University of Osnabrueck
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Bachelor's Thesis

Studying Neural Correlates of Mind Wandering with Mobile EEG

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Abstract

Mind wandering is a phenomenon that illuminates the rich imaginative mental capacity of the human mind. Lived experience is not limited to external sources of stimulation but can also contain self-generated thought content. Studying the neural correlates of higher cognitive functions such as mind wandering in natural environments can be facilitated by mobile Electroencephalography (EEG). Therefore, the present study investigates to what extent higher cognitive functions can be studied using the *Traumschreiber*, a mobile EEG device developed at the University of Osnabrueck. Moreover, the present study utilizes a neurophenomenological approach by combining Electroencephalography with first person reports of mind wandering.

In order to compare the *Traumschreiber* to stationary research graded EEG systems, the present work constitutes a replication of a study by Braboszcz and Delorme (2011) who identified neural markers of low alertness during mind wandering. Participants performed a breath counting task and pressed a button whenever they realized their attention had drifted away from the task while they were exposed to a passive auditory oddball paradigm. The replication revealed significantly decreased alpha (9-11 Hz) and beta (15-30 Hz) frequency band power during mind wandering in comparison to breath focus state and thus provides further evidence for alterations in neural dynamics that are associated with mind wandering. However, the replication demonstrates that studying higher cognitive functions in a mobile setup using the *Traumschreiber* does not yield equivalent results compared to a stationary research graded EEG system.

Furthermore, the first person reports have highlighted that the phenomenology of mind wandering is of paramount importance in order to assess its costs and benefits. A differentiated account of mind wandering uncovers that not the frequency of mind wandering *per se* but the thought content and the context in which mind wandering occurs seem to determine whether mind wandering is beneficial or detrimental to mental health.

List of Abbreviations

ADC Analog-to-Digital Converter.

AEP Auditory Evoked Potential.

API Application Programming Interface.

BLE Bluetooth Low Energy.

CSV Comma-Separated Values.

DMN Default Mode Network.

ECG Electrocardiography.

EEG Electroencephalography.

EMG Electromyography.

EOG Electrooculography.

ERP Event-Related Potential.

fMRI Functional Magnetic Resonance Imaging.

ICA Independent Component Analysis.

MMN Mismatch Negativity.

PSG Polysomnography.

SNR Signal-to-Noise Ratio.

WAVE Waveform Audio File Format.

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1 Introduction

In the absence of any external stimulation, one might think that the human mind is at rest. However, the human mind rather seems to be a *restless mind*, uncovering a rich imaginative mental life than can occur even if humans are engaged in cognitively demanding tasks (Smallwood and Schooler, 2006). For example, it is quite likely that the reader of this thesis will at some point loose focus of the text and starts to think about unrelated thoughts and feelings. This phenomenon, known as *mind wandering*, has been brought into the spotlight of mainstream science about 15 years ago and also started to attract attention in cognitive neuroscience (Smallwood and Schooler, 2015).

At the same time, a trend to study cognition in the natural environment emerged, following the conceptions of embodied and situated cognition (Varela et al., 2016). Therefore, mobile experimental setups have become increasingly popular and studying cognition is no longer restricted to the laboratory. Researchers of the Institute of Cognitive Science at the University of Osnabrueck have developed the *Traumschreiber* (Appel and Leugering, 2017), a low-cost mobile EEG device that has already been tested in well established experimental paradigms (Reimann, 2018; Schalkamp, 2018; Vidal De Palol, 2019a).

The present Bachelor's thesis illuminates the neural dynamics associated with mind wandering and investigates to what extent the *Traumschreiber* is a suitable device to study higher cognitive functions in mobile setups. In order to assess the *Traumschreiber's* capacities and limitations, the present Bachelor's thesis project is a replication of a study by Braboszcz and Delorme (2011) who identified neural markers of low alertness during mind wandering with EEG. Furthermore, the present work relates neuroscience to the phenomenology of mind wandering, following a research direction called *neurophenomenology* (Lutz and Thompson, 2003).

1.1 Mind Wandering

Mind wandering is characterized by "[...] a shift in the contents of thought away from an ongoing task and/or from events in the external environment to self-generated thoughts and feelings" (Smallwood and Schooler, 2015, p. 488). *Self-generated* refers to the characteristic that thoughts occurring during mind wandering are generated by the individual and not derived directly from immediate perceptual input (Smallwood and Schooler, 2015). Likewise, self-generated thoughts are not necessarily task unrelated. Mind wandering allows for both strategic or deliberate elements and spontaneous or unintentional thought content, the former are associated with task related and the latter with task unrelated self-generated thoughts (Smallwood and Schooler, 2015).

According to Smallwood and Andrews-Hanna (2013), mind wandering is a valuable cognitive capacity "reflect[ing] an evolutionary adaptation that allows agents to perform actions that are not simply a reflexive response to the outside world" (Smallwood and Andrews-Hanna, 2013, p. 4). Yet, mind wandering comes at costs and benefits. A real-world experience sampling study suggests that individuals spend 30-50% of their wake time mind wandering (Killingsworth and Gilbert, 2010). Therefore, many everyday activities are vulnerable to the effects of mind wandering (Smallwood and Schooler, 2015). For example, in the educational context, mind wandering impairs reading comprehension (Soemer and Schiefele, 2019) or attending to lectures (Farley et al., 2013). With respect to transportation safety, decreased alertness during driving due to mind wandering poses a risk factor (Baldwin et al., 2017; Lin et al., 2016). Furthermore, attention deficit hyperactivity disorder (ADHD) and dysphoria are associated with greater mind wandering (Franklin et al., 2017; Smallwood et al., 2007). On the other hand, mind wandering is considered to be beneficial for creativity and future planning (Baird et al., 2011; Gable et al., 2019). A study by Franklin et al. (2013) has pointed out that *interesting* mind wandering episodes actually contribute to a positive mood, stressing the importance of the *content* of mind wandering episodes for evaluating the functional role of mind wandering (Franklin et al., 2013).

The *content regulation hypothesis* as well as the *context regulation hypothesis* illustrate why the *task context* and the *thought content* are critical factors in order to assess the costs and benefits of mind wandering (Smallwood and Andrews-Hanna, 2013). According to the *context* regulation hypothesis, situations which do not demand external attention coincide with greater mind wandering frequency and poorer performance in cognitively demanding tasks such as reading is linked to more frequent mind wandering (Smallwood and Schooler, 2015). In order to minimize the negative effects of mind wandering on task performance, task unrelated self-generated thoughts should ideally be constrained to situations which do not demand continuous attention (Smallwood and Schooler, 2015). Additionally, the *content* regulation hypothesis addresses the relationship between mind wandering and mental health by assuming a dependency of individuals' happiness on the content of their mind wandering episodes (Smallwood and Andrews-Hanna, 2013). Simultaneously down-regulating perseverative and past focused self-generated thoughts while up-regulating interesting and future orientated thoughts would be most beneficial for individuals' mental health (Smallwood and Andrews-Hanna, 2013).

Studying mind wandering experimentally is challenging due to the covert nature of self-generated thoughts (Smallwood and Schooler, 2015). Common approaches in empirical mind wandering research are probe-caught and self-caught experience sampling methods. Probe-caught techniques interrupt participants at (pseudo-) random time points of the experiment and query if participants are still focused on the task or whether they have been mind wandering (Smallwood and Schooler, 2015). In contrast, self-caught methods rely on *meta awareness*, i.e. the participant's explicit awareness of their current contents of thoughts, realizing that their mind is wandering (Smallwood and Schooler, 2015). However, participants often fail to notice that their minds have wandered. Therefore, an approach known as *triangulation* is especially suited to study mind wandering which combines self- or probe-caught experience sampling with behavioral and neurocognitive measures (Schooler and Schreiber, 2004).

The present work is a replication of a study by Braboszcz and Delorme (2011) who identified neural markers of low alertness during self-caught mind wandering with EEG. The following section gives an overview of the underlying neurological basis of EEG and the common approaches of analyzing EEG data which were also used in the present work.

1.2 Electroencephalography (EEG)

Electroencephalography (EEG) is a non-invasive brain imaging technique measuring radial and tangential electrical dipoles on the scalp. The dipoles recorded with EEG arise from synchronized synaptic activity in populations of cortical neurons (Jackson and Bolger, 2014). Since the brain consists of billions of neurons, any voltage value measured by one of the EEG electrodes on the scalp is the sum of thousand or millions of dipoles, some of which may cancel out each other (Jackson and Bolger, 2014). Therefore, identifying the source of electrical activity measured with EEG is challenging. The so-called *inverse problem* that is related to EEG source localization can only be mathematically approximated (Cohen, 2014). However, EEG can capture cognitive dynamics in the magnitude of milliseconds due to its high temporal resolution (Cohen, 2014). In contrast to indirect measures like Functional Magnetic Resonance Imaging (fMRI), which measures hemodynamic activity, EEG records neural activity directly and thus represent a direct reflection of biophysical phenomena at the level of populations of neurons (Cohen, 2014).

Due to its spatial resolution, EEG is not well suited to precisely study hypothesized localizations of cognitive functions in the brain. EEG rather reveals brain rhythms associated with particular cognitive phenomena (Cohen, 2014). Typical EEG data analysis procedures include Event-Related Potential (ERP) and time-frequency analysis. ERPs are time-locked to a particular event of interest and different conditions or stimuli can easily be contrasted by comparing ERP waveforms. Moreover, time-frequency analysis conceptualizes neural dynamics as a multidimensional signal of time, frequency, space and additional dimensions corresponding to any particular set of experimental conditions (Cohen, 2014). Neural oscillatory activity is usually grouped into frequency bands and power differences in those frequency bands associated with distinct experimental conditions can be examined by means of time-frequency analysis (Cohen, 2014).

1.3 Neural Correlates of Mind Wandering

Neural correlates of mind wandering cannot only be studied with EEG but also with other neuroimaging methodologies like fMRI for instance. Before outlining the current state of research on neural correlates of mind wandering, it is important to understand the components of a mechanistic account of mind wandering on a conceptual level first.

Any theory regarding the neurophysiological underpinnings of mind wandering needs to address three aspects: First, how can higher cognition become disengaged from processing external stimuli, second, how do individuals self-generate task unrelated mental content, and third, how are disengagement from external processing and self-generation of task unrelated thoughts coordinated and regulated by the individual (Smallwood and Schooler, 2015). Accordingly, the *component process hypothesis* postulates that a flexible combination of a smaller number of underlying neurophysiological processes gives rise to a complex variety of experiences occurring during mind wandering (Smallwood, 2013).

Neuroimaging studies have identified neural correlates of mind wandering that are in line with the component process hypothesis and can be associated with each of the three requirements of a neurophysiological theory of mind wandering. Studying the amplitude of evoked responses revealed a decreased P3 ERP component and attenuated Mismatch Negativity during mind wandering in comparison to task focus states (Braboszcz and Delorme, 2011; Kam et al., 2011). Those findings in EEG have been interpreted as evidence for perceptual decoupling during mind wandering, a process that is assumed to disengage higher cognition from processing external stimuli (Smallwood and Schooler, 2015). Moreover, fMRI studies elucidated the role of the Default Mode Network (DMN) during mind wandering (Andrews-Hanna et al., 2014; Christoff et al., 2009; Mason et al., 2007). The DMN as well as episodic memory and affective processes are associated with the process of self-generation of task unrelated mental content (Smallwood and Schooler, 2015). Interestingly, not only the DMN but also executive networks are activated during mind wandering episodes (Christoff et al., 2009). The interaction between the DMN and executive networks is assumed to allow to regulate and coordinate disengagement from processing external stimuli and self-generation of task unrelated thoughts (Andrews-Hanna et al., 2014). This regulative capacity also refers to the *context regulation hypothesis*, since individuals with greater cognitive control seem to suppress task unrelated thoughts if the task is demanding and tend to mind wander more if the situation is non-demanding (Smallwood and Schooler, 2015).

Furthermore, the neural correlates of mind wandering identified by neuroimaging studies have been more prominent during unaware mind wandering episodes, i.e. those mind wandering episodes that are not accompanied by meta awareness (Smallwood and Schooler, 2015).

1.4 Studying Self-Caught Mind Wandering with EEG

Braboszcz and Delorme (2011) conducted one of the first EEG studies that purely relied on introspective subjective reports in order to identify mind wandering episodes and contrast alterations in brain activity associated with different attentional states. Participants performed a breath counting task while they were exposed to a passive auditory oddball paradigm and pressed a button whenever they became aware their attention had drifted away from the breath counting task. Brain activity was recorded with a 128-channel conventional EEG system (Braboszcz and Delorme, 2011; see section **2.4** for a detailed description of the experimental design).

The breath counting task was designed such that it likely induces mind wandering (Braboszcz and Delorme, 2011). In the context of mind wandering, button presses were regarded as meta awareness events. It was assumed that participants are in a mind wandering state for some time prior to the button press and in a task focused state immediately after the button press, up until thoughts started to drift away again and meta awareness re-occurred. Braboszcz and Delorme (2011) specified ten seconds intervals prior and post button presses which were classified as mind wandering or breath focus episodes, respectively (section **4.2** critically discusses this aspect of the experimental design).

Comparing mind wandering to breath focus state, Braboszcz and Delorme (2011) found significantly increased power in the delta (2-4 Hz) and theta (4-7 Hz), as well as significantly decreased power in the alpha (9-11 Hz) and beta (15-30 Hz) frequency bands.

The passive auditory oddball paradigm aims at identifying neural correlates of perceptual decoupling, one of the processes associated with mind wandering (see section **1.3**). Mismatch Negativity (MMN), one of the neural correlates in question, can be understood in the context of predictive coding. The predictive coding theory hypothesizes that the brain generates and updates a mental model of the environment in a Bayesian fashion (Friston and Kiebel, 2009). In predictive coding research, oddball paradigms are a popular way of studying how such mental models form and what might be neural correlates of theoretical prediction errors. The standard stimulus appears much more frequently than the oddball stimulus. Therefore, it is hypothesized that a mental model forms that predicts the standard stimulus (Garrido et al., 2009). Whenever an oddball stimulus occurs, the sensory input does not match the prediction. Hence, a prediction error is elicited and the mental model is updated. According to the predictive coding theory, Mismatch Negativity - MMN is obtained by subtracting the ERP elicited by the standard stimulus from the ERP related to the oddbal stimulus - is considered a neural correlate of theoretical prediction errors (Garrido et al., 2009). With respect to perceptual decoupling, generating prediction errors presuppose that the external environment is processed. Therefore, alterations in MMN, a neural correlate of theoretical prediction errors, potentially shed a light on perceptual decoupling. The rationale behind the experimental design of Braboszcz and Delorme (2011) is that the effects of mind wandering on processing external stimulation can be illuminated by studying neural responses related to an auditory oddball paradigm.

The results of Braboszcz and Delorme (2011) revealed that Auditory Evoked Potentials (AEPs) related to the auditory oddball paradigm showed an ERP positive component peaking at about 200 milliseconds after stimulus presentation which was significantly higher during mind wandering than during breath focus for both standard and oddball stimuli. Moreover, Braboszcz and Delorme (2011) observed a significant interaction effect between the auditory stimulus type (oddball or standard) and the attentional state (mind wandering or breath focus) on the early ERP negative component between 90 and 120 milliseconds post stimulus onset. After the presentation of an oddball stimulus the ERP was significantly more negative than after the presentation of a standard stimulus in both conditions, but the amplitude of the ERP negative component related to oddball stimuli was higher during breath focus than during mind wandering. Hence, the Mismatch Negativity (MMN) - the difference between the ERP elicited by the oddball stimulus and the ERP related to the standard stimulus - was significantly decreased during mind wandering compared to breath focus (Braboszcz and Delorme, 2011).

In summary, Braboszcz and Delorme (2011) have identified neural markers of decreased alertness and attenuated sensory processing during mind wandering. Moreover, they have demonstrated that introspective self-caught techniques can indeed reveal neural correlates of mind wandering (Braboszcz and Delorme, 2011).

The present work investigates whether the findings of Braboszcz and Delorme (2011) can be replicated using the *Traumschreiber*, in order to examine to what extent the *Traumschreiber* is a suitable device to study higher cognitive functions in mobile setups.

