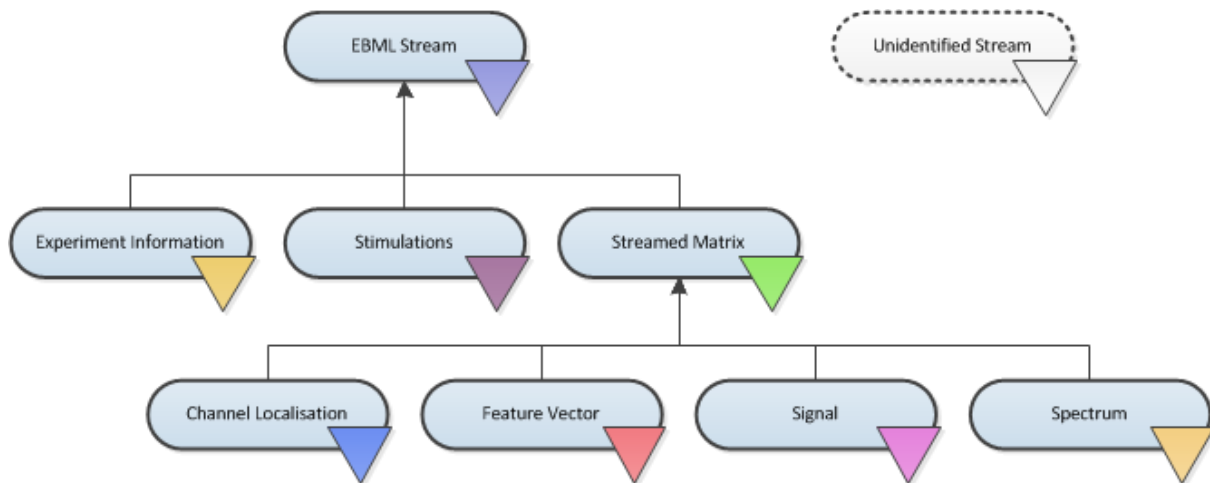
- Stream Structures: Information flow between OpenVibe and other
- The executable files of OpenVibe
- Folder Structures
- Configuration files

B. Stream structure ([as in the OpenVibe Website](#))

All the streams are defined using EBML (Extensible Binary Meta-Language). They are all structured in 3 sections:

- **HEADER:** that part is the first ever sent and received on the stream, when the user presses “play” in a scenario. It usually contains the stream description used by the boxes and algorithms to initialize everything properly (e.g. size of an internal buffer)
- **BUFFERS:** the number of buffers that may then transit through the stream is unlimited. Buffers contain the payload, e.g. the current signal matrix.
- **END:** that last part is received once, when the user presses “stop” in a scenario. This mechanism is not concretely used in existing boxes; however, everything is implemented to handle it.

The stream hierarchy is displayed on figure 1 below. Every lower stream also contains the information specific to the upper stream. The color of the corresponding input and output in the Designer are also displayed ([From the Openvibe website](#)).



3. Acquisition Server

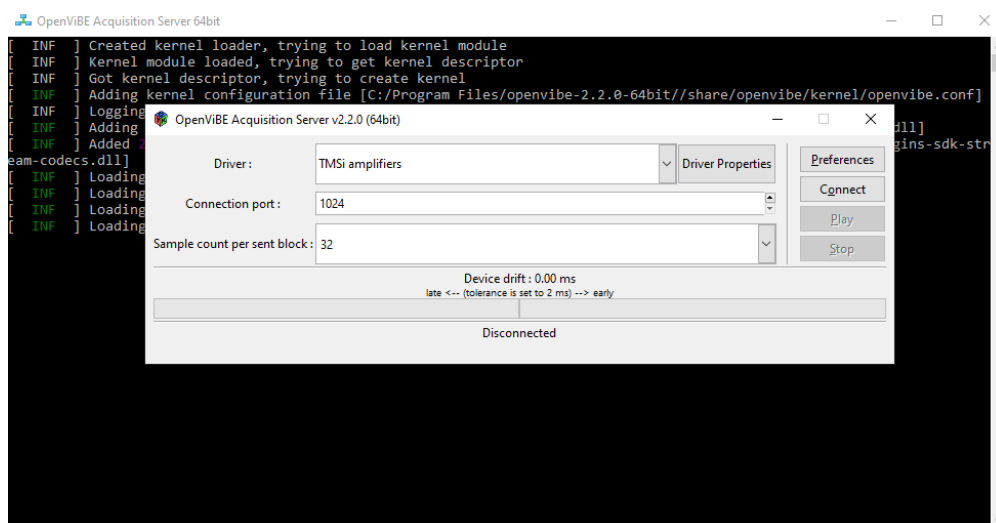
A. Initializing and Choosing the right user interface options

