Investigating Mind-Wandering Episodes While Using Digital Technologies: An Experimental Approach Based on Mixed-Methods

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Abstract In today's fast-paced world, our brain spends almost half of our waking hours distracted from current environmental stimuli, often referred to as mind wandering in the scientific literature. At the same time, people frequently have several hours daily screen time, signifying the ubiquity of digital technologies. Here, we investigate mind wandering while using digital technologies. Measuring mind wandering (i.e., off-task thought), however, comes with challenges. In this research-in-progress paper, we present an experimental approach based on EEG, eye-tracking,

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questionnaires, and performance data to measure wind wandering. Our work draws upon the Unusual Uses Task, a widely used task to measure divergent thinking (as a proxy for mind wandering). We describe the experimental setup and discuss initial findings.

Keywords Mind-wandering · EEG · Eye-tracking · Unusual uses task · NeuroIS

1 Introduction

Mind-wandering episodes are described as a shift of attention away from a primary task and toward dynamic, unconstrained, spontaneous thoughts [1]. In times of constant use of digital technologies (hereafter: use of technology), it is almost impossible not to get distracted. Our thoughts frequently and automatically wander back and forth [2]. Killingsworth and Gilbert showed that our minds wander nearly half of our waking time (46.9%), with a tendency to wander to negative content and get stuck in rumination [3]. In contrast to initial research that stresses the negative effects, the more current literature refers to mind wandering as a positive feature and as something purposeful we all experience [4]. Specifically, mind wandering can promote problem-solving and creative skills [5, 6]. Such skills are highly relevant Information Systems (IS) phenomena because creativity is a crucial characteristic for knowledge workers [7].

So-called "Aha moments" let ideas appear true, satisfying, and valuable [8]. Although breakthrough ideas often seem to happen when inventors think about completely unrelated things, there is a paucity of research on technological tools to foster mind-wandering episodes and thus "Aha moments" [9]. Consequently, discovering and manipulating mind wandering while using technology is a critical endeavor. In particular, the development of neuroadaptive systems [10–15] that could induce mind wandering would constitute a breakthrough in research and innovation. Yet, to accomplish this goal, it is necessary to measure mind-wandering episodes in a valid manner.

So far, mind-wandering episodes are mainly studied with experience samples and questionnaires [16]. Given the potential shortcomings of self-reports (e.g., social desirability), we pursue a triangulation approach to achieve more valid measurement. Validity refers to "the extent to which a measurement instrument measures the construct [mind wandering] that it purports to measure" [17, p. 14]. In this context, triangulation is used to increase the robustness and validity of our research findings. The goal is to measure mind-wandering episodes while using technology more accurately compared to the extant literature.

The measurements involved include electroencephalography (EEG), eye-tracking, questionnaires, and creative performance. First, EEG is an established brain imaging tool that non-invasively assesses mind-wandering episodes without interfering with a task [18]. It allows temporal inferences at the millisecond level. Second, eye-tracking acts as a reliable time-critical indicator of visual attention by detecting changes in eye behavior [19]. Three visual mechanisms were observed in the present study: visual uncoupling, perceptual uncoupling, and internal coupling. Third, we present questionnaires to investigate spontaneous as well as deliberate mind-wandering episodes while solving a task [20]. Fourth, creative performance is operationalized based on the number of new and useful answers to a divergent thinking task.

The present work is adapted to a technology-related environment because all steps can only be carried out using a computer and involve a specific reference to technological hardware. The experiment is based on the Unusual Uses Task (UUT) [21, 22] and the work by Baird et al. [23]. The UUT measures divergent thinking. The participants are asked to generate as many unusual uses for everyday life objects as possible, for example, newspapers or headsets. The number and originality of the responses are taken as an index of creative thinking. All in all, the combination of brain data, eye-tracking data, self-reports, and behavioral data promises to shed light on mind-wandering episodes while using technology in an innovative way. Our overall expectation is that if we can design technologies that allow users to let their mind wander, we can increase the likelihood of "Aha moments" and overall creativity.

2 Theoretical Background

2.1 Detecting Mind Wandering with EEG

EEG is a widely used tool for the non-invasive measurement of bioelectrical brain ac-activity, in many areas, from basic sciences to diagnosis and treatment [24]. Here, we use EEG for the detection of mind-wandering episodes [18, 25]. The method enables recording of cognitive processes underlying perception, memory, and attention, among others, by measuring electrical signals generated by the brain (e.g., ideas) on the scalp. The most significant advantage of EEG is its temporal resolution, allowing for detection of complex patterns of neural activity which are a consequence of stimulus perception on a millisecond level [24]. For a detailed comparison of EEG with two other major brain imaging tools (fMRI, fNIRS), please see Table 1 in [26].