1.5 The Traumschreiber

The *Traumschreiber* is a low-cost mobile eight-channel EEG device designed by Kristoffer Appel and Johannes Leugering at the University of Osnabrueck (Appel and Leugering, 2017). Originally, the *Traumschreiber* was intended to conduct Polysomnography (PSG) studies outside designated sleep laboratories (Appel et al., 2016). Since the *Traumschreiber* features ten electrodes recording electrical potentials, it can be used to collect Electroencephalography (EEG), Electrooculography (EOG), Electrocardiography (ECG) and Electromyography (EMG) data. Each of the eight channels measures the voltage difference of two neighboring electrodes, the tenth electrode is a ground electrode, intended to filter out power line noise from the measured data (Appel, 2018). For the present study, a *Traumschreiber* version 2.5 with ten electrode pins was used (see **Fig 1**).

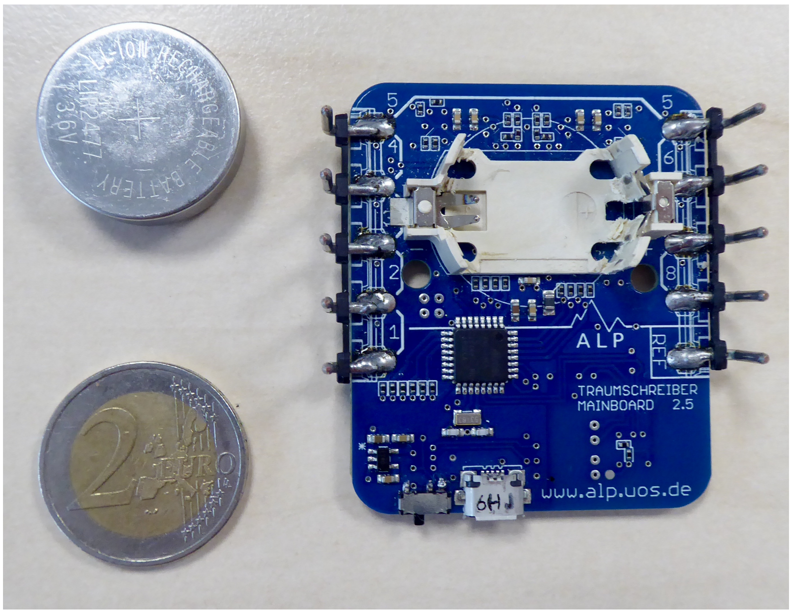

Figure 1: **Traumschreiber version 2.5** with ten electrode pins and its battery next to it. Note the two euro coin as a reference for the compact size of the *Traumschreiber*.

One of the unique features of the *Traumschreiber* is that it transmits data via Bluetooth Low Energy (BLE), allowing to control EEG experiments with a smartphone or tablet (Vidal De Palol, 2019a). The *Traumschreiber's* mobility is underlined by its compact dimension and a 3.6 V lithium-ion rechargeable coin cell battery, providing power autonomy for up to eight hours (Appel, 2018). Since the *Traumschreiber* is not equipped with a battery indicator, its actual battery capacity could not be verified without risking a power loss in the middle of the present experiment.

Furthermore, the *Traumschreiber's* hardware comprises a 12 bit Analog-to-Digital Converter (ADC) and a built in analog band-pass filter with a low-frequency cutoff at 0.04 Hz and a high-frequency cutoff at 72 Hz (Appel, 2018). Additionally, electric potentials are amplified by a factor of 1000, which can be further enhanced via a gain selector (Appel, 2018).

In theory, the *Traumschreiber* samples EEG data at 250 Hz resolution (Appel, 2018). However, the experimental sampling rate in the present study did not exceed 222 Hz on average, corresponding to one octet of EEG data every 4.5 milliseconds. Previous *Traumschreiber* studies already identified an inconstant sampling rate, caused by Bluetooth Low Energy buffering, which poses a challenge with respect to EEG data analysis (Reimann, 2018; Schalkamp, 2018; Vidal De Palol, 2019a).

According to its developers, the production costs of the *Traumschreiber's* main board amount to 93 euros (Appel, 2018). Hence, excluding electrodes, the equipment for conducting EEG studies with the *Traumschreiber* can be obtained for less than 100 euros, underlining the *Traumschreiber's* affordability. In comparison, a research graded eight channel Biosemi ActiveTwo EEG system costs approximately 13,500 euros, excluding value-added tax (BioSemi, 2020).

1.6 Aim of the Present Study

The aim of the present study is two-fold: First, to investigate whether the *Traumschreiber* is a suitable device to study higher cognitive functions such as mind wandering in mobile setups. In this respect, replicating the study by Braboszcz and Delorme (2011) is representative, because it examined higher cognition by means of Event-Related Potential (ERP) and time-frequency analysis based on EEG data recorded with a 128-channel stationary EEG system. Second, the present study addresses the phenomenology of mind wandering and relates subjective experiences to neuroscientific findings, an approach known as *neurophenomenology* (Lutz and Thompson, 2003). Braboszcz and Delorme (2011) demonstrated that neural correlates of mind wandering can indeed be revealed by means of introspective self-caught techniques and thus implemented a neurophenomenological approach. This is why the study was chosen fore replication.

2 Materials and Methods

The following chapter covers the methodology applied in order to investigate each of the two research questions of the present study. The first section introduces the app controlling the *Traumschreiber* and describes how the app was modified according to the demands of the experimental paradigm of Braboszcz and Delorme (2011) that was replicated in the present study. Moreover, participant recruitment and material selection are summarized and the experimental design is elucidated in detail. The main part of this chapter comprises how EEG and behavioral data were analyzed.

2.1 The App

One of the aims of the present study is to investigate to what extent the *Traumschreiber* is a suitable device to study higher cognitive functions in mobile experimental setups. Whilst a conventional EEG study requires several computers to control the EEG system, present stimuli and record participants' behavior, a mobile study makes it infeasible to carry around several computers. Therefore, an Android app has been developed to control EEG recordings with the *Traumschreiber*. Several students of the Institute of Cognitive Science at the University of Osnabrueck were involved in developing the app called *EEGDroid* (Rojas, 2019; Vidal De Palol, 2019a, 2019b; Zerfowski et al., 2019). In its latest version, the app is capable of controlling the *Traumschreiber* via Bluetooth Low Energy (BLE), displaying incoming data in real time and replaying previously recorded EEG sessions. Additionally, *EEGDroid* features a chatbot that provides information about epilepsy, as it has been intended to use the *Taumschreiber* in combination with the app as a means to assist diagnosis and inform about epilepsy in regions with poor medical infrastructure (Rojas, 2019).

2.1.1 Modifications to the App

For the present study, a new feature for conducting an experiment on mind wandering was integrated into the existing framework. None of the features of the latest version of *EEG-Droid* were affected by the modification, instead of exclusively tailoring the app to the needs of the present study, *EEGDroid* has been enriched by an additional feature. This approach was chosen in order to demonstrate that the existing app can serve as a framework for conducting different types of experiments with the *Traumschreiber*. With respect to the present study, a new experimental design could be implemented with reasonable effort by making use of several core functionalities that already have been implemented in *EEGDroid*. **Fig 2** shows the home screen and the side bar of *EEGDroid*. The new feature to conduct an experiment on mind wandering is highlighted. For development, Android Studio (Google Developers, 2019) was used, the code is written in Java (Oracle,

2014) and is publicly accessible on GitHub (Bammel, 2020).

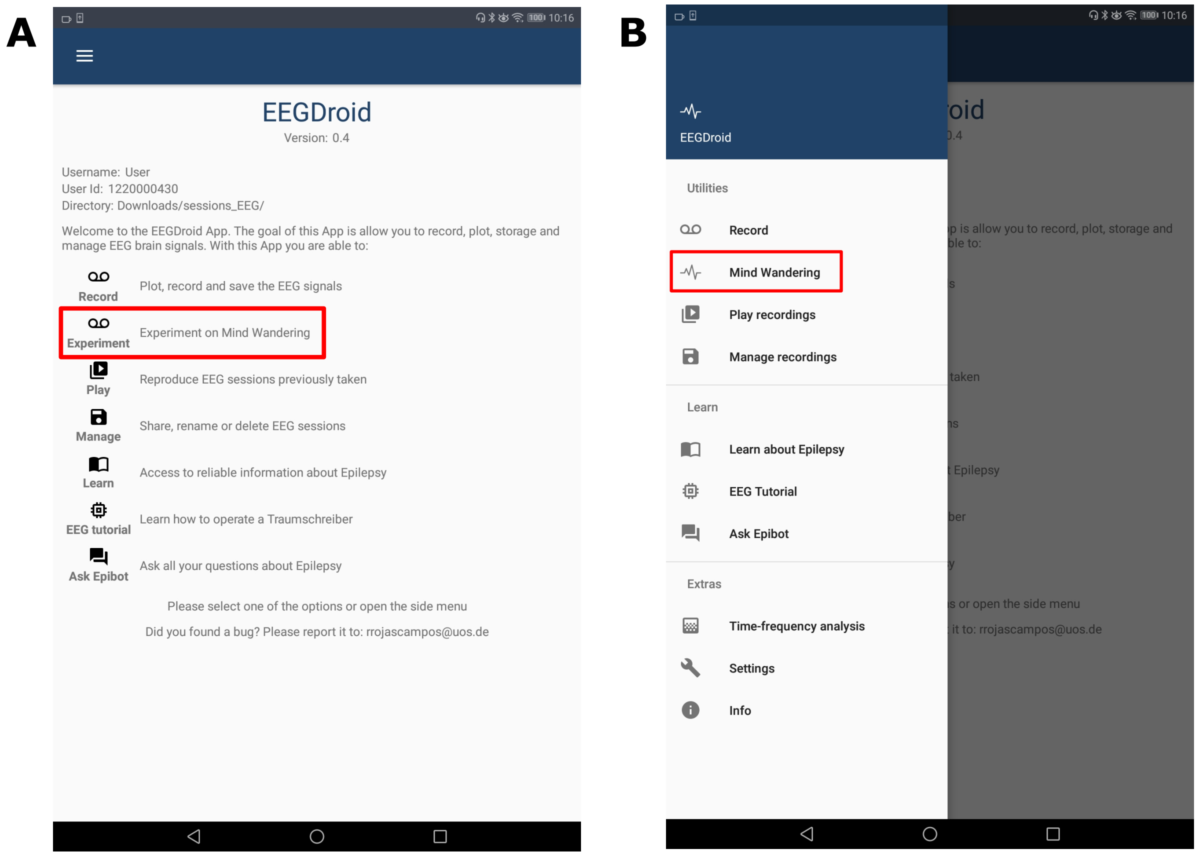

Figure 2: **EEGDroid home screen**. The red rectangles indicate the new activity which was added for the present study on mind wandering. **A**: Home screen. **B**: Side-bar.

Android apps are composed of multiple components such as activities, services, broadcast receivers and content providers. Those components function as entry points through which the user or the operating system can enter an Android app. An activity represents a single screen with a user interface and thus functions as an entry point for user interaction. Each activity is complemented by a layout file defining what is displayed on the screen. The activity itself is a class which contains the logic of the functionalities that can be executed by the user in that particular activity. Activities are independent from each other, though activities work together to form a cohesive user experience (Google Developers, 2020a).

For the modified version of *EEGDroid*, a new activity called *experiment* activity and a corresponding layout file were created. Some of the logic of the new *experiment* activity is based on the pre-existing *record* activity that controls recording, saving and real-time visualization of EEG sessions. Core features such as the BLE module and the logic responsible for receiving EEG signals were also re-used for the new *experiment* activity. Minor changes in the *main* activity were necessary such that the new *experiment* activity can be accessed from the home screen.

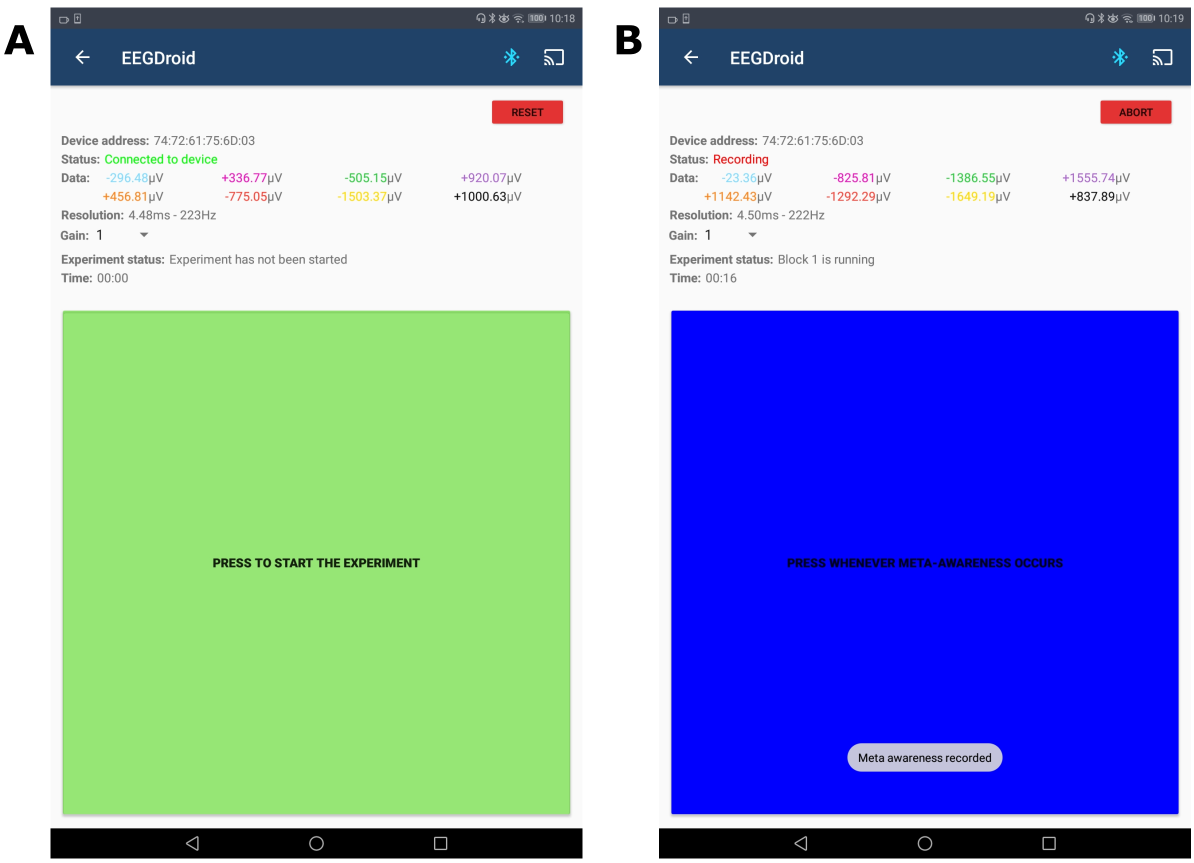

Figure 3: **EEGDroid experiment activity**. **A**: Experiment has not been started yet. **B**: Experiment is running. Every time participants press the oversized blue button a notification appears at the bottom of the screen stating *Meta awareness recorded*.

Fig 3 A shows what the screen corresponding to the *experiment* activity looks like after the *Traumschreiber* was connected via BLE but before the experiment is started. The upper part of the layout is identical to the layout associated with the *record* activity, except for the red *RESET* button. Below the gain selector, the layout diverges from the *record* activity. For the experiment on mind wandering, two new text views were added, the upper one shows the current status of the experiment and the lower one keeps track of the time once a block of the experiment has been started. Below that, an oversized rectangular button was added that covers almost all of the remaining screen. The button is oversized because participants are supposed to press the button with their eyes closed during the experiment (see section **2.4** for details on the experimental design). Two experimental states are distinguished by a change of the button color from green to blue or vice versa. Whenever no recording is in process and no auditory stimuli are presented the button appears green. As soon as the recording starts and auditory stimuli are presented the button changes its color to blue. In the original *record* activity, the space consumed by the oversized rectangular button is used for real-time plotting of incoming EEG data. This feature is no longer accessible within the *experiment* activity, though real-time data visualization is still possible by switching to the *record* activity.