The Acquisition software acquires the EEG signal from the EEG amplifier, in our case Nexus32 amplifier.

This program can be found in windows in the following folder after installation:

C:\Users\[your-user-name]\AppData\Roaming\Microsoft\Windows\Start Menu\Programs\OpenVibe 2.2.0 (64bit)

When we initialize OpenVibe Acquisition software, we get:



The interface offers the next options:

- Driver – Driver Properties
- Connection Port
- Sample count per sent block
- Preferences
- Connect

Driver – Driver Properties

The acquisition acquires the signal from the EEG amplifier, in order to achieve this, we need something called “drivers”. A driver is a software that allows you acquire the EEG signal from the amplifier to OpenVibe and it provides a friendly user interface for regular users. Every amplifier (BrainVision Amplifier, OpenBCI....) has a specific driver for OpenVibe. In our case, we don’t have a driver for MindMedia Nexus32 in the 64-bit OpenVibe Version version. Therefore, we need to use the **TMSi amplifier**. Why? Because MindMedia and TMSi apparently have the same driver program. Don’t forget that. Note that Nexus-10-MKII cannot connect with OpenVibe due to the lock system which opens only by using Biotrace+. Although I didn’t contact Mind Media on this issue, it seems worth exploring whether they would let you connect Nexus-10 MKII.

In our case, we don't need to worry about other drivers but keep in mind that in order to make connection with the respective device, we need to have the correct driver. No driver = no connection. The TMSi Universal driver has different configurations:

- Subject Settings

- Identifier: Subject number
- Age
- Gender

- Driver settings

- Connection protocol: USB, Wi-Fi, network, or Bluetooth
- Device: Our device Nexus-32 + Serial Number
- Sampling frequency

- Additional settings

- Impedance Limit: set the threshold for yourself
- Check impedance: control if all the impedances are below a certain level.

In case you have the idea to develop your own driver, you can use the skeleton software of OpenVibe, for more information refer to the documentation of the OpenVibe. If that is the case, you would need a certain knowledge of C++.

Connection port

The connection port is a virtual port that connects the acquisition software with the designer software, it is by default 1024. Without this port, there would be no data transfer between both software's. If you want to define other port, it is okay but keep in mind that you would need to change the settings of designer software. For more detailed information, check the website of OpenVibe.

4. Designer Software

A. Introduction

See “Scenario Launch Manual” in the OpenVibe_experiment folder.

B. Scenarios – Special Boxes

EOG Denoising

EOG denoising is divided in two different steps:

1. Calibration
2. Filtering

Before filtering online your data from EOG artifacts, you need to calibrate your data with the box: EOG_Denoising calibration, found in Boxes >> Signal Processing >> Denoising. First, create a scenario with the EOG denoising calibration box. This box needs to receive input from two different signal streams: EOG and EEG. The output will be automatically saved as a matrix:

`${Player_ScenarioDirectory}/b-Matrix-EEG.cfg.`

The box can be configured to be started through a stimulus, for instance “pressing bottom A” and it can be configured to be finished after “pressing bottom U”. The main reason to not set an automatically start and end, is that we can check first if the EEG signal goes through correctly. After pressing A, you will receive as output in the console:

```
[ INF ] At time 13.375 sec <Box_algorithm::(0x0000416e, 0x00001e7e) aka EOG_Denoising_Calibration> Start time: 14
```