Regarding EEG, the first indicator we use is the event-related potential (ERP), which is "a waveform complex resulting from an external stimulus or an event." [24, p. 932]. A participant is repeatedly exposed to a defined number of stimuli (i.e., visual information on a screen), which allows for the measurement of such an evoked potential (EP). This includes amplitudes, positive or negative polarity (P and N), millisecond latency, and scalp distribution. The P-N appears to be attenuated during mind-wandering episodes due to perceptual decoupling [27–29].

The second indicator is to detect oscillatory EEG components varying in different frequency bands. According to Müller-Putz et al. [24, p. 918], these are defined as alpha (8–13 Hz), beta (13–25 Hz), gamma (25–200 Hz), delta (1–4 Hz) and theta (4–8 Hz) bands (note that slight deviations from these bands can be observed in the scientific literature, hence the bands are rough specifications). Studies that examined mind wandering concluded that considering alpha waves is crucial [30]. Alpha waves are primarily found during relaxation [24] and low stimulation [31]. They tend to increase during mental imagery [32] and before solving a creative problem with insight [33]. In addition, higher internal processing demands were found to increase EEG alpha activity in posterior brain regions and the parietal/occipital alpha power could be a neural correlate of mind wandering [34–36].

2.2 Detecting Mind Wandering with Eye-Tracking

Eye-tracking can be used to detect a possible daydream and to draw conclusions about the onset of relevant time points in the EEG signal. Eye-tracking is a consumer-friendly tool for detecting mind-wandering episodes. It can be considered a "time-critical [indicator] of internal attentional demands" that captures eye behavior [19, p. 1]. Mind wandering can increase blink rates and may come along with longer blink durations [37, 38]. Similarly, the number of saccades decreases, indicating less rapid, simultaneous, and voluntary eye movements. In addition, saccade amplitude increases [19] and pupil diameter (PD) increases [39]. In this context, gaze aversion is reduced during cognitive load (i.e., demanding activities) by decreasing the processing of distracting external stimuli to shield internal processes [40, 41]. During mind-wandering episodes, pupillary activity tends to be less guided and more spontaneous [42]. Eye-closing measures are shown to promote performance in creativity tasks [10].

3 Research Design

Experimental design. The participants' brain activity and eye movements were measured while sitting in front of a computer working on a creative task. In addition, a short questionnaire was presented. The experiment took place in the EEG laboratory at Graz University of Technology, which guaranteed freedom from interference. The procedure is non-invasive, painless, and injury-free. The local ethics committee at Medical University Graz approved the study.

Following Baird et al. [23], the experiment was conducted with three groups (rest, demanding task, undemanding task) [22]. The instruction for all participants was to list as many unusual uses as possible for each stimulus (i.e., four objects, for details see next paragraph) and to solve UUT problems. Before the experiment, participants were equipped with EEG (BrainProducts GmbH, Germany) and an eye-tracking device (Pupil Labs, Germany). An ultra-sound sensor system (Zebris) was used to record the thirty-two electrode positions on the participants' head to allow and facilitate later analyses. The impedance of the electrodes was set at 15 k Ohm. The pupil headset was calibrated with a baseline before onset. The participants were instructed to limit movement. Instructions for the measurement procedure were given once participants were seated.

After EEG and eye-tracking montage the experiment started, and the participants solved four UUT tasks (two minutes each). Two images showed non-technological artifacts (bricks, newspaper), and two images showed technological artifacts (headset, computer mouse). The participants verbally expressed their responses, which were then recorded by sound and video. This method reduced motor distortions in the EEG to a minimum.

After completing the UUT problems, participants were randomly assigned to one of three groups (rest, demanding task, undemanding task) following a between-subjects design. Participants in the demanding-task condition performed a 3-back task, while those in the undemanding-task condition performed a 1-back task [11]. In the 1 or 3-back task, participants had to remember whether a given number was the same as 1 or 3 numbers before and confirm or deny this by pressing the left or right key on a keyboard. In the rest condition, participants were asked to sit quietly and look at a grey screen. The intervention lasted twelve minutes. After that, all participants answered a short questionnaire about spontaneous mind wandering during the UUTs [19]. Next, the participants completed the same four UUTs as before (two minutes each). After that, they were released from the EEG and eye-tracking tools. They were asked to complete a longer questionnaire about spontaneous and deliberate mind-wandering episodes in their everyday life. Finally, they were thanked and debriefed.

In sum, the participants' cognitive processes while using technology were recorded using an EEG and eye-tracking device. The high temporal resolution of the tools (millisecond level) made it possible to determine thought patterns and highlighted the typical course of thought. Self-reports on perceived mind wandering were also collected. Creative performance was analyzed by two independent raters.

Participants. In this study, a total of 45 healthy volunteers aged between 21 to 47 years (average 29.2 years) took part (24 females, 21 males). All participants gave written consent, were informed by the experimenters regarding the aim of the study, its content, and how the investigation will be conducted. The participants could terminate or discontinue their participation at any time without giving any reason and without any consequences. The recorded data of each participant was anonymized.