In principle, the experiment can be controlled by using a single button only. To start the experiment, one has to press the oversized green button. A prompt appears, asking to provide a filename for saving the experimental data. After that, the oversized green button has to be pressed once again to actually start the recording and stimulus presentation. Once the first block of the experiment has been started, the color of the oversized button changes to blue, the status indicator of the *Traumschreiber* changes to *Recording* and the label of the top right red button changes to *ABORT*. Additionally, the current block number and the time that has passed since the current block was started are displayed. While a block is running, participants are sometimes supposed to press the oversized blue button (see section **2.4** for more details). In the recording state of the experiment, a notification stating *Meta awareness recorded* appears for a couple of seconds at the bottom of the screen whenever the oversized blue button is pressed (see **Fig 3 B**).

As soon as a block of the experiment is completed, the color of the oversized rectangular button changes back to green, indicating that the recording is paused. Moreover, the experiment status indicator updates accordingly and the top right red bottom becomes the *RESET* button again. The next block can be started by simply pressing the oversized green button again. Upon completion of the experiment, the user is informed by a notification appearing at the bottom of the screen and the respective label of the experiment status indicator. Now the reset functionality can be used to prepare the *experiment* activity for the next participant, there is no need to restart the activity if one wants to conduct several experiments successively.

The *RESET* and *ABORT* button allow to either reset the whole experiment or abort the current block only. If a block is aborted, that block can be restarted and the experiment proceeds as usual. *RESET* terminates the current experiment and a new experiment can be started subsequently after all variables have been reset. Whenever *RESET* or *ABORT* is pressed, a prompt appears that requires explicit confirmation in order to avoid accidentally aborting or resetting the experiment. As a precaution, the data of the current block or experiment are not automatically deleted upon calling *ABORT* or *RESET*. If one wants to reset the experiment while a block is running, *ABORT* has to be called first, followed by *RESET*.

With respect to the implementation, multi-threading is used (Google Developers, 2020b). The main tasks that need to be controlled by the *experiment* activity are the presentation of auditory stimuli, recording button presses, keeping track of the time and writing the data into Comma-Separated Values (CSV)-files. Timer tasks are used to schedule the presentation of auditory stimuli and to terminate blocks after 20 minutes (Google Developers, 2020d). The Android sound pool library allows to play short sounds lasting for

100ms without experiencing click sound artifacts at stimulus onset (Google Developers, 2020c). Waveform Audio File Format (WAVE) auditory stimuli were generated using SoX (Bagwell, 2008; Bagwell et al., 2015). The data are written into CSV-files in a pseudo-real-time fashion using multi-threading. Three CSV-files are created for each block, one for EEG data, one for auditory data and one for button presses. Arriving EEG data from the *Traumschreiber* as well as the time stamps of auditory stimuli and button presses are buffered in local memory for a very short amount of time only. A separate thread, independent of the main thread, is constantly checking whether there are data in the buffer and if so, data are written into CSV-files and deleted from the buffer. In practice, only EEG data are actually buffered in local memory, since a new chunk of data arrives every 4.5 milliseconds on average. Auditory data and the timestamps of button presses are written into CSV-files immediately upon data arrival most of the time. Since one block of the experiment lasts for 20 minutes, it is crucial to ensure low local memory loads as achieved by a pseudo-real-time data writing procedure. In contrast, keeping all the data in local memory and writing it to CSV-files only after a block terminated would imply a high memory demand, possibly resulting in bugs and a compromised user experience.

As outlined above, multi-threading is a powerful tool to speed up computation and use memory more efficiently, however, it also increases complexity that needs to be handled appropriately. For instance, during development it happened that after the first block of the experiment had been aborted and restarted, the subsequent blocks terminated a couple of seconds too early. Eventually, it turned out that the thread which was responsible for terminating the first block was not correctly stopped upon aborting the first block. Thus, it stayed alive silently in the background and terminated the subsequent blocks too early. This example illustrates that multi-threading adds complexity and if not handled carefully, unforeseen and unwanted behavior can emerge from multi-threading.

2.2 Participants

15 Cognitive Science undergraduate students were recruited at the University of Osnabrueck for the present study (7 females and 8 males; age 18-28 years old, mean 22). Participants gave written consent (see **Appendix D**) and received course credits for their participation. All participants confirmed to be neurologically healthy and to not have a history of major psychological disorders or auditory deficits. Before the experiment, participants were informed to not consume any kind of substances prior to the experiment that could potentially affect their concentration during the experiment such as drugs, certain types of medication, energy drinks, or high amounts of caffeine. In the final questionnaire, participants confirmed that their concentration during the experiment was not affected by any kind of substances. Moreover, none of the participants indicated to be overly tired prior to the start of the experiment. In order to assist with the EEG

recordings, participants were asked to not use any kind of hair products on the day of participation. The languages of instructions during the experiment were English and German.

2.3 Materials

The experiment was conducted at the EEG lab of the Neurobiopsychology group at the Institute of Cognitive Science. EEG recordings took place in a non-shielded room, which marks a major difference to many conventional EEG studies that make use of electromagnetically shielded rooms in order to reduce noise in the data. Due to the mobile setup of the present study, any other location that is not explicitly dedicated to conducting EEG experiments would have been suitable as well. In addition to the *Traumschreiber*, an EEG cap manufactured by EASYCAP (https://www.easycap.de) was used for the recordings. Ten silver chloride ring electrodes were connected to the *Traumschreiber*. Conventional EEG systems have 32, 64, or 128 electrodes, but the *Traumschreiber* is equipped with ten electrodes only. The electrodes were arranged according to the international 10-20 system over fronto-central and occipital regions (see **Fig 5**). These regions were selected based on the findings of the original study by Braboszcz and Delorme (2011). For conductance reasons, EASYCAP SuperVisc Electrolyte-Gel for Active Electrodes was applied during the preparation phase of the experiment. The gain factor of the *Traumschreiber* was set to 1 during EEG recordings, meaning that the measured electrical potentials were not further amplified than by a factor of 1000. This corresponds to the default internal voltage amplification factor of the *Traumschreiber* (Appel, 2018).

No computers were required for conducting the present experiment, both the EEG recordings and the experimental stimuli were controlled via a Huawei MediaPad T5 tablet (Huawei Technologies Co., 2020) running on Android API 26. The modified version of *EEGDroid*, which is capable of running the entire experiment (see section **2.1.1**), was installed on the tablet. The *Traumschreiber* connected to the tablet via Bluetooth Low Energy (BLE). Since the experiment involves the presentation of auditory stimuli, VIVANCO earphones (Vivanco GmbH, 2020) were connected to the tablet.

Fig 4 portrays the experimental setup including the *Traumschreiber* with ten electrodes connected to an EEG cap as well as the tablet and earphones.

2.4 Experimental Design

The experimental design of the present study is a replication of the paradigm developed by Braboszcz and Delorme (2011). In short, the experiment comprises a breath counting task and a passive auditory oddball paradigm.

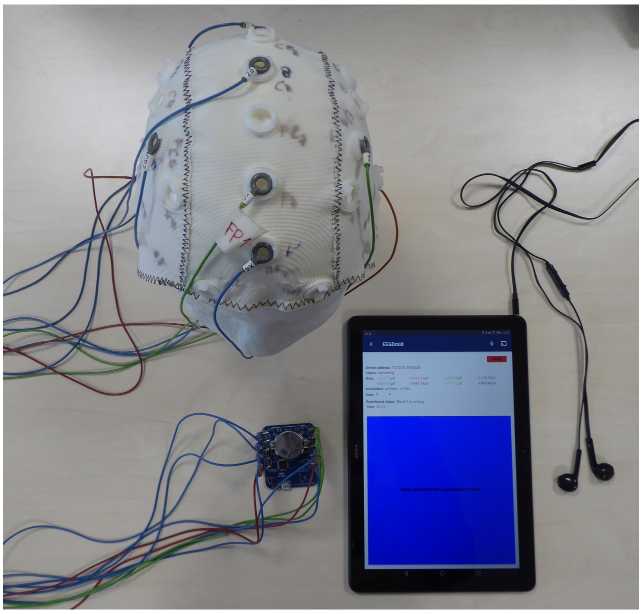

Figure 4: **Experimental setup**. Note that this is a theoretical setup only.

Participants sat in a dark room and were instructed to count their natural breath cycles from one to ten, starting again at one as soon as they reached ten. Inhaling and exhaling once makes up one breath cycle. Whenever participants became aware of having lost track of their breath count, they were supposed to press a button. Precisely, loosing track of one's breath count means that one either stopped counting at all, counted over ten breath cycles, or that one had to reflect intensively in order to figure out what the next count was. In the present version of the experiment, participants pressed a button on the touchscreen of the tablet instead of an external button. After pressing the button, participants were instructed to bring their focus back to the breath counting task and to start counting again from one. This procedure was repeated for 20 minutes, making up one block of the experiment. In total, the experiment consisted of three blocks, with short pauses in between the blocks. Excluding these short pauses, the experiment lasted for 60 minutes in total. Furthermore, participants were instructed to keep their eyes closed during the experiment.

The breath counting task was complemented by a passive auditory oddball paradigm. Passive means that participants were instructed to ignore the sounds since these were not important for the breath counting task. Braboszcz and Delorme (2011) chose frequency deviants for their oddball paradigm. The standard stimulus was a 500Hz tone and the oddball stimulus was a 1000Hz tone, both lasting for 100 milliseconds with 10 milliseconds linear amplitude rising and falling times. 80% of the stimuli were standards and 20% were oddballs. Auditory stimuli were presented pseudo-randomly such that two oddball stimuli were never presented successively. Inter-stimulus intervals were randomized, ranging from 750 to 1250 milliseconds.

Importantly, the paradigm developed by Braboszcz and Delorme (2011) relies on a self-report procedure of mind wandering. Hence, only those mind wandering episodes that participants were explicitly aware of were detected in the experiment. There are also mind wandering episodes which lack meta awareness and thus cannot be captured in a self-report paradigm (Smallwood and Schooler, 2015; see section **1.1**).

After the experiment, participants completed a questionnaire. Up to that point, the present study followed the protocol described in Braboszcz and Delorme (2011), the questionnaire, however, is an independent addition and thus distinguishes the present study from Braboszcz and Delorme (2011). In the first section of the questionnaire, the aim of the study was revealed and short explanations on mind wandering and meta awareness were provided. In the following, the questionnaire tried to assess the participant's general perspective on mind wandering and focused on a phenomenological account, i.e. the subjective experience of mind wandering. Different statements about mind wandering were presented and participants rated their agreement on a five-point Likert scale. Additionally, a free text question illuminated the participant's subjective experience of mind wandering episodes during the experiment. Moreover, a couple of validation questions were included in order to assure that participants followed task instructions correctly as well as to investigate potential deviations between retrospective self-estimations and experimental data (see **Appendix E**).

2.5 Data Analysis EEG

Investigating whether the *Traumschreiber* is a suitable device to study higher cognitive functions in mobile experimental setups also includes the choice of data analysis tools. In consequence, EEG data were analyzed using MNE-Python 0.17.1 (Gramfort et al., 2013), a toolbox that is designed to analyze data recorded with conventional EEG systems. Previous *Traumschreiber* studies did not use standard EEG analysis toolboxes (Reimann, 2018; Schalkamp, 2018; Vidal De Palol, 2019a). Since the present study is a replication of Braboszcz and Delorme (2011), the analysis pipeline is largely adapted from the original study. However, the specifications of the *Traumschreiber* required some changes in the analysis procedure that will be further discussed in the next sections. Yet, Braboszcz and Delorme (2011) performed data processing under Matlab EEGLAB 7 (Delorme and Makeig, 2004) and not under MNE-Python.

The following sections describe each step of the EEG data analysis performed in the present study and highlight issues as well as workarounds. In general, EEG data analysis can be summarized as follows. First, the data are preprocessed in order to increase the Signal-to-Noise Ratio (SNR), involving re-referencing, removing bad electrodes, artifact rejection and filtering. Since experiments typically consist of several trials and blocks, epochs time-locked to particular events are extracted from the data. These epochs can either be analyzed in the time domain or in the frequency domain. Event-Related Potentials are analyzed in the time domain, whereas frequency band power is analyzed in the time-frequency domain.

Five subjects were excluded from the subsequent analysis because they did not show enough mind wandering episodes. The remaining ten subjects accumulated 376 mind wandering episodes in total, the number of mind wandering episodes ranges from 15 to 92 per subject. For comparison, Braboszcz and Delorme (2011) excluded four out of 16 subjects, the total number of mind wandering episodes summed up to 358 with a minimum of 13 and a maximum of 52 mind wandering episodes per subject. During the first block of subject seven, EEG recordings stopped about two minutes too early. Nevertheless, the first block of subject seven was taken into account for the subsequent analysis, since only a small fraction of data were missing for that block.

2.5.1 Preprocessing

MNE-Python presupposes that the first sample of EEG data corresponds to the onset of the experiment. However, due to Bluetooth Low Energy buffering, there was a short delay of less than 100 milliseconds between experiment onset and the arrival of the first octet of EEG data. In order to account for this delay, the timescales of auditory and meta awareness data had to be adjusted by subtracting the delay between experiment onset and the arrival of the first octet of EEG data from the timestamps of auditory and meta awareness data. Hence, the timestamps of auditory and meta awareness data were relative to the onset of EEG recordings and treating the first sample of EEG data as the experiment onset did not lead to any confounding effects.

In the next step, EEG data were re-referenced. One of the constraints of the *Traumschreiber's* hardware is a limitation to bipolar referencing, i.e. the voltage difference between two electrodes. Therefore, taking the average of all electrodes as the reference is not possible. By default, each channel of the *Traumschreiber* corresponds to the voltage difference of two neighboring electrodes. All channels were re-referenced to electrode TP_9 such that all channels shared the same reference electrode. Electrode TP_9 was chosen as a substitute for electrode M_1 (left mastoid), which Braboszcz and Delorme (2011) used as their reference electrode. **Fig 5** illustrates the process of re-referencing. For example, channel 2 which used to be the voltage difference between electrodes Fz and FC_3 was relabeled as channel Fz during re-referencing, representing the voltage difference between electrodes Fz and TP_9.

MNE-Python uses so-called raw objects to store EEG data. The data recorded with the *Traumschreiber* were saved as CSV files, a file format that is not support by MNE-Python.

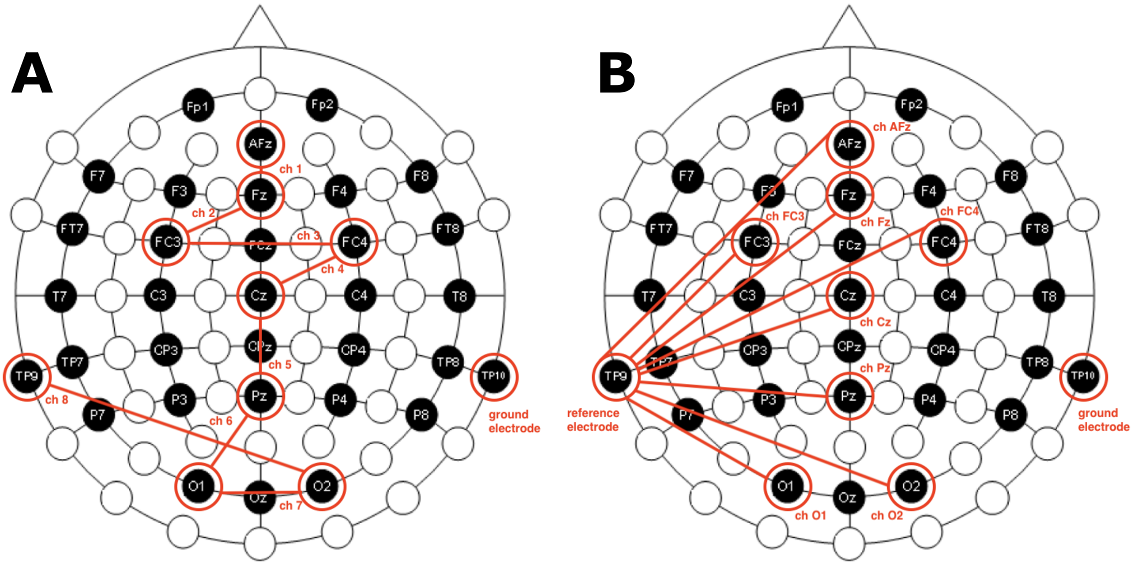

Figure 5: **EEG montage and re-referencing**. The red circles indicate electrode positions. **A**: Default bipolar referencing. **B**: Re-referenced montage, TP_9 becomes the reference electrode for all channels. Adapted from FieldTrip (2020).