After pressing U, you will receive as output in console:

```
[ INF ] At time 28.250 sec <Box algorithm::(0x0000416e, 0x00001e7e) aka EOG_Denoising_Calibration> End time: 29
```

It will take a while (30' – 1 minutes) before the algorithm calculates the EOG noise matrix. Afterwards the console will print:

```
[ INF ] At time 77.000 sec <Box algorithm::(0x0000416e, 0x00001e7e) aka EOG_Denoising_Calibration> b Matrix was successfully calculated
```

This means that the EOG file has been saved, if you don't get this file, restart again with the denoising file. Also, you need to watch out that when you read a file, that you don't overpass the reading capacity (For instance: if you have a file that is 10 times points long, and you exceed time point 10, your calculation will fail).

Second, you need to create a new scenario with the box algorithm of EOG denoising, which follows the same input rules as the box mentioned above. After initializing the EOG denoising, your EEG will be cleaned from EOG artifacts. What EOG denoising basically does is to use the EOG calibration matrix as a reference to clean the EOG's artifacts following Schlogl's article of 2007. In the case you want to clean the EOG noisy in any other way, you will have two main options: program the filter with MATLAB or develop an OpenVibe box with the algorithm you want implement.

Fast Fourier Transformation

The FFT is performed by the box: Spectral analysis, which gets input from your EEG signal and translates your signal in its phase and amplitude. It is recommended after a FFT to perform to corroborate that the FFT calculation goes as planned. The output of the FFT can be amplitude and phase, which can be displayed trough a Stacked bitmap. The real and imaginary part of the FFT can be mixed in the IFFT box which reconstructs again in a signal for instance.

Power Spectrum display

If you want to display the power of the amplitude, use instant bars. Which can be found in Visualization >> Advanced Visualization >> Instant Bars. It gets input from the spectral analysis, therefore a spectrum.

C. Settings OpenVibe Boxes

Since this feature has not been well documented, I will explain here an interesting option to save your settings in a certain box of a scenario. Remember that some boxes have features that can be edited by just clicking in the box configuration? Well this configuration can be saved by doing the next:

1. Create an empty text file or Notepad++ file (not tested).
2. Go to OpenVibe Designer and click on save of the configuration settings.
3. Insert the location of the text file you created
4. Save it and apply

When you open the text file you will see that the settings have been saved, this can be quite useful if you want to save complex configuration that did take you a while to make.

Example:

```
<OpenViBE-SettingsOverride>
```

```
  <SettingValue>32</SettingValue>
```

```
  <SettingValue>C:/Program Files/MATLAB/R2019a/bin/win64/MATLAB.exe</SettingValue>
```

```
  <SettingValue>${Player_ScenarioDirectory}</SettingValue>
```

```
<SettingValue>tuto2_FFT_filter_Initialize</SettingValue>
```

```
<SettingValue>tuto2_FFT_filter_Process</SettingValue>
```

```
<SettingValue>tuto2_FFT_filter_Uninitialize</SettingValue>
```

```
<SettingValue>20</SettingValue>
```

```
<SettingValue>10</SettingValue>
```

```
<SettingValue>5</SettingValue>
```