Data analysis. A major indicator for possible mind-wandering episodes is the gaze, more specifically, gaze fixations. Thus, the first task was to find a suiting value for the minimum time a fixation lasts. We analyzed the eye-tracking data with a fixation detection algorithm and placed our minimum fixation time at one second. This was done, on the one hand, to find a value that was small enough to show possible mind-wandering episodes and, on the other hand, to limit the number of epochs to be analyzed later. The logic is as follows: If a person engages in mind wandering, it is highly unlikely that this person—at the same time—moves gaze from one to another point on the screen. To clean the EEG data, we used an independent component analysis (ICA). Independent components like eye movements or muscle artifacts were rejected based on visual inspection. Thereafter, the data was bandpass filtered from 0.5 to 40 Hz. The fixation timings delivered from the eye-tracker were then used

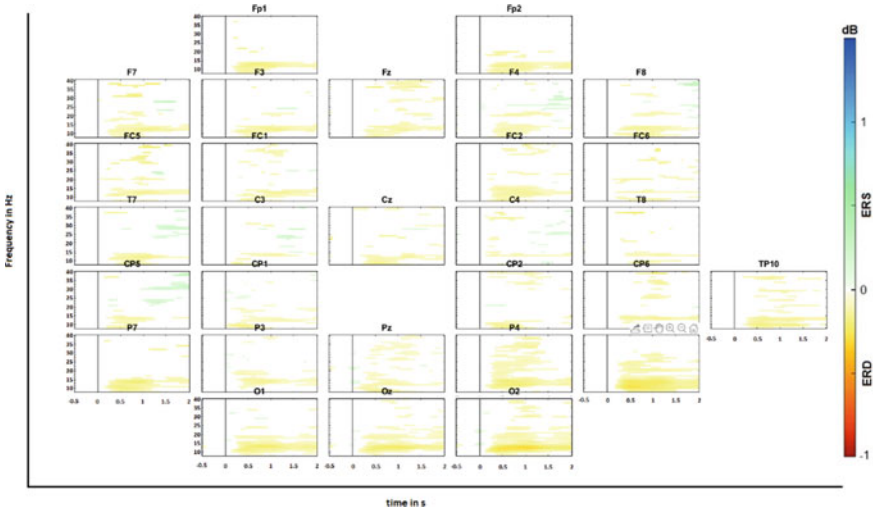

Fig. 1 Grand average ERD/ERS topographical map of 45 participants during mind-wandering episodes during the first block of UUTs (total of 3336 trials). x-axes: shows the time: [−0.5, 0.05, 2]s with the reference period from [−0.5, 0]s. y-axes show the frequency [8, 40]Hz in overlapping 2-Hz bands. Scale −100 to +150. Bootstrap significance test ($\alpha = 0.05$)

to calculate and plot an event-related desynchronization/synchronization (ERD/S) map in overlapping 2 Hz bands. EEG epochs around the gaze fixation time points [−0.5, 2]s during the four UUTs of all 45 participants were used. As a reference interval, we defined [−0.5, 0]s. A bootstrapping method was then used to test for significant ERD/ERS (0.05) values.

Preliminary results. Preliminary findings can already be drawn from the ERD analysis of the whole group during mind-wandering episodes detected through gaze fixation during the initial four UUT problems. Figure 1 shows only significant changes (alpha = 5%) in band power compared to the reference. Generally, an alpha band ERD can be observed on almost all channels, which is more pronounced in the occipital region (O1, Oz, O2). This ERD starts immediately as eye gaze is fixated (second 0) and could be an indication of visual processing during mind wandering. The next steps are ERD analyses group specific for the second block of UUTs after the intervention of rest, 1-back and 3-back tests. In later studies, the data will be analyzed separately, with particular attention to alpha power and the parietal/occipital regions.

4 Future Work

For in-depth statistical analysis, we will use correlation, regression analysis, analysis of variance, and multivariate analysis. This far, our experimental approach demonstrated how and whether neurophysiological data (brain, eye-tracking) can be used to detect mind wandering while using technology. In the future, we seek a triangulation of the data. This analysis will be based on EEG, eye-tracking, questionnaires, and creative performance. Specifically, we will compare group-wise differences using perceived measures with more objective neurophysiological measures.

Our work contributes to the current literature by identifying and measuring a crucial cognitive process while using technology that can foster creativity, namely mind wandering. This can pave the way for designing innovative neuroadaptive systems [12–15, 43, 44]. Our study presents a first step towards automatic observation and interpretation of mind-wandering episodes while using digital technology, which could help to design human–computer interaction tasks and human-centered technological artifacts in the future. We strongly believe that neuroadaptive systems offer significant theoretical and practical potential and that this study contributes to related NeuroIS research.

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