However, it is possible to manually create MNE-Python raw objects (MNE Developers, 2020a). This approach was chosen for the present data analysis. The timestamps of EEG data samples are not explicitly represented in MNE-Python raw objects. Instead, the timestamps of EEG data samples are inferred from the sampling rate (MNE Developers, 2020c). Although it is memory efficient, the downside of this approach for analyzing EEG data recorded with the *Traumschreiber* is that it presupposes a constant sampling rate. As mentioned in section **1.5**, the *Traumschreiber* does *not* have a constant sampling rate. This is a serious issue, because the divergence of the timestamps inferred from the sampling rate compared to the true timestamps of the EEG data samples increases over time. At the end of a 20 minutes block, the timestamps associated with the MNE raw objects diverged by up to one second from the true timestamps. Given the temporal resolution of EEG data in the magnitude of milliseconds, a divergence of one second would yield essentially meaningless results. Importantly, the amplitude by which the sampling rate of the *Traumschreiber* deviates from its average sampling rate of 222 Hz varies over time. Therefore, simply shifting the timescale of EEG data by a constant factor does not solve the issue. A workaround addressing the inaccurate timestamps associated with the MNE raw objects will be presented in section **2.5.2**.

Furthermore, artifact detection and rejection is an important part of preprocessing. Artifacts like eye blinks, lateral eye movements, heart beat, muscle noise or electrical activity contaminate EEG data. By filtering out those artifacts, the Signal-to-Noise Ratio (SNR) can be enhanced. It is possible to manually check the data and mark artifacts, however, given the amount of data of the present study - ten hours of EEG recordings remained after subject exclusion -, manual artifact detection was infeasible. EEG data recorded at different electrodes at a time are highly correlated and thus contain much redundant information. Independent Component Analysis (ICA) is a technique that separates EEG processes whose time waveforms are maximally independent of each other (Delorme et al., 2007). The sources of these processes may be located within the brain or outside of it. The maximal number of independent components corresponds to the number of sensors (Makeig et al., 1996). Hence, ICA is a means to remove artifacts by separating these from neural sources within the brain. Braboszcz and Delorme (2011) used Infomax Independent Component Analysis for artifact detection. *Infomax* refers to a particular algorithm to compute independent components.

Running Infomax ICA on the data of the present study yielded eight independent components. Since ICA is sensitive to low-frequency drifts, the EEG data were high-pass filtered at 1 Hz before fitting the ICA. None of the resulting components could be clearly identified as an artifact. In fact, all components seemed to contain a lot of noise. Recording EEG data with just eight electrodes makes it more difficult to separate artifacts from neural sources within the brain (section **4.2** discusses the quality of the data recorded with the *Traumschreiber*).

In addition to high-pass filtering the data at 1 Hz, a low-pass filter at 30 Hz was applied, yielding a band-pass filter from 1 Hz to 30 Hz. High-pass filtering at 1 Hz removed low-frequency drifts, a low-pass filter at 30 Hz was chosen because the maximal frequency of interest for the time frequency decomposition was 30 Hz (see section 2.5.4). Furthermore, low-pass filtering at 30 Hz removed high-frequency electrical artifacts that could be attributed to the tablet (see section **4.1** for more detail).

2.5.2 Epoching

For the subsequent analysis, 20 seconds epochs centered on button presses were extracted from the data. Each button press signified a meta awareness event. The time interval ten seconds prior to the meta awareness event was regarded as the mind wandering condition, the time interval ten seconds post meta awareness as the breath focus condition (Braboszcz and Delorme, 2011). Additionally, three seconds auditory epochs were extracted for mind wandering and breath focus conditions. Each auditory epoch started one second prior to stimulus onset and lasted until two seconds after stimulus onset. In order to avoid confounding effects of the button press itself, auditory epochs were selected such that they did not include button presses. Only those auditory stimuli which occurred at least two seconds prior to button presses or one second after button presses were considered for further analysis (Braboszcz and Delorme, 2011). **Fig 6** illustrates how both 20 seconds epochs and three seconds auditory epochs were extracted from the data.

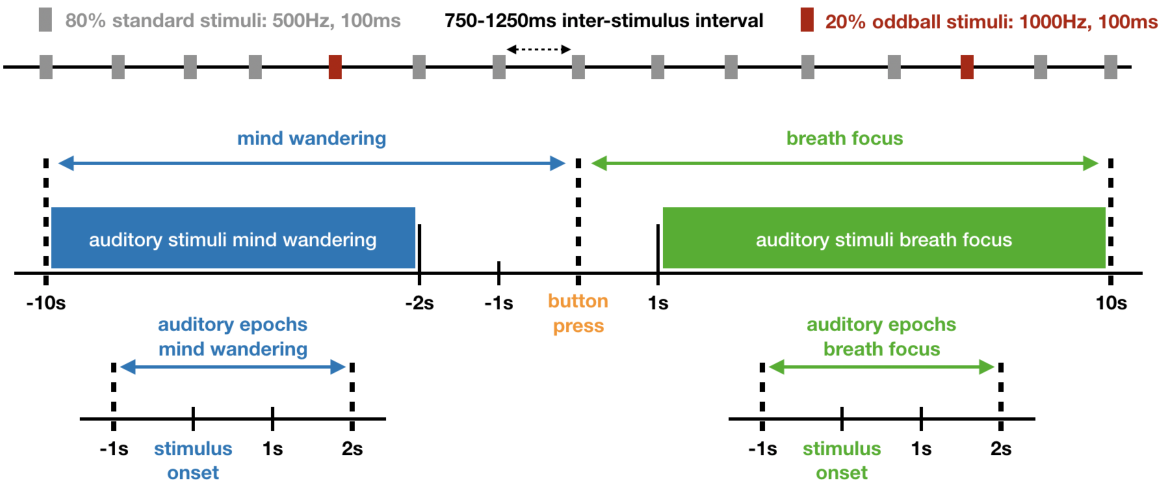

Figure 6: **Epoching**. For each condition, mind wandering and breath focus, 3s auditory epochs were extracted such that these epochs did not include button presses. The passive auditory oddball paradigm is illustrated at the top of the figure. Additionally, 20s epochs were extracted centered on button presses.

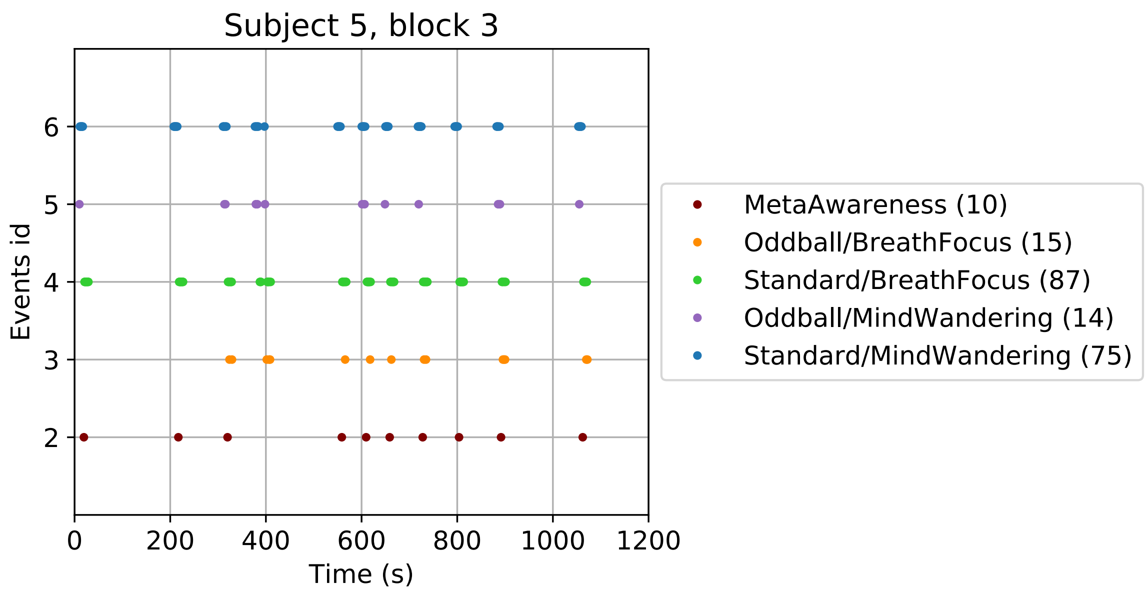

Figure 7: **Exemplary event distribution**. Taken from subject 5, block 3. Note that no meta awareness is indicated at approximately 400 seconds because two consecutive meta awareness events were identified as ambiguous. Auditory events associated with epochs containing artifacts are also not shown.

On rare occasions, two meta awareness events occurred within less than 20 seconds. Hence, the two 20 seconds epochs centered on each meta awareness event overlapped. Since the overlapping time interval could not be unambiguously classified as either mind wandering or breath focus state, all auditory stimuli that occurred within the overlapping time interval were marked as ambiguous and excluded from ERP analysis. Both 20 seconds epochs were also excluded from time-frequency analysis if the two meta awareness events were separated by less than 20 seconds.

Fig 7 exemplifies the event distribution for one block of the experiment. Highlighted are all meta awareness events (dark red) and the auditory stimuli that fell within mind wandering or breath focus condition. Auditory stimuli outside those time windows are not shown. One can see that standard and oddball auditory stimuli which appeared shortly before each meta awareness event were associated with the mind wandering condition (purple and blue), whereas auditory stimuli shortly after each meta awareness event were associated with the breath focus condition (orange and green).

Conventional EEG systems store event triggers in the same file as the EEG data. Short direct current pulses of fixed magnitude in dedicated stimulus channels encode stimulus onsets or button presses. The EEG sample number of the onset of each direct current pulse is stored in MNE-Python event arrays as the event time (MNE Developers, 2020b). In the present study, MNE-Python's automatic event recognition functionality could not be used, because meta awareness events and auditory stimulus onsets were saved in separate CSV-files. In consequence, MNE-Python event arrays had to be created manually instead, which required converting event onset times to EEG sample numbers. MNE-Python offers a function that converts a time in seconds into the integer index of the EEG sample occurring closest to that time (MNE Developers, 2020c). Unfortunately, this function yielded inaccurate results, since the timestamps associated with MNE raw objects diverged from the true timestamps of EEG samples, as it has already been discussed in section **2.5.1**.

As a workaround, the correct EEG sample numbers corresponding to the respective event onset times were inferred from the index of the CSV-file into which EEG data were written during recording. A function was written that returns the index of the EEG data sample whose timestamp was closest to a given event onset time. Those indices were passed as the correct EEG sample numbers to the MNE-Python event array.

Despite the workaround described above, a constant sampling rate had to be assumed within each epoch, even though that is a false assumption, given the inconstant sampling rate of the *Traumschreiber*. In fact, not all epochs comprised the same number of EEG samples due to variations in the sampling rate in the respective time intervals. Computing ERPs requires averaging over epochs which in turn presupposes an identical number of EEG samples in each epoch. By assuming a constant sampling rate for the respective time interval of each epoch, all epochs now comprised the same number of EEG samples. Although epochs were still time-locked to the correct event onset times, taking into account an additional EEG sample or disregarding an EEG sample in order to equalize the EEG sample number of all epochs distorted the true epoch durations.

2.5.3 Event-Related Potentials

After epochs were extracted from the EEG data, Event-Related Potentials were computed on auditory epochs obtained for standard and oddball stimuli over two conditions, mind wandering and breath focus. To this end, brain activity from electrode Fz was processed for auditory ERP analysis. First, epochs were baseline corrected in order to attenuate patterns of activity that are unrelated to the stimuli by using a a baseline window of -300 to 0 milliseconds and subtracting the mean of that baseline period from the data. Since ICA did not yield any meaningful insights (see section **2.5.1**), epochs which exceeded a threshold of 200 microvolts were rejected based on the voltage value of channel Fz. In total, 382 out of 5656 auditory epochs were rejected. In the following, auditory epochs were cropped to a time interval starting 100 milliseconds before stimulus onset and lasting until 450 milliseconds after stimulus onset since the ERP components of interest are known to occur in this time window. The grand average of Auditory Evoked Potentials was computed under the assumption of a constant sampling rate for the respective time interval of each shortened epoch (see section **2.5.2**).

Furthermore, Mismatch Negativity (MMN) was computed for both mind wandering and breath focus conditions by subtracting the ERP elicited by the standard stimulus from the ERP elicited by the oddball stimulus (Garrido et al., 2009). Mismatch Negativity was first computed for each block and subject and averaged afterwards, yielding the grand average of auditory MMN.

2.5.4 Time-Frequency Decomposition

Analyzing the 20 seconds epochs centered on meta awareness events (button presses), time-frequency decomposition was applied. Data from electrodes O_1 and O_2 were processed for time-frequency analysis. Like for auditory epochs, epochs which exceeded a threshold of 200 microvolts were rejected based on the voltage values of channels O_1 and O_2. 10 out of 277 epochs were rejected. In contrast to the auditory epochs used for ERP analysis, the 20 seconds epochs were neither baseline corrected nor averaged.

Morlet wavelet decomposition was applied to the 20 seconds epochs using a series of 30 linearly spaced frequencies ranging from 1 Hz to 30 Hz. The number of wavelet cycles started at 1.5 cycles at 1 Hz and increased linearly up to eight cycles at 30 Hz (Braboszcz and Delorme, 2011). Time-frequency decomposition was computed separately for the delta (2-4 Hz), theta (4-7 Hz), alpha (9-11 Hz) and beta (15-30 Hz) frequency bands on non-averaged epochs. After running Morlet wavelet decomposition, the time-frequency representations were splitted into two ten seconds segments corresponding to mind wandering and breath focus condition, respectively. For visualization only (**Fig 10** and **Fig 11**), an independent Morlet wavelet decomposition was applied to averaged 20 seconds epochs for the entire frequency spectrum from 1 to 30 Hz.

Next, the mean of channels O_1 and O_2 was taken for each data point and the differences in time-frequency data between mind wandering and breath focus conditions were computed for each frequency band. Power differences were calculated between temporally symmetric time-frequency data points in the two conditions. For example, time-frequency data two seconds prior to meta awareness (mind wandering condition) was subtracted from time-frequency data two seconds post meta awareness (breath focus condition). Finally, power differences in each frequency band were tested for significance using one non-parametric cluster-level two-tailed paired t-test for each frequency band with a precluster threshold of $p = 0.05$ and 1000 permutations (Maris and Oostenveld, 2007). The results were corrected for multiple comparison using the cluster method developed by Maris and Oostenveld (2007).

2.6 Data Analysis Questionnaire

In addition to the EEG data, behavioral data collected in the questionnaire were analyzed. Python 3.6.7 (Python Software Foundation, 2020) and the packages pandas 0.24.2 (McKinney, 2011) as well as NumPy 1.17.2 (Walt et al., 2011) were used for general data processing. Data were visualized using the Python plotting packages Matplotlib 3.0.3 (Hunter, 2007) and Seaborn 0.9.0 (Waskom, 2020). Statistical analyses of behavioral data were performed with Statsmodel 0.9.0 (Seabold and Perktold, 2010). In contrast to the EEG data analysis, data of all 15 participants were taken into account for analyzing behavioral data and no participant was excluded.

After the intention of the experiment had been revealed, participants were confronted with nine different statements about mind wandering and indicated their agreement or disagreement on a five-point Likert scale. Five of those statements could be associated with a positive perspective on mind wandering, for example: *Mind wandering has a positive effect on my psychological wellbeing.* In contrast, three statements reflected a rather negative perspective on mind wandering, for instance: *I would like to mind wander less.* The remaining two statements were classified as neutral and not considered for the following analysis. A complete overview of all statements can be seen in **Appendix E**.

In order to quantify participants' perspective on mind wandering, Likert-scale agreement ratings were transformed to a so-called *mind wandering attitude index.* Numerical values were assigned to each Likert-scale answer. For positive statements, +1 corresponded to *I agree*, for negative statements, on the contrary, +1 corresponded to *I disagree.* Next, all numerical ratings for positive and negative statements were summed up and dived by the number of statements, resulting in a normalized index of participants' attitude towards mind wandering in the interval $[-1, +1]$. A *mind wandering attitude index* of 0 can be considered as neutral, $+1$ denotes a very positive perspective on mind wandering and -1 indicates a very negative perspective on mind wandering.