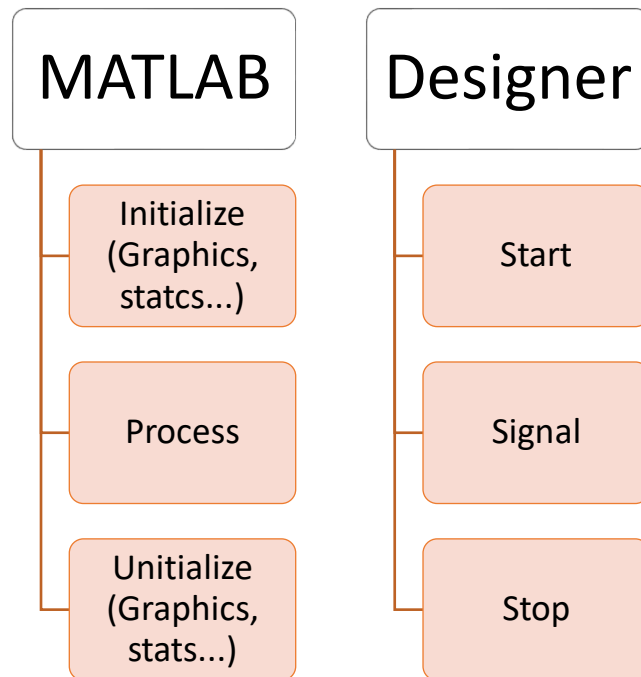
```
<SettingValue>50</SettingValue>
```

```
</OpenViBE-SettingsOverride>
```

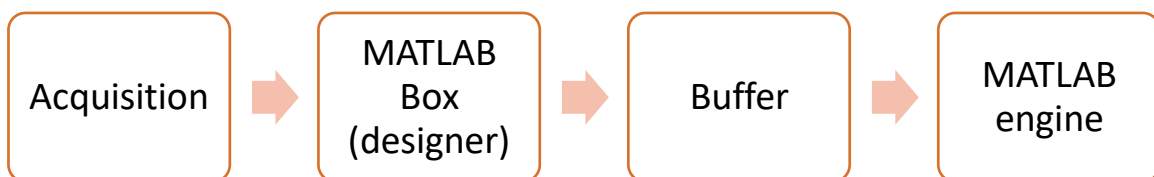
5. MATLAB Environment

A. Understanding The MATLAB – Openvibe interaction

OpenVibe MATLAB box requires three different function: a initialize function, a process function and the unitalize function. The Initializing function is called when in we press play in the designer function, and it stops right after. The process function is initialized after play and will repeat each time the same function, here we can add FFT, Wavelet convolution, filters and so on.... The unitalize function will be stopped after pressing stop in the designer. Here is an overview on how the communication simply works:



Remember that we get the EEG signal from the acquisition software? Well, in this case data is sent from the acquisition software to the acquisition client to the buffer in chunk pieces to MATLAB. Why does it matter? Because we will use the pieces of chunk to make calculations (e.g FFT). It looks like this:



Generally, we can use MATLAB to generate data, visualize data or process data. Depending on what case we are talking about, we will have a different outcoming/incoming data.

B. Main Code structure MATLAB-OpenVibe

As I already mentioned, designer boxes can have inputs, outputs, settings.... These variables can be called through MATLAB.

box.clock	DOUBLE the current openvibe time, updated at every clock tick.
box.clock_frequency	DOUBLE the box clock frequency.
box.settings	an array of setting structure(s)
box.inputs	a cell array of input structure(s).
box.outputs	A cell array of output structure(s).
box.user_data	empty user-space structure.

Notice in the description that some parameters are cell arrays. This is quite important since we will be doing indexing most of the time, we will need to be aware of what index we will use to a single or multiple EEG channels.