In the following, a one sample t-test was used to test whether the mean *mind wandering attitude index* of the present sample is significantly different from a neutral attitude of 0.0.

Furthermore, correlations between mind wandering frequency in the experiment and participants' attitude towards mind wandering or self-estimations of daily mind wandering time were computed by means of linear regression.

3 Results

This chapter reviews the results of the present study. The first two sections cover the results of EEG data analysis and thus constitute an important source of information for comparing the results of the present work to the original study by Braboszcz and Delorme (2011). The latter two sections review the answers participants provided in the questionnaire, a novel addition to the experimental design of Braboszcz and Delorme (2011) that targets participants' attitude towards mind wandering as well as first person reports of the phenomenology of mind wandering.

3.1 Auditory Evoked Potentials

Auditory Evoked Potentials (AEPs) were obtained for standard and oddball stimuli over mind wandering and breath focus conditions. Typically, AEPs show auditory brainstem responses as early components, followed by mid-latency and long-latency responses (Luck, 2014). Well known long-latency responses are for example the negative component N2, which is associated with repetitive non-target stimuli and shows a larger amplitude for deviant stimuli, or the positive component P3, which seems to be elicited by unpredictable infrequent shifts in tone pitch or intensity (Luck, 2014).

Fig 8 shows the grand average of AEPs for each of the four groups. In the present data, none of the standard AEP components can be clearly identified. The AEP waveform related to oddball stimuli in the mind wandering condition (purple) shows two distinct negative peaks at around 160 and 230 milliseconds post stimulus onset. Counterintuitively, those negative AEP components related to oddball stimuli are more negative during mind wandering (purple) than during breath focus (orange). Additionally, the present data does not indicate any trend with respect to a higher positive component 200 milliseconds post stimulus onset during mind wandering than during breath focus, as it was reported by Braboszcz and Delorme (2011). Moreover, the AEPs associated with standard auditory stimuli for either mind wandering (blue) or breath focus condition (green) cannot be clearly distinguished. In comparison to ideal AEP waveforms, the present AEP waveforms show a high number of densely arranged positive and negative peaks, pointing towards high frequency noise in the signal (see Picton (2010) for ideal AEP waveforms).

Auditory Mismatch Negativity (MMN) is a negative component of the AEP waveforms that is obtained by subtracting the event-related response to the standard stimulus from the response elicited by the oddball stimulus (Garrido et al., 2009). In general, auditory MMN is associated with sudden changes in stimulation and peaks at about 100 to 250 milliseconds after stimulus onset, most prominently at frontal and temporal electrodes. From the predictive coding perspective, it is believed that MMN reflects prediction errors (Garrido et al., 2009; see section **1.4**).

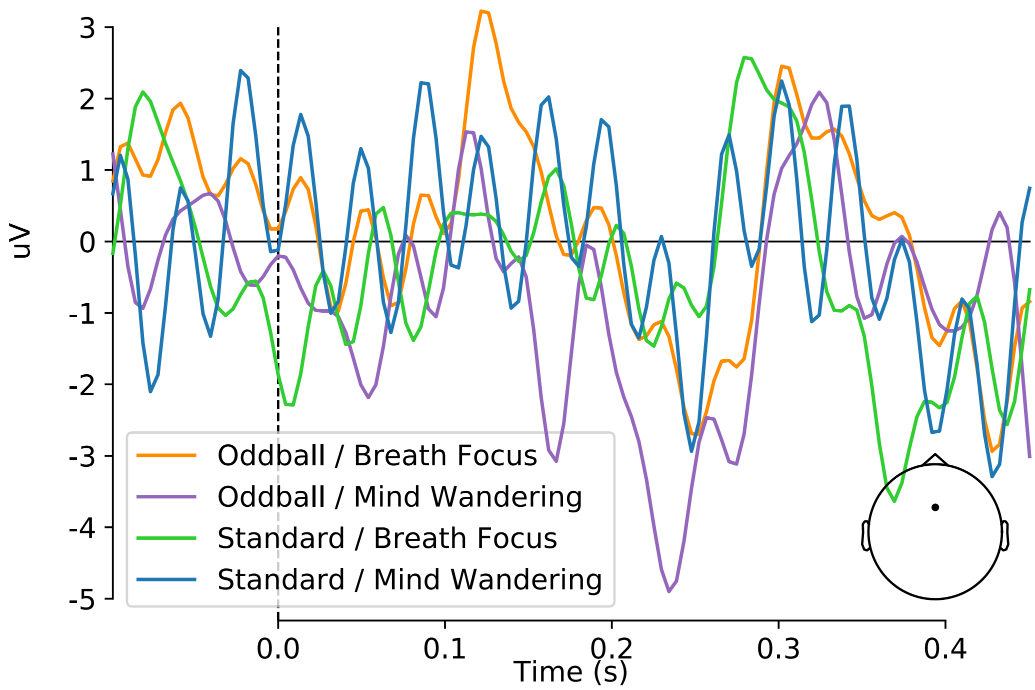

Figure 8: **AEP grand average at electrode Fz**. Time 0.0s refers to stimulus onset. The black dot on the scalp topography represents the location of electrode FZ.

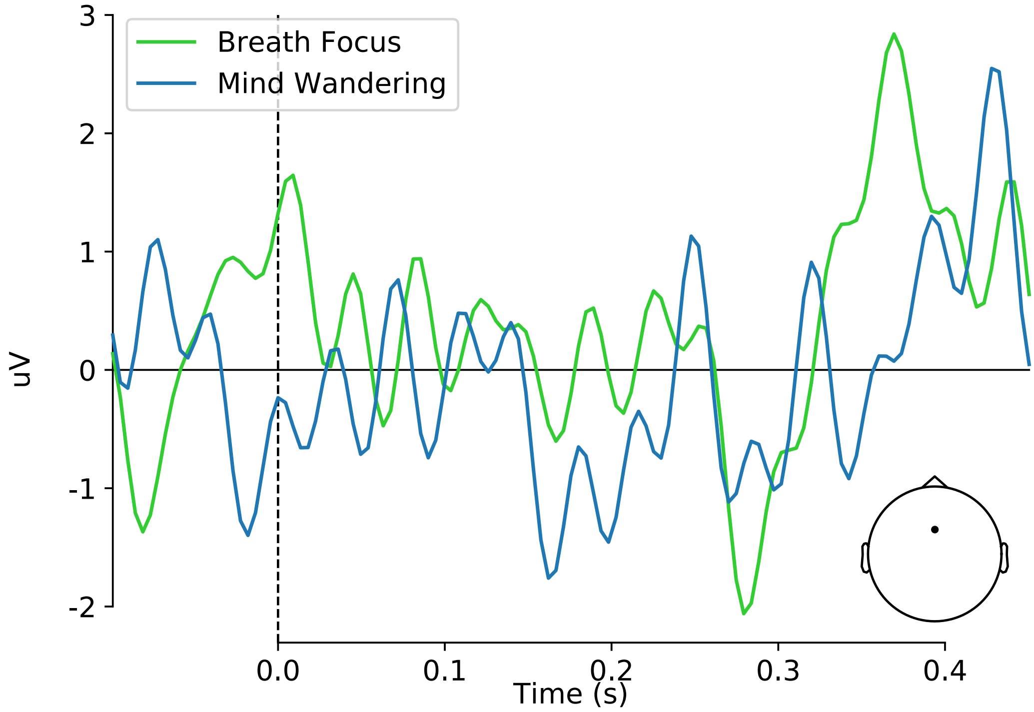

Figure 9: **Auditory MMN grand average at electrode Fz**. Time 0.0s refers to stimulus onset. The black dot on the scalp topography represents the location of electrode FZ.

Fig 9 portrays the grand average of auditory MMN, contrasting mind wandering (blue) against breath focus (green) condition. There is no isolated high amplitude negative peak between 100 and 250 milliseconds post stimulus onset in the data as it would be characteristic of an ideal MMN waveform (see Garrido et al. (2009) for an ideal MMN waveform). The most prominent negative peak of MMN can be seen at 280 milliseconds post stimulus onset for the breath focus condition and at 160 milliseconds post stimulus onset for the mind wandering condition, though the latter peak is not isolated. Temporally aligned negative components showing a clear attenuation in the mind wandering condition would be indicative of attenuated sensory processing of the external environment, also known as perceptual decoupling (see sections **1.3** and **1.4**). However, the isolated negative component in the breath focus condition occurs later than one would expect and is not temporally aligned with an attenuated negative component in the mind wandering condition in the typical MMN time window. Due to high frequency noise in the signal, the attenuation of auditory MMN in the mind wandering condition might be concealed by high frequency noise.

Individual plots of AEPs and MMN for each subject and experimental block can be seen in **Appendix A** and **Appendix B**.

3.2 Time-Frequency Analysis

Analyzing power differences in time-frequency data between mind wandering and breath focus conditions revealed significantly decreased power in the alpha (9-11 Hz) and beta (15-30 Hz) frequency bands during mind wandering. The results suggest disparities in neural oscillations that might be attributed to dissimilar cognitive processes underlying the mind wandering and breath focus states. **Fig 10** displays an averaged time-frequency slice time-locked to meta awareness (button press).

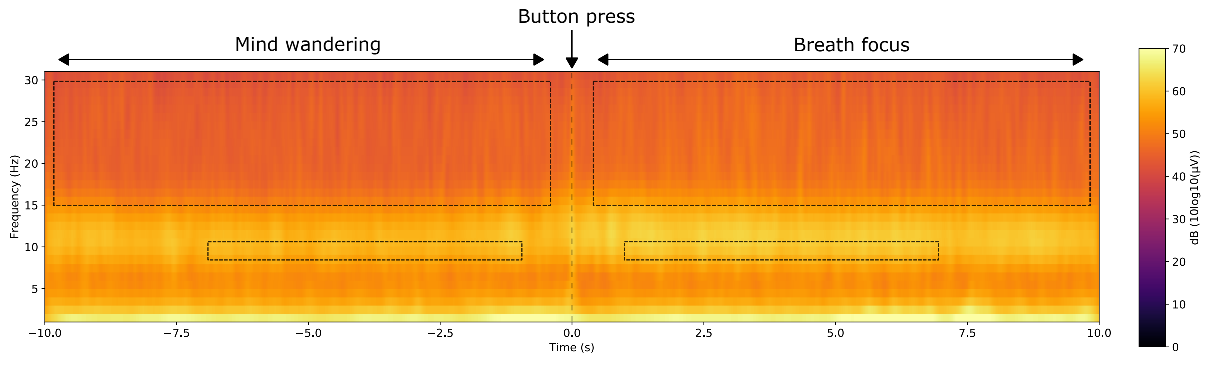

Figure 10: **Time-frequency slice** at occipital electrodes showing the transition from mind wandering to breath focus. The dashed rectangles refer to areas of significant power differences in the alpha (9-11 Hz) and beta (15-30 Hz) frequency bands, see Fig 11 for more details.

Separate non-parametric cluster-level two-tailed paired t-tests for each frequency band with a precluster threshold of 0.05 yielded 19 clusters for the delta frequency band (2-4 Hz), 41 clusters for the theta frequency band (4-7 Hz), 11 clusters for the alpha frequency band (9-11 Hz) and 45 clusters for the beta frequency band (15-30 Hz). After performing 1000 permutations and correcting for multiple comparison, one cluster of the alpha frequency band and one cluster of the beta frequency band exhibited significant power differences contrasting mind wandering to breath focus (p = 0.001 for both clusters). None of the clusters of the delta or theta frequency bands turned out to be significant. In **Fig 11**, each subplot illustrates time-frequency power in either mind wandering or breath focus condition for one frequency band each. Colored masks corresponding to the significant clusters of the alpha and beta frequency bands are superimposed on the respective time-frequency slices. Non-significant clusters are grayed out. See **Appendix C** for a visualization of power differences in each frequency band between mind wandering and breath focus conditions and the corresponding cluster level statistics.

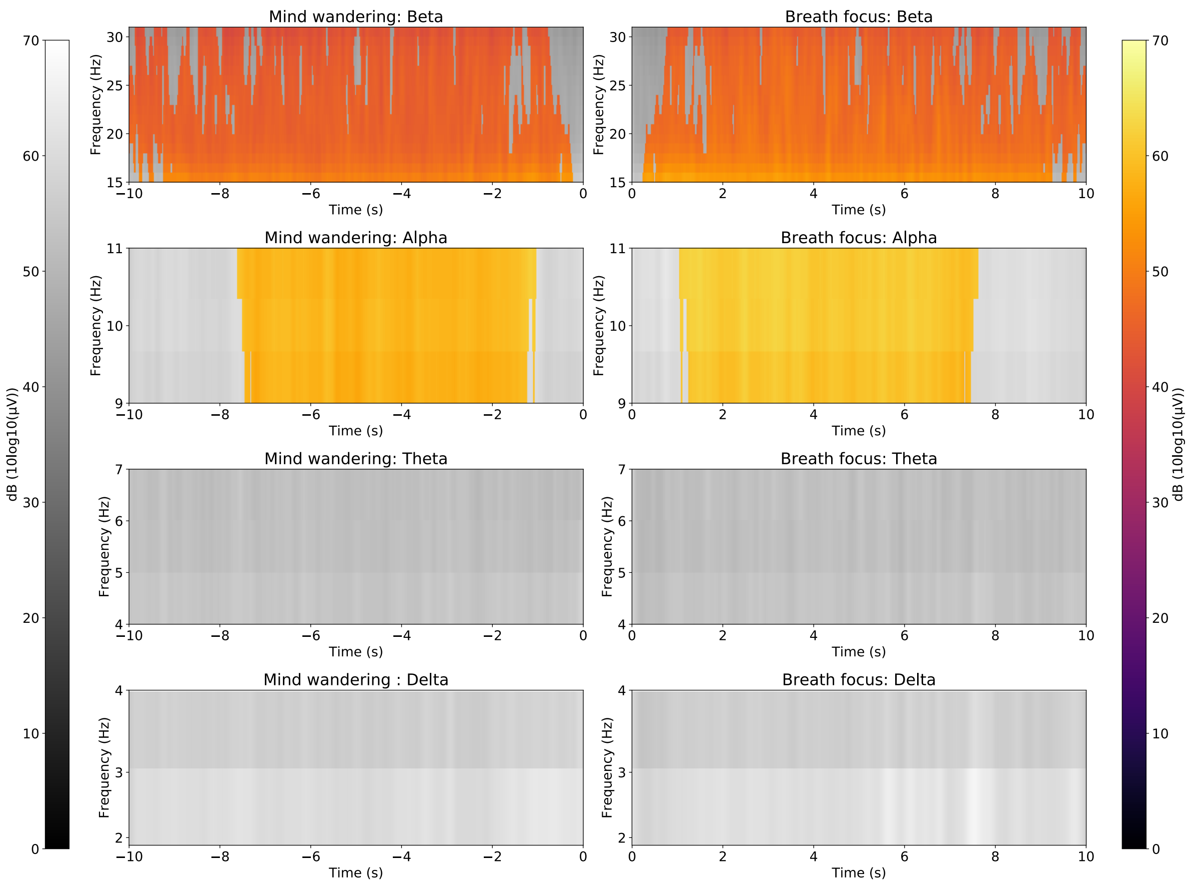

Figure 11: **Significantly decreased power in alpha and beta frequency bands during mind wandering**. Time-frequency power is shown for the delta (2-4 HZ), theta (4-7 Hz), alpha (9-11 Hz) and beta (15-30 Hz) frequency bands. Regions of significant power differences comparing mind wandering to breath focus are color coded ($p = 0.001$), the gray scale refers to non-significant regions.

3.3 Behavioral Data

During the experiment, participants were instructed to press a button whenever they became aware of having lost track of their breath count. Those button presses indicated self-awareness of mind wandering episodes. After the experiment, participants answered a questionnaire which also included a retrospective self-estimation of how often participants think they mind wandered in each block of the experiment. **Fig 12** compares participants' retrospective self-estimations of mind wandering frequencies (green) against participants' self-awareness of mind wandering during the experiment (orange).

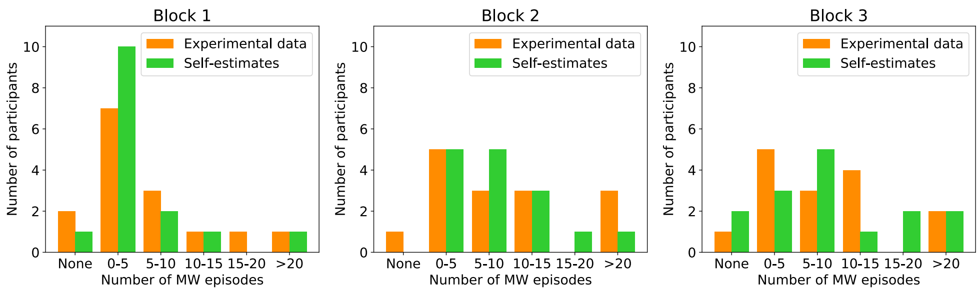

Figure 12: **Experimental self-awareness vs. retrospective self-estimations of mind wandering episodes**. Each histogram corresponds to one of the three experimental blocks.

First, there seems to be no evidence of a general tendency to over- or underestimate mind wandering frequencies in retrospect. Second, the accuracy of retrospective self-estimations seems to be similar over the three experimental blocks. Since the time difference between experimental self-awareness and retrospective self-estimations is greater for the first block compared to the second or third block, one might have hypothesized that retrospective self-estimations would be less accurate for earlier blocks, but there is no such evidence in the data.

Additionally, participants were asked to judge how much of their daily wake time they spent mind wandering on average over the last couple of weeks. **Fig 13** shows a regression plot investigating whether the total number of mind wandering episodes in the experiment correlates with participants' self-estimations of their daily mind wandering time.

There is no significant correlation ($R^2 = 0.107, p > 0.05$) between the total number of mind wandering episodes in the experiment and self-estimations of daily mind wandering time. Hence, the total number of mind wandering episodes during the experiment cannot predict self-estimations of daily mind wandering time. Critically, one can question the accuracy of self-estimations of daily mind wandering time. Likewise, it is questionable to assume that the particular setup of the present experiment is representative of daily activity.

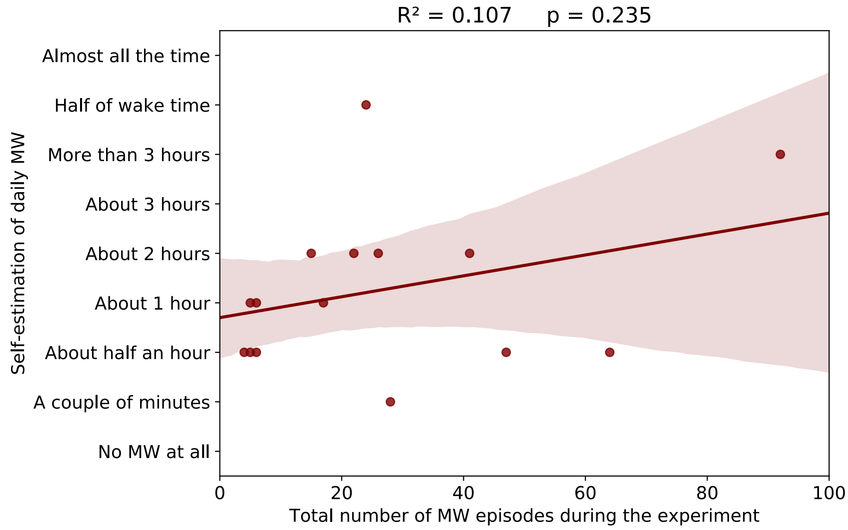

Figure 13: **Predicting daily mind wandering time**. The total numbers of mind wandering episodes during the experiment are plotted against participants' self-estimations of daily mind wandering time. The shaded region corresponds to the 95% confidence interval of the regression estimate.

A large-scale probe-caught experience sampling study suggests that people are mind wandering 30-50% of their wake time, depending on the activity they are occupied with (Killingsworth and Gilbert, 2010). In the present study, only one participant indicated spending half of their wake time mind wandering, all other self-estimations were considerably lower. Thus, it is difficult to predict presumably inaccurate self-estimations of daily mind wandering time based on experimental mind wandering frequencies. Real-world probe-caught experience sampling studies as conducted by Killingsworth and Gilbert (2010) seem to be a more suitable approach to assess how much of people's conscious experience is occupied by mind wandering.

Furthermore, participants' attitude towards mind wandering was assessed by analyzing agreement or disagreement to different statements about mind wandering. A so-called *mind wandering attitude index* was calculated that tried to quantify participants' perspective on mind wandering (see section **2.6**).

As portrayed in **Fig 14 A**, the attitude of the present sample towards mind wandering seems to be predominantly positive. The mean mind wandering attitude index of 0.334 is significantly different from a neutral mind wandering attitude index corresponding to 0.0 ($p = 0.002$, one sample t-test).

Interestingly, there is a a significant negative correlation between the total number of mind wandering episodes in the experiment and participants' mind wandering attitude indices ($R^2 = 0.29, p = 0.038$). It seems like participants' attitude towards mind wandering is biased by personal mind wandering habits such that more frequent experimental mind wandering correlates with a less positive perspective on mind wandering (see **Fig 14 B**).

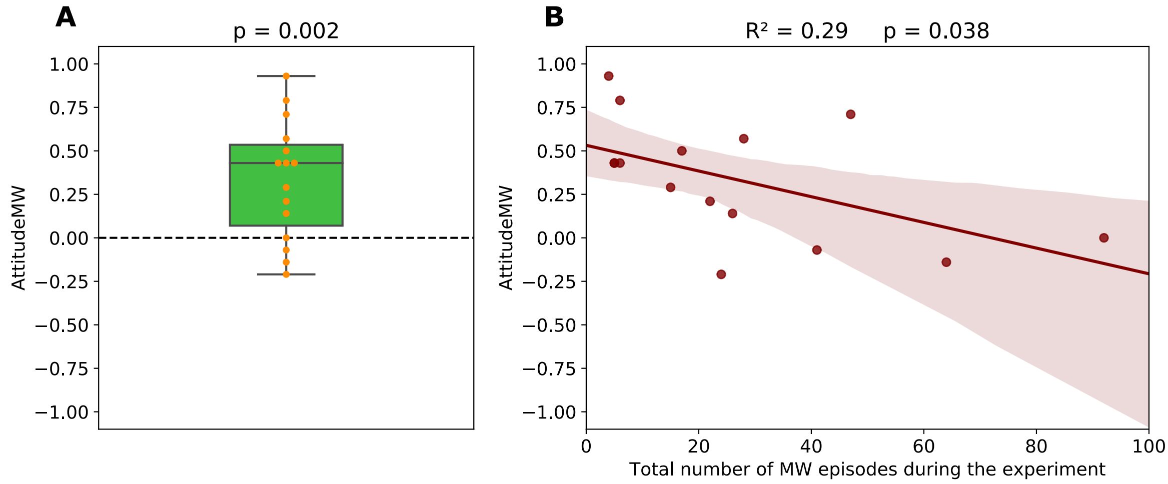

Figure 14: **Attitude towards mind wandering**. **A**: Mind wandering attitude index. **B**: The total numbers of mind wandering episodes during the experiment are plotted against participants' mind wandering attitude indices. The shaded region corresponds to the 95% confidence interval of the regression estimate.

However, these results must not be overinterpreted. The so-called *mind wandering attitude index* is based on a small set of statements only, moreover, a single quantified value can hardly give a differentiated account of someone's perspective on mind wandering. Methodological issues with respect to self-estimations of daily mind wandering time have already been discussed. Therefore, the behavioral results presented in this section cannot be generalized.

3.4 First Person Accounts of Mind Wandering

At the end of the questionnaire, participants were asked to provide a free text answer on how they experienced mind wandering episodes during the experiment, targeting a detailed phenomenological account of mind wandering. **Fig 16** displays a word cloud highlighting linguistic commonalities in participants' free text answers.

Reviewing the participant's reports revealed several interesting insights about mind wandering as a phenomenon. For instance, some participants reported to be able to keep track of their breath count while they were mind wandering, at least for a short time. Phenomenological accounts thus challenge a mutually exclusive distinction between mind wandering and breath focus. Taking together all responses, a four stage model emerged describing the transition from task focus to mind wandering and back to task focus (see **Fig 15** for a schematic overview).

In the first stage, participants are focused on their breath count (*Task Focus*), followed by an intermediary stage in which thoughts start to drift away but participants are still able to keep track of their breath count (*Transition State*). In the third stage, participants are lost in thoughts, being fully distracted from the breath counting task (*Mind Wandering*). The moment of realizing that one's thoughts have drifted away marks the final stage (*Meta Awareness*). Participants were instructed to re-focus on the breath counting task as soon as they realized their thoughts had drifted away, hence, meta awareness terminates a mind wandering episode and brings participants back to task focus.

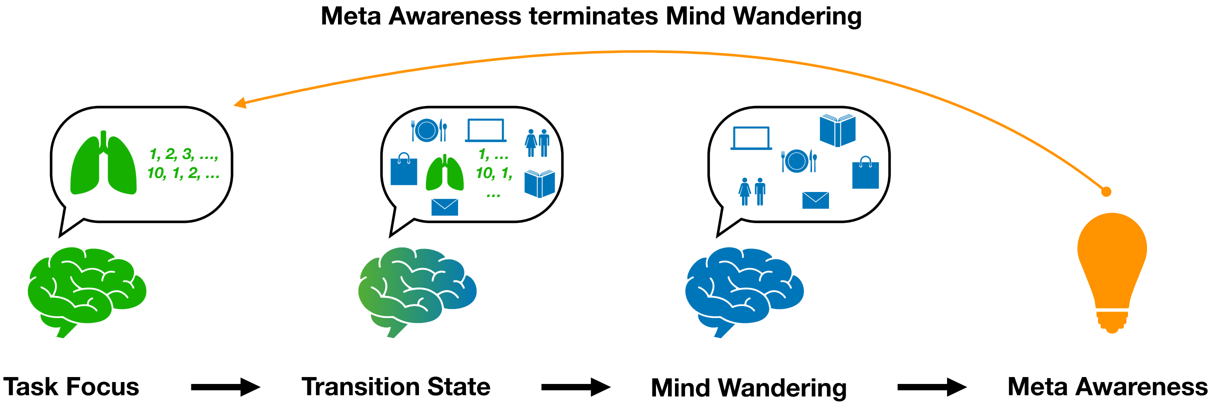

Figure 15: **4-stage model** portraying the transition from task focus to mind wandering and back to task focus. Participants' reports suggest that there is a transition state during which breath focus and mind wandering are not mutually exclusive.

According to most first person reports, mind wandering itself was experienced as pleasant, however, some participants characterized mind wandering as a loss of control and thus experienced mind wandering as unpleasant. The realization that one had been mind wandering and had lost track of the task was experienced as unpleasant by all participants though. Meta awareness was described as waking up from a dream while regretting waking up. The participants also referred to a sleep analogy in order to describe how they felt during the transition state from task focus to mind wandering, using terms like *relaxing* or *calm*, and compared the transition state to the moment of falling asleep.

The content of mind wandering episodes was mostly about daily concerns related to university, what to eat, making plans for the rest of the day or reflecting on recent conversations with other people. Moreover, all participants reported that the experiment made them feel tired and that it was sometimes difficult not to fall asleep.

Picking up on the sleep analogy that has been brought up by some participants, the first person accounts of mind wandering in the present study can be summarized as follows: *Dreaming seems to be a pleasant experience most of the time, until you have to wake up.* Mind wandering episodes itself were experienced predominantly pleasantly, whereas most participants regretted the moment of meta awareness.

Note that this summary is not meant to be a representative phenomenological account of mind wandering. Nevertheless, the first person accounts of the present study point towards a more general discussion regarding the costs and benefits of mind wandering that will be addressed in section **4.3**.

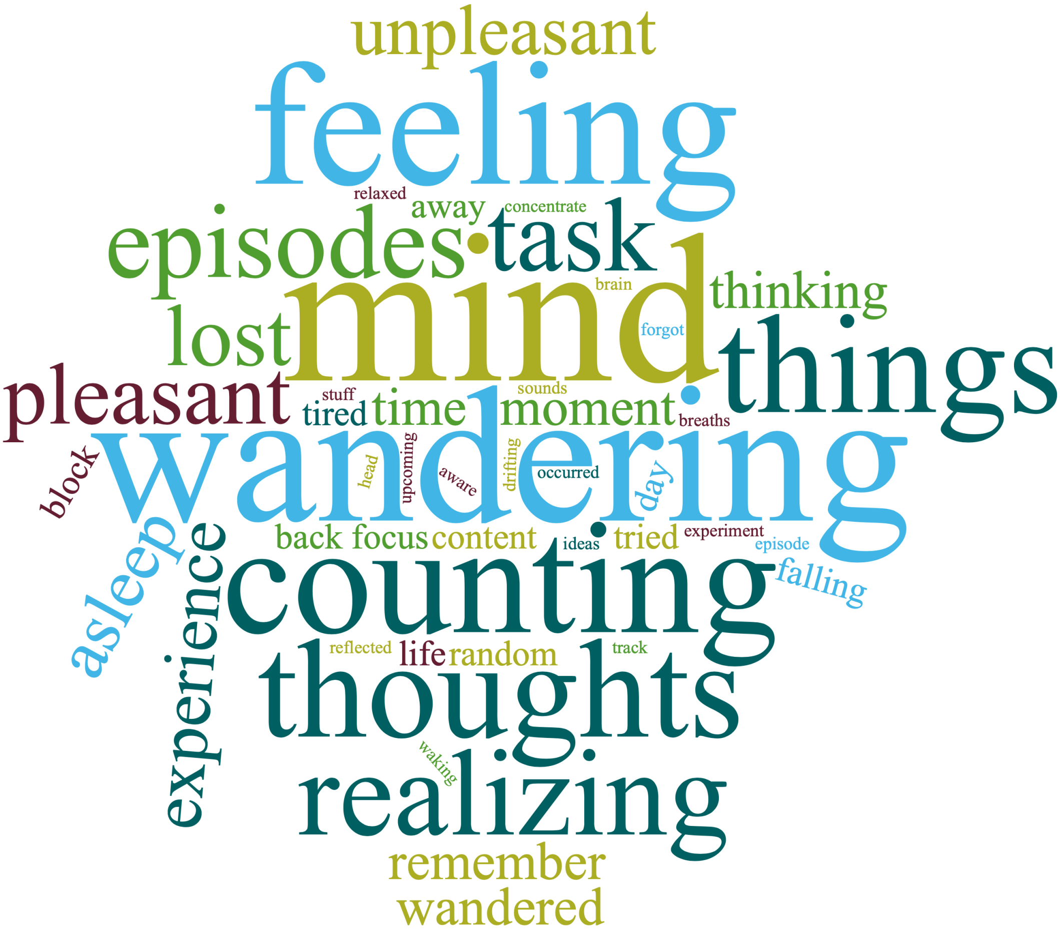

Figure 16: **Word Cloud** illustrating linguistic commonalities in free text answers on how mind wandering was experienced.

4 Discussion

In this chapter, the findings of the present study are discussed and contextualized. The first section elaborates on the feasibility of conducting EEG studies with the Traumschreiber, followed by a rigorous analysis why the present work could not replicate all findings of Braboszcz and Delorme (2011) and to what extent the results of the original study can be regarded as valid. The final section of this chapter is about *Neurophenomenology*, a research approach that is particularly suited to study mind wandering.

4.1 Working with the Traumschreiber

Conducting an EEG study with the *Traumschreiber* proved to work with relatively few interferences. In the course of 15 recordings, each lasting for one hour, recordings interrupted only once and a small fraction of data were lost. Apart from that, transmitting EEG data via BLE and controlling the *Traumschreiber* via the app *EEGDroid* functioned smoothly.

Future versions of the *Traumschreiber* would profit from a battery indicator and some means to monitor the electrode's impedance, as the only way to check the signal quality during experiment preparation was to use the life plot functionality of *EEGDroid*. Other issues like air gaps between the scalp and some electrodes that had to be fixed provisionally by tightening the cap with the help of tape could be easily solved if additional accessory parts like EEG caps of different sizes were purchased.