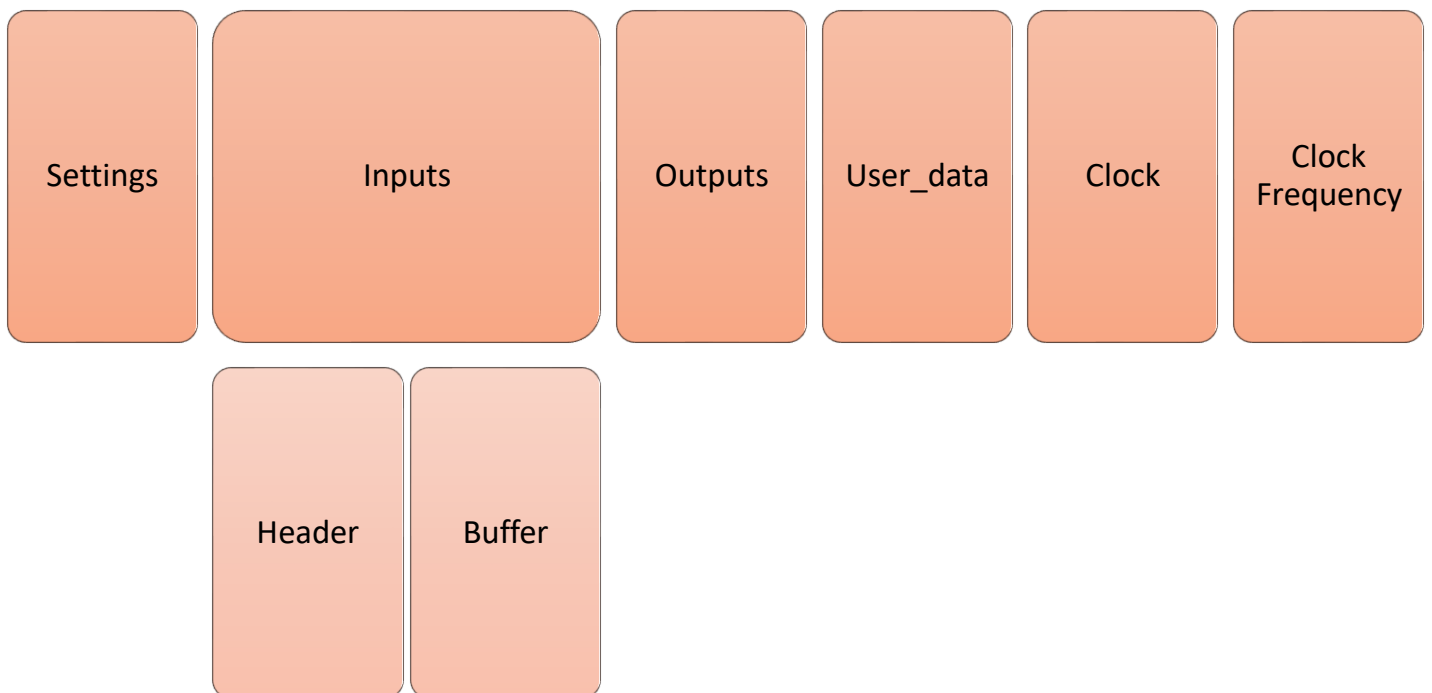
- **Box.settings:** user-defined settings that can be added in the MATLAB box in the OpenVibe designer. `Box.setting.value(1)` is the value of the first box setting that has been defined by the user.
- **Box.inputs:** here you get your data. You don't need `box.inputs` in the case you want to generate data.
- **Box.outputs:** here you will output your data .
- **Box.user_data:** you can define here a value, Boolean... Example: define in the initialize function like `mean_calculation = box.user_data(1)`. In the process function you can further define what you do with `mean_calculation` and in the unitalize function you can save the data for instance the mean of the two last seconds.

Here are some functions we can use to call different chunks. The setting functions are used to set the stimulations, spectrum and so on.

Setting Functions	
<code>OV_SetStreamedMatrixOutputHeader</code>	
<code>OV_SetFeatureVectorOutputHeader</code>	
<code>OV_SetSpectrumOutputHeader</code>	
<code>OV_SetChannelLocalisationOutputHeader</code>	

OV_SetStimulationsOutputHeader	
Chunk	
OV_getNbPendingInputChunk	Used to get pending chunk in buffer
OV_popInputBuffer	First chunk to be processed
OV_addOutputBuffer	New chunk added in an output buffer

Box In



The figure used here is the header structure of Openvibe, it is quite useful if you want to refer to for instance `box_in.inputs.Header(1) = signal`.