The inconstant sampling rate of the *Traumschreiber*, however, posed a challenge that significantly corrupted the results of EEG data analysis. Most EEG data analysis techniques require a constant sampling rate in order to average over epochs. Thus, having to falsely assume a constant sampling rate or having to shorten epoch durations in order to minimize the confounding effect of assuming a constant sampling rate impeded the replication of Braboszcz and Delorme (2011). Since the inconstant sampling rate is caused by BLE buffering, only redesigning the *Traumschreiber's* hardware and using an alternative wireless data transmission technology would potentially solve the issue. An updated version of the *Traumschreiber* that transmits data via WiFi instead of BLE is currently under development at the Neuroinformatics group, University of Osnabrueck. Future studies will investigate whether WiFi is an advantageous wireless interface to conduct mobile EEG studies.

The mobile setup of the present study was more prone to noise distortions than conventional EEG studies that try to set up the experiment such that as many sources of noise are eliminated as possible. Placing the *Traumschreiber* right next to the tablet possibly resulted in increased electrical artifacts. However, artifacts that can be attributed to the display, the touchscreen refresh rate or electrical noise in general are typically localized above the frequency ranges of brain related activity (Török et al., 2014). All those frequencies were eradicated by low-pass filtering the data at 30 Hz.

Moreover, EEG data analysis revealed that a standard EEG data analysis toolbox like MNE-Python is not ideally suited to analyze EEG data recorded with the *Traumschreiber*. For future studies, it would be advisable to find an alternative toolbox or implement custom made analysis software prior to data collection. Manipulating the *Traumschreiber's* file format such that event triggers are stored in the same file as the EEG data itself, analogous to how conventional EEG systems encode event triggers in dedicated stimulus channels, would further aid data analysis.

Unfortunately, the present work could not provide a proof of concept that the *Traumschreiber* is on a par with conventional EEG systems, at least in its present version. However, given the *Traumschreiber's* mobility and affordability, one cannot expect the quality of the data recorded with the *Traumschreiber* to be equivalent to the signal quality of stationary EEG systems with a higher number of channels. Therefore, it is promising to further promote the development of more sophisticated versions of the *Traumschreiber* that can hopefully address the technical issues that have been encountered in the present study.

4.2 Comparing Replication to Original Study

In the present study, the results of time-frequency analysis of Braboszcz and Delorme (2011) could be replicated in part. Like in the original study, power in the alpha (9-11 Hz) and beta (15-30 Hz) frequency bands was significantly reduced during mind wandering. However, the present study did not find increased power in the delta (2-4 Hz) and theta (4-7 Hz) frequency bands, contrasting mind wandering to breath focus.

Grand average Auditory Evoked Potentials (AEPs) obtained in the present study differ considerably from the results of Braboszcz and Delorme (2011). Neither the attenuated Mismatch Negativity (MMN) during mind wandering, nor the higher ERP positive component at 200 milliseconds post stimulus onset, comparing mind wandering to breath focus, could be replicated. Critically, Auditory Evoked Potentials obtained in the present study do not show any of the characteristics of typical AEPs, suggesting that the failure to replicate the findings of Braboszcz and Delorme (2011) might be attributed to the *Traumschreiber*. ERPs recorded at electrode *Fz* seem to contain a lot of high frequency noise, even though the auditory epochs were band-pass filtered from 1 to 35 Hz.

Furthermore, technical issues, especially the inconstant sampling rate, likely corrupted some of the data recorded with the Traumschreiber. Having had to assume a constant sampling rate for both types of epochs yielded incorrect results of averaging over epochs if the true epoch duration deviated from the specified epoch duration due to inconsistencies in the sampling rate. Additionally, the *Traumschreiber* offers no means to monitor each electrode's impedance value, which made it difficult during experiment preparation to ensure recording clean signals. Since the experiment lasted for one hour, electrodes which seemed to receive a clean signal during experiment preparation might have become noisy later on during the course of the experiment, due to electrode gel leakages, or failures of provisional solutions as described in the previous section.

Due to some of the *Traumschreiber's* technical specifications, EEG data could not be processed exactly the same way as reported by Braboszcz and Delorme (2011), a factor that possibly also impeded replication. For example, the limited number of EEG channels of the *Traumschreiber* made it difficult to successfully filter out artifacts during preprocessing by means of Independent Component Analysis (ICA). Instead, bad epochs had to be rejected based on a voltage threshold, a procedure which does not guarantee that all good epochs are actually completely free of artifacts (Delorme et al., 2007).

Of course, one might also argue that the failure to replicate all findings of Braboszcz and Delorme (2011) suggests a lack of robustness of their findings, instead of arguing that the data recorded with the *Traumschreiber* was too noisy for a thorough ERP analysis. However, AEPs evoked by auditory oddball paradigms have been an active area of research for a long time and the results of Braboszcz and Delorme (2011) are in line with other findings of AEPs elicited by auditory oddball paradigms (Garrido et al., 2009; Huang et al., 2019; Näätänen et al., 2007). Regarding the power alterations in the delta, theta, alpha and beta frequency bands reported by Braboszcz and Delorme (2011), comparing their results to other studies does not yield a conclusive answer. On the one hand, a recent study by van Son et al. (2019) found increased theta and decreased beta power at frontal electrodes during mind wandering compared to breath focus, thus, supporting the results of Braboszcz and Delorme (2011) and those of the present replication. On the other hand, Compton et al. (2019) found that alpha power was significantly higher while participants were mind wandering, which is contradictory to the results of Braboszcz and Delorme (2011) and those of the present study. However, differences in the experimental design are a potential explanation for contradictory results. van Son et al. (2019) implemented the same experimental design as Braboszcz and Delorme (2011), in contrast, Compton et al. (2019) used a probe-caught experience sampling method while participants were engaged in a speeded performance task. Since self-caught experience sampling paradigms only reveal those mind wandering episodes that are accompanied with meta awareness, it might be that the neural correlates associated with unaware mind wandering, those studied by Compton et al. (2019), differ from the neural correlates linked to explicit awareness of mind wandering as studied by Braboszcz and Delorme (2011), van Son et al.

(2019) and in the present work.

Given the self-caught mind wandering detection technique implemented by Braboszcz and Delorme (2011), it was impossible to experimentally assess how long each mind wandering episode actually lasted, be it shorter or longer than ten seconds. Likewise, it is rather likely that not all mind wandering episodes were captured by self-awareness of mind wandering, since not all mind wandering episodes are necessarily accompanied by meta awareness (Smallwood and Schooler, 2015). However, Braboszcz and Delorme (2011) underline that their study is a proof of concept, demonstrating that neural correlates of mind wandering can actually be studied by means of introspective mind wandering awareness, even though a self-caught paradigm is not capable of detecting each and every mind wandering episode. Varao-Sousa and Kingstone (2019) explicitly compared self-caught to probe-caught experience sampling methods in a natural environment and provide further evidence regarding the reliability of the self-caught methodology to study mind wandering.

With respect to the experimental design of Braboszcz and Delorme (2011), it is not clear why exactly they defined 20 seconds epochs time-locked to meta awareness events, presupposing that participants mind wandered at least ten seconds prior to meta awareness and focused on the breath counting task for at least ten seconds post meta awareness. In the present experiment, few participants indicated two meta awareness events within less than 20 seconds. Nevertheless, it seems plausible that participants were not always focused on their breath count for the entire ten seconds period following meta awareness, especially towards the end of the experiment, as participants reported that the experiment made them feel tired.

A minor criticism is that the experimental design of Braboszcz and Delorme (2011) does not counterbalance standard and oddball auditory stimuli. In consequence, one might argue that differences in Auditory Evoked Potentials of standard and oddball stimuli might not arise from differences in stimulus presentation frequencies, but from varying tone frequencies. However, it is well established in the literature that MMN for example is a typical AEP evoked by auditory oddball paradigms (Näätänen et al., 2007).

In conclusion, even though not all findings of Braboszcz and Delorme (2011) could be replicated in the present study, their results are in line with other research on neural correlates of mind wandering and thus seem to be valid. In consequence, the fact that the results of the present study are based on fairly noisy data recorded with an eight channel mobile low-cost EEG device seems to be a more plausible explanation why not all findings of Braboszcz and Delorme (2011) could be replicated.

4.3 Neurophenomenology of Mind Wandering

In the 1990s, Francisco Varela envisioned a research direction called *neurophenomenlogy* (Varela, 1996), an approach belonging to a family of non-reductionist approaches to study the human mind, like for example the 4E approaches in cognitive science. According to Varela, lived experience - phenomenology describes the study of the structures of consciousness as experienced from a first person point of view (Stanford Encyclopedia of Philosophy, 2020) - is fundamentally irreducible (Varela, 1996). Therefore, Varela (1996) proposes to circulate between external and phenomenological analysis in order to study the human mind. He points out that precise first person accounts and correlating neurophysiological processes mutually constrain each other (Varela, 1996). More recent interpretations of *neurophenomenology* state that cognitive scientists should not only be skilled in neuroscience, mathematics and psychology, but also in phenomenology and contemplative practices like mediation (Thompson, 2014).

With respect to mind wandering, Schooler and Schreiber (2004) have proposed to combine self-reports, behavioral and neurocognitive measures to study mind wandering. Schooler and Schreiber (2004) titled their research strategy *triangulation*, but it could also be called a neurophenomenological approach. Moreover, Braboszcz and Delorme (2011) demonstrated that it is indeed possible to conjoin phenomenological experience and neuroscience. Instead of gauging participants' attentional state behaviorally by means of performance in a control task Braboszcz and Delorme (2011) relied on participants' meta awareness and identified alterations in brain dynamics which correlated with low alertness of the external environment during mind wandering.

In the following, the participant's first person reports of the present study are related to what is known about the phenomenology of mind wandering and correlating neurophysiological processes in the literature.

Killingsworth and Gilbert (2010) claim that "[...] a wandering mind is an unhappy mind" (Killingsworth and Gilbert, 2010, p. 932). However, in the present study, most participants described their experience of mind wandering as positive. As already discussed in section **1.1**, the content regulation hypothesis emphasizes that mind wandering is not associated with an unhappy mood *per se*, instead, the *thought content* is a crucial factor in determining the effects of mind wandering on mental health (Smallwood and Andrews-Hanna, 2013). Interesting mind wandering episodes actually seem to contribute to a positive mood (Franklin et al., 2013). In line with the findings of Franklin et al. (2013), Smallwood and Schooler (2015) have identified a *prospective bias* regarding the thought content of beneficial mind wandering episodes according to which positive mind wandering episodes contain a bias towards thinking about the future (Smallwood and Schooler, 2015). A more detailed analysis of the results of Killingsworth and Gilbert (2010) reveals that happiness ratings during *pleasant* mind wandering episodes were indistinguishable from those collected when participants were not mind wandering. Therefore, concluding that "a human mind is a wandering mind, and a wandering mind is an unhappy mind" (Killingsworth and Gilbert, 2010, p. 923) seems to be overly generalized and simplified.

Furthermore, the participant's reports highlight that it might be a false conception to regard mind wandering and task focus as two mutually exclusive attentional states. Rather, a smooth transition from mind wandering to breath focus, during which self-generated thoughts start to arise but external stimuli are still processed, seems to be a more appropriate conception. A study by Hasenkamp et al. (2012) analyzed cognitive fluctuations between mind wandering and attentional states, derived from practicing focused attention mediation in fMRI. Hasenkamp et al. (2012) propose a model of dynamic cognitive states occurring during focused attention meditation according to which mind wandering and sustained attention are separated by a period of shifting attention following meta awareness. Hence, the cognitive model of natural dynamics between mind wandering and attention by Hasenkamp et al. (2012) supports the conception of one or more transition states between mind wandering and task focus. Regarding the neurophysiology, increased hemodynamic activity in the DMN was associated with mind wandering, whereas executive networks seemed to be active during shifting and sustained attention. Meta awareness correlated with greater activity in saliency networks, yet another functional brain network that might play a role in understanding the neurophysiological processes linked to mind wandering (Hasenkamp et al., 2012).

Smallwood and Schooler (2015) hypothesize that mind wandering might ultimately turn out to serve a functional role similar to sleeping, a particularly stimulating hypothesis if one takes into account the number of sleep analogies that were referred to by participants in the present study while describing how they experienced mind wandering episodes. A study combining neuroimaging and first person reports found parallels between mind wandering and dream states, both in terms of the phenomenology and in terms of activity in various brain networks (Fox et al., 2013).

Beyond the scope of Western science, the Buddhist tradition for example criticizes mind wandering, because mind wandering is a major obstacle to concentrative meditation practices and hinders individuals to live in the present (Braboszcz and Delorme, 2011). If one seeks to minimize the negative effects of mind wandering, for example in order to be more focused during studying, practicing meditation or other mindfulness practices can enhance meta awareness of mind wandering and can thus help to reduce its occurrences (Mrazek et al., 2013).

In conclusion, the study of mind wandering highlights the strengths of a holistic neurophenomenological approach in contrast to reductionist accounts of the human mind.

Neuroimaging studies have revealed brain networks that seem to be involved in perceptual decoupling, self-generation of task unrelated thoughts and executive control, and the interaction of those might be the neurophysiological underpinning of mind wandering, but only by taking into account the phenomenological experience of mind wandering as well, one can precisely elucidate the costs and benefits of mind wandering. Frequent mind wandering does not correlate with poor mental health *per se*, instead, the content and context of each mind wandering episode seem to determine whether mind wandering is beneficial or detrimental to mental health. Identifying neural markers may assist in classifying whether individuals are mind wandering or not in a particular situation, but neuroimaging cannot illuminate the thought content and thus cannot assess the effects of mind wandering on mental health without taking into account phenomenological experience as well.

5 Conclusion

The present work is the first of its kind to study a higher cognitive function like mind wandering using the *Traumschreiber*. Conducting EEG experiments with the *Traumschreiber* enables mobile experimental setups and thus allows to study higher cognitive functions in natural environments. The present study could not provide a proof of concept that the *Traumschreiber* is on a par with conventional EEG systems, though one has to acknowledge that the results obtained with a stationary 128-channel EEG system were compared to the data collected with an eight channel low-cost mobile EEG device. Nevertheless, the present study demonstrated that at least some of the results of Braboszcz and Delorme (2011) could be replicated using the *Traumschreiber*. Future versions of the *Traumschreiber* might be capable of narrowing the gap in terms of data quality in comparison to conventional EEG systems, although mobile EEG systems are facing a trade-off between mobility and affordability on the one hand and the number of channels and the signal quality on the other hand.

Furthermore, the present study showed that even individuals who are not trained in carefully observing their current conscious experience can provide insightful reports on the phenomenology of mind wandering. Phenomenological experience seems to be invaluable to understand mind wandering in all its facets. Exclusively illuminating neurophysiological processes associated with mind wandering does not suffice in order to obtain a differentiated account of the costs and benefits of mind wandering. Instead, a neurophenomenological approach that integrates both neuroscience as well as phenomenology assists in understanding how the content and context of mind wandering episodes influence the effects on mental health or task performance and when seeking to reduce mind wandering occurrences might be advisable, for example by means of mindfulness training. As Smallwood and Schooler (2015) conclude their review, "[t]he costs and benefits that arise from mind wandering can be understood as reflecting the ways in which we balance our desire for freedom from immediacy with the demands of attending to the moment" (Smallwood and Schooler, 2015, p. 510).