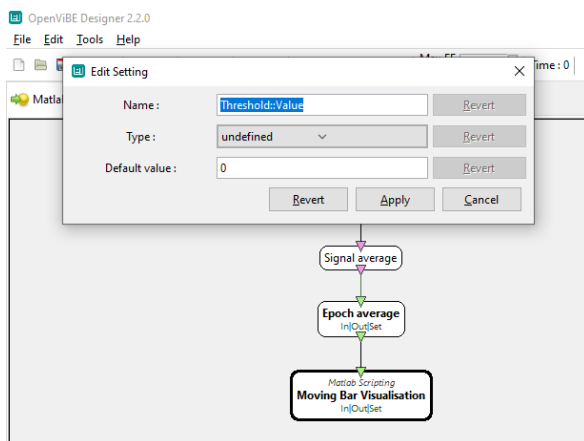
For a more detailed and accurate explanation, you can go to:

<http://openvibe.inria.fr/tutorial-using-matlab-with-openvibe/>

Also, refer to the OpenVibe presentation which has a real-life example of OpenVibe.

C. MATLAB box settings

As I told you already you can basically add any box settings in the MATLAB OpenVibe box. However, we need to perform a little trick to make that happen.



If we add an option, OpenVibe will override the box to undefined. In order to avoid unnecessary struggles with OpenVibe you will need to do the next:

- Every scenario is being saved in a XML file which is overwritten every time you change your scenario.
- Go to the XML file of your excenario e.g MATLAB-example.xml
- Open it with the text reader or notepad++.
- You will see the next code:

```

<Box>
  <Identifier>(0x0000631b, 0x00006816)</Identifier>
  <Name>Moving Bar Visualisation</Name>
  <AlgorithmClassIdentifier>(0x03303e0e, 0x39fe10df)</AlgorithmClassIdentifier>
  <Inputs>
    <Input>
      <Identifier>(0x007ff92b, 0x357aa2b8)</Identifier>
      <TypeIdentifier>(0x544a003e, 0x6dcba5f6)</TypeIdentifier>
      <Name>Input_A</Name>
    </Input>
  </Inputs>
  <Settings>
    <Setting>
      <TypeIdentifier>(0x007deef9, 0x2f3e95c6)</TypeIdentifier>
      <Name>Box clock frequency in Hz</Name>
      <DefaultValue>64</DefaultValue>
      <Value>64</Value>
      <Modifiability>>false</Modifiability>
    </Setting>
    <Setting>
      <TypeIdentifier>(0x330306dd, 0x74a95f98)</TypeIdentifier>
      <Name>Matlab executable (path)</Name>
      <DefaultValue>C:/Program Files (x86)/MATLAB/R2013b/bin/win32/matlab.exe</DefaultValue>
      <Value>C:/Program Files/MATLAB/R2019a/bin/win64/MATLAB.exe</Value>
      <Modifiability>>false</Modifiability>
    </Setting>
    <Setting>
      <TypeIdentifier>(0x79a9edeb, 0x245d83fc)</TypeIdentifier>
      <Name>Matlab working directory</Name>
      <DefaultValue>${Player_ScenarioDirectory}</DefaultValue>
      <Value>C:/Users/monte/AppData/opencv-2.2.0/scenarios/box-tutorials/matlab/Trys</Value>
      <Modifiability>>false</Modifiability>
    </Setting>
    <Setting>
      <TypeIdentifier>(0x79a9edeb, 0x245d83fc)</TypeIdentifier>
      <Name>Initialize function</Name>
      <DefaultValue>matlab_initialize</DefaultValue>
      <Value>simple_vis_initialize</Value>
      <Modifiability>>false</Modifiability>
    </Setting>
    <Setting>
      <TypeIdentifier>(0x79a9edeb, 0x245d83fc)</TypeIdentifier>
      <Name>Process function</Name>
      <DefaultValue>matlab_Process</DefaultValue>
      <Value>simple_vis_process</Value>
      <Modifiability>>false</Modifiability>
    </Setting>
  </Settings>
</Box>
<Setting>
  <Identifier>(0x002e4fef, 0xcc30d31)</Identifier>
  <TypeIdentifier>(0xffffffff, 0xffffffff)</TypeIdentifier>
  <Name>Threshold: Value</Name>
  <DefaultValue>0</DefaultValue>
  <Value>2</Value>
  <Modifiability>>true</Modifiability>
</Setting>
<Setting>
  <Identifier>(0x004123a7, 0xd2bfc64)</Identifier>
  <TypeIdentifier>(0x2cdb2f0b, 0x12f231ea)</TypeIdentifier>
  <Name>Threshold: Y: N</Name>
  <DefaultValue>>false</DefaultValue>
  <Value>>false</Value>
  <Modifiability>>true</Modifiability>
</Setting>