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Appendix A Auditory Evoked Potentials

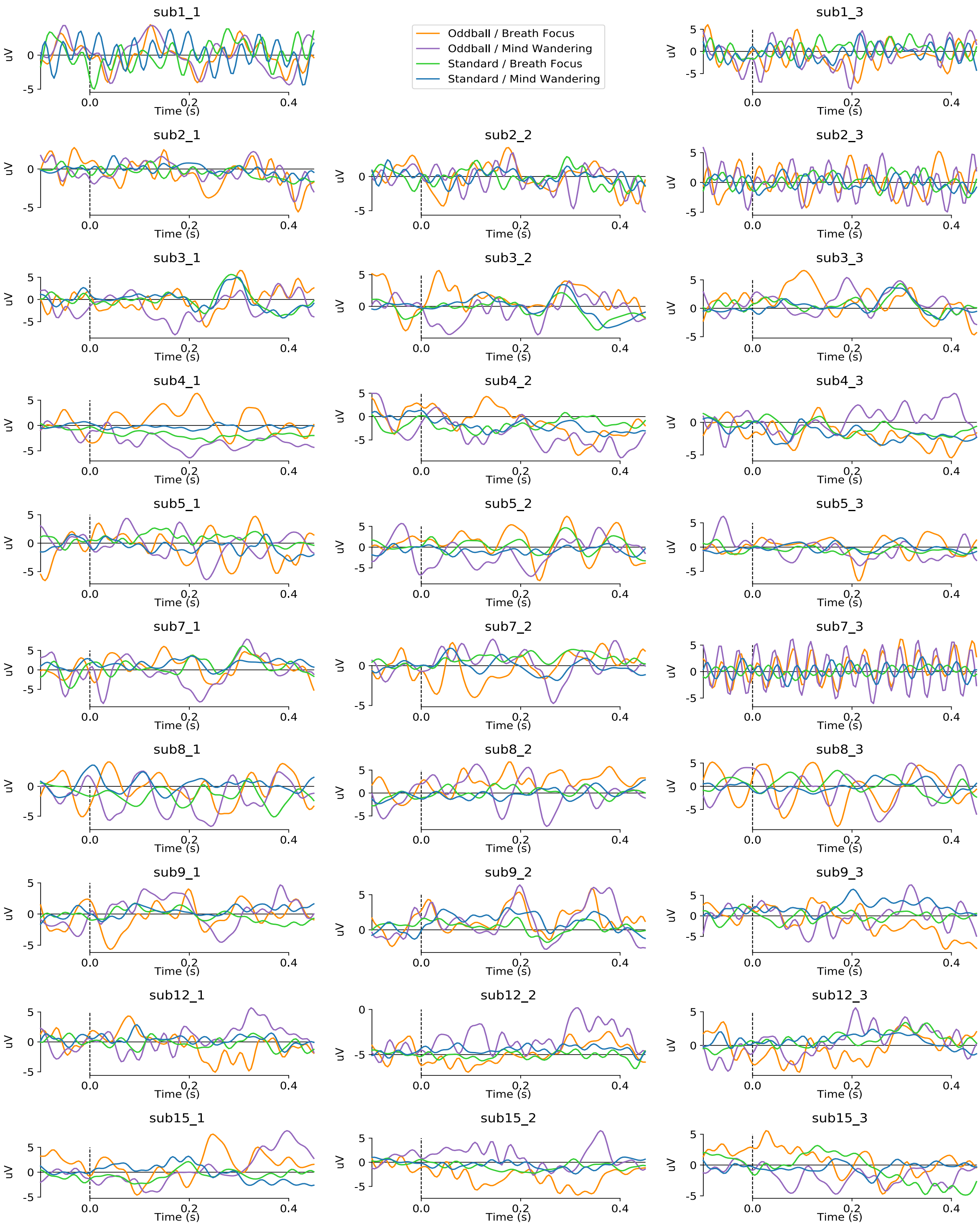

Figure 17: **Individual AEPs**. Each plot shows the averaged AEP at electrode Fz for one subject. The data of each experimental block is displayed separately (indicated by underscore *1*, *2*, or *3*). The second block of subject 1 is not shown because there were not enough clean epochs after filtering. Time 0.0s refers to stimulus onset.

Appendix B Mismatch Negativity

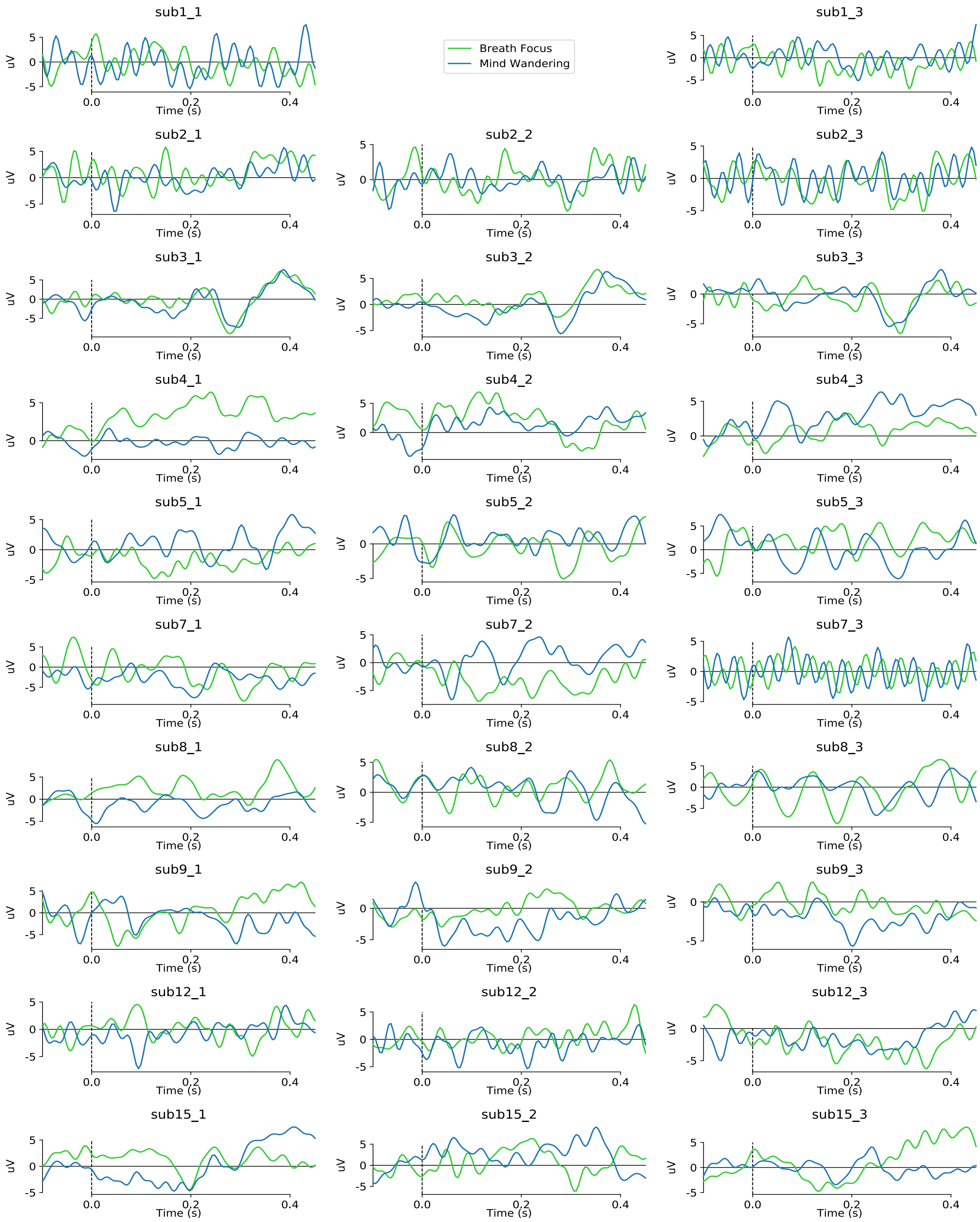

Figure 18: **Individual auditory Mismatch Negativity**. Each plot shows the averaged Mismatch Negativity at electrode Fz for one subject. The data of each experimental block is displayed separately (indicated by underscore *1*, *2*, or *3*). The second block of subject 1 is not shown because there were not enough clean epochs after filtering. Time 0.0s refers to stimulus onset.

Appendix C Statistics Power Differences

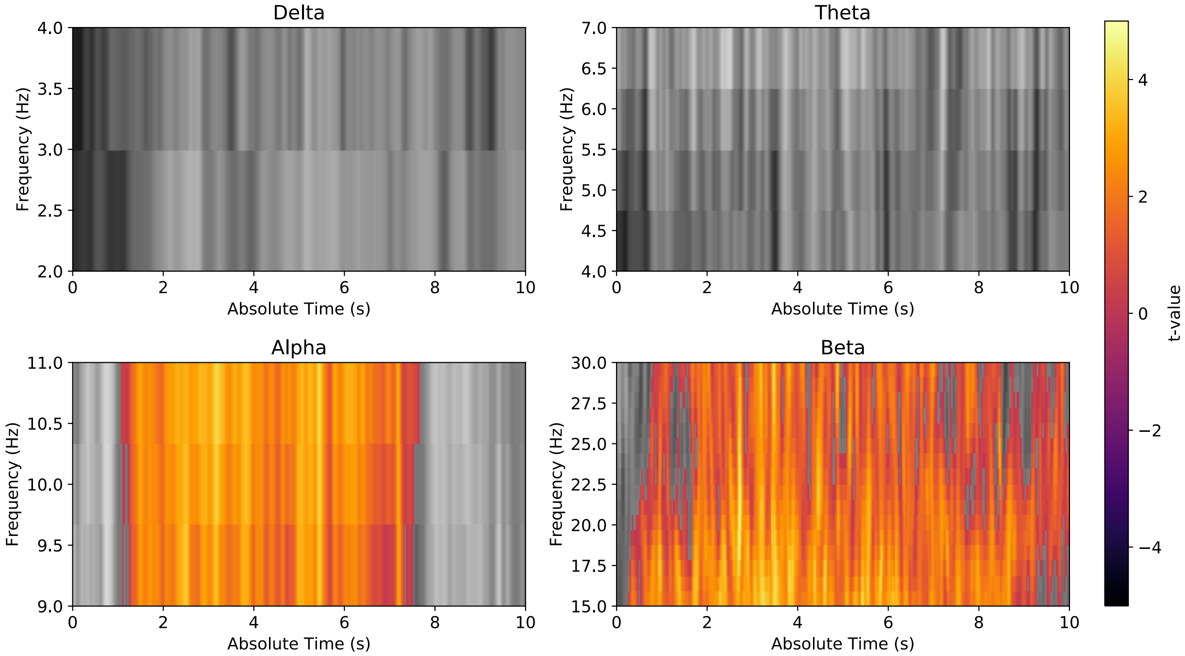

Figure 19: **Cluster level statistics of power differences**. T-values of power differences in time-frequency data are shown for the delta (2-4 Hz), theta (4-7 Hz), alpha (9-11 Hz) and beta (15-30 Hz) frequency bands. Power differences between mind wandering and breath focus conditions were computed by subtracting temporally symmetric data points. Absolute time refers to the time prior or post meta awareness. Significant clusters are color coded in the alpha and beta frequency bands ($p = 0.001$), non-significant clusters are grayed out.

Appendix D Consent Form

Participation in the study: Testing mobile EEG - Traumschreiber

I, ____________________ (name), born on ______________ (date), agree to participate in the study of the Institute of Cognitive Science at the University of Osnabrueck. My participation is voluntary and can be cancelled at any time, without having to state reasons or having to risk any negative consequences.

I am informed that my data will be stored anonymously without attribution for evaluation and archiving. All employees of the department are subject to secrecy. In addition, I agree that the data may be used in scientific contributions, e.g. at meetings, courses or publications. Your consent on storing and using the data can be revoked at any time, in this case your data will be deleted.

The following persons are going to work with the data:
Moritz Bammel and the Neuroinformatics group at the Institute of Cognitive Science, University of Osnabrueck.

I agree that during the experiment electrical signals on the scalp will be recorded with electroencephalography (EEG). I agree that the Traumschreiber will be used to obtain EEG recordings. The Traumschreiber was developed by Johannes Leugering and Kristoffer Appel in order to collect data during sleep. This study investigates whether the Traumschreiber can be used as a mobile EEG system to replicate a conventional EEG study.

I confirm that I am neurologically healthy.

I was informed about the content and the course of the study. All questions have been answered by the experimenter.

I have read and understood the information above and provide consent by signing this form.

You can revoke this consent at any time without stating reasons.

____

Date, signature

If you have any questions about the study, please contact:

Moritz Bammel
University of Osnabrueck, Institute of Cognitive Science
Wachsbleiche 27 (building 50)
49090 Osnabrück
Email: mbammel@uni-osnabbrueck.de

Appendix E Questionnaire

Questionnaire Mind Wandering

* Erforderlich

1. **Participant ID: ***

Thank you very much for participating in this experiment and for supporting my Bachelor thesis! The following questionnaire finalizes the experiment. Please take a couple of minutes to carefully read the information provided below and to answer the questions as precise as possible.

Rationale of the experiment:

You just participated in an experiment about mind wandering. Mind wandering denotes “a shift in the contents of thought away from an ongoing task and / or from events in the external environment to self-generated thoughts and feelings” (Smallwood 2015). ‘Self-generated’ refers to the characteristic that thoughts occurring during mind-wandering episodes are not directly derived from immediate perceptual input (Smallwood 2015). The breath counting task in this experiment is designed such that it is likely to loose track of your breath count and to start mind-wandering. As soon as you realized that you lost track of your breath count, you pressed a button on the tablet. In this experiment, your button press is interpreted as a self-reported indicator of 'meta-awareness'. 'Meta awareness' describes "the mental state that arises when attention is directed toward explicitly noting the current contents of consciousness, [in this case], realizing that [your] mind is wandering" (Smallwood & Schooler 2015). After realizing that your mind has wondered away from the breath counting task and the associated button press, you were instructed to re-focus on the breath counting task, until your mind starts to wonder away again.

2. **Did you experience mind wandering episodes during the experiment at all? ***
   Markieren Sie nur ein Oval.

   - Yes
   - No

3. **Did you press the button whenever 'meta-awareness' of mind wandering occurred? ***
   Markieren Sie nur ein Oval.

   - Yes
   - No

4. **If your answer to the previous questions is *No*, please elaborate when you did or did not press the button and in how far you followed the experiment's instructions.**

   ____
   ____
   ____
   ____
   ____

5. **Please estimate how many mind wandering episodes you experienced in the *first* block of the experiment. ***
   Markieren Sie nur ein Oval.

   - none
   - 0 - 5
   - 5 - 10
   - 10 - 15
   - 15 - 20
   - more than 20

6. **Please estimate how many mind wandering episodes you experienced in the *second* block of the experiment. ***
   Markieren Sie nur ein Oval.

   - none
   - 0 - 5
   - 5 - 10
   - 10 - 15
   - 15 - 20
   - more than 20

7. **Please estimate how many mind wandering episodes you experienced in the *third* block of the experiment.** *
   Markieren Sie nur ein Oval.

   - none
   - 0 - 5
   - 5 - 10
   - 10 - 15
   - 15 - 20
   - more than 20

8. **Did you fall asleep during the experiment?** *
   Markieren Sie nur ein Oval.

   - Yes
   - No

9. **Did you meditate during the experiment?** *
   Markieren Sie nur ein Oval.

   - Yes
   - No

10. **Did you consume any drugs, medication or other substances prior to the experiment that may have affected your concentration during the experiment?** *
    Markieren Sie nur ein Oval.

    - Yes
    - No

11. **If your answer to the previous question is *Yes*, please name the substance and describe in how far it affected your concentration during the experiment:**

12. **Please estimate how much of your daily wake time you spent mind wandering on average over the last couple of weeks. Try to accumulate all the mind wandering episodes of one day.** *
Markieren Sie nur ein Oval.

- I don't mind wander at all
- A couple of minutes per day
- About half an hour per day
- About an hour per day
- About two hours per day
- About three hours per day
- More than three hours per day
- Half of my wake time
- I'm mind wandering almost all the time I'm awake

Please indicate in how far you agree or disagree to the following statements:

13. **"I enjoy mind wandering."** *
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

14. **"I would like to mind wander less."** *
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

15. **"Mind wandering has a positive effect on my psychological wellbeing."** *
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

16. **"Mind wandering hinders me to live in the present."** *
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

17. **"Mind wandering helps me with future planning."**
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

18. **"I fell better if I spent less of my wake time mind wandering."**
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

19. **"Mind wandering is boosting my creativity."**
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

20. **"The way I experience mind wandering depends on the content and the context of my mind wondering episodes."**
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

21. **"Mind wandering is an important component of my conscious experience."** *
Markieren Sie nur ein Oval.

- I disagree
- I somewhat disagree
- I don't have an opinion on that
- I somewhat agree
- I agree

22. **Please describe how you experienced mind wandering episodes during the experiment. How did you feel during the mind wandering episodes and after you realized that your mind wandered? Was it pleasant or unpleasant? Please try to be as specific as you can and as detailed as you want to. If you like, you may also describe the content of your mind wandering episodes. If you don't feel comfortable providing this kind of information, it's perfectly fine to leave this field blank.**

Thank you so much for your time! Please click below to submit the questionnaire.

Declaration of Authorship

I hereby certify that the work presented here is, to the best of my knowledge and belief, original and the result of my own investigations, except as acknowledged, and has not been submitted, either in part or whole, for a degree at this or any other university.

Osnabrück, 09.04.2020