```

- After every box name, the xml file declares the box that is used in one scenario.
- Every setting defines an identifier, type of identifier, name, default value, value and modifiability
- We need to change:

- Type of identifier to the identifier code of your setting e.g Boolean
 - 0x007deef9, 0x2f3e95c6
- Modifiability: from false to true

Boolean Identifier	0x2cdb2f0b, 0x12f231ea
Integer Identifier	0x007deef9, 0x2f3e95c6

Other identifiers are unknown... you will need to look it up for yourself if you want to add another setting.

D. How to create an Animation in MATLAB

This information has been taken from a YouTube video, since OpenVibe information about its interaction with MATLAB is quite limited.

1. Run a simulation or generated data:
 - a. Load
2. Draw/ render the scenario time data
 - a. Plot, plot 3 surf
 - b. Hold on
3. Take a snapshot of scenarios
 - a. getframe
4. Advance time to tk
 - a. Continue
5. (save movie) (not relevant for us)
 - a. Videwriter
 - b. writeVideo function

E. Troubleshooting and best practices

Most of the time when the Process box fails to process the incoming data, it will print the next code. What do you do? Look at your MATLAB code, there will be a mistake in the Process code.

```
[ ERROR ] At time 0.063 sec <Box algorithm::(0x000011de, 0x0000330d) aka Matlab Scripting> {Error description} : {Error calling the Process
}, {Error type} : {OpenViBE::Kernel::ErrorType::BadProcessing (code 6)}
[ ERROR ] {Error description} : {Box algorithm <Matlab Scripting> processInput function failed}, {Error type} : {ErrorType::Internal (code :
[ ERROR ] {Error description} : {Process failed for box with id (0x000011de, 0x0000330d)}, {Error type} : {ErrorType::Internal (code 2)}, {i
[ ERROR ] Scheduler loop failed.
```

Use the display function of MATLAB ('disp') to display a text after every time a function have been called initialized, processed and unitialized. By doing that, you will know exactly where in your code something went wrong. Most of the error message can be attributed to the fact that you didn't call the header before processing the incoming matrix data.

Before we start programming MATLAB functions for OpenVibe we should ask ourselves the next questions:

1. Is there a box in OpenVibe that can do the same thing I want MATLAB to do?
2. How many input electrodes will I have?
3. How does my input look like?
4. Do I want to have an output? Should I add it to the output buffer?
5. Know the index of your channel
6. Know the index of the input: is it a Signal, Stimulus? (Look at the designer by clicking with your right mouse and looking into the input.

7. Draw, draw and rewrite. Ask yourself: what do I want that this program produces? Feedback after 10 seconds with 10% threshold? Or Display in the console like “Matlab has been Initialized, these are the parameters”.
8. Which are the parameters you want to include in the user define box in OpenVibe?

6. More Reading go to....

The software developer had a personal blog where he posts his career path within Inria Technologies, sometimes he explains about some specific features of OpenVibe, it is worth it to take a look [LINK](#).

BrainVision developed a more exhaustive guideline than these one specific for the Brain Vision Amplifier, therefore look at it, I have included in the zip-file in the laptop of the lab.

