

Behavioural and Physiological Correlates of Sustained Attention and Its Improvement via Transcranial Random Noise Stimulation



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Malin
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Authorship Declaration

I, Malin Inga Karstens, declare that this thesis is entirely my own work and that I am the sole author of all materials presented herein, except where explicitly acknowledged. The work was supervised by Prof. Cohen Kadosh (University of Surrey, UK), Prof. Husain (University of Oxford, UK), and Dr. Nir Shalev (University of Oxford and University of Haifa, Israel).

The continuous monitoring task used in Chapter 2 was originally designed by O’Connell et al. (2012) and replicated as published in Harty & Cohen Kadosh (2019). The airplane control task (ACT) used in Chapters 3 to 5 was initially designed by Nelson et al. (2014) and adapted by me, incorporating valuable feedback from the supervisory team and Dr. Sanjay Manohar.

Data from our lab, previously published in Harty & Cohen Kadosh (2019) was used for further analysis in Chapter 2. All credit for the experimental design and data collection goes to the authors. I implemented the experiments and collected data for Chapters 3-5. For Chapter 3, I received assistance from undergraduate students Holly Haines and Natasha Harper, who contributed to programming parts of the online version of the ACT. For Chapter 4, I was supported during part of the in-person study sessions by undergraduate students Sean Miles and Joshua Polychronopoulos.

All data analyses and writing were undertaken solely by me.

Abstract

Maintaining focus on one task over long periods is known as sustained attention, which supports higher order cognition such as learning. Suboptimal sustained attention is characterised by poor task performance, response variability, and task disengagement. Cortical and subcortical mechanisms of arousal and cognitive control modulate moment-to-moment changes in sustained attention. This thesis investigates the relationships between baseline markers of sustained attention, including behaviour, pupil dynamics, and cortical markers, during low and high demand. Furthermore, I test their utility in the context of transcranial random noise stimulation (tRNS) as a way to predict sustained attention benefits in young adults. My first results from a secondary analysis using a continuous sustained attention task with tRNS, indicated that high baseline response variability was the better predictor of performance gains from tRNS, compared to sham tRNS. Next, in a series of online and lab-based experiments, I investigated changes in performance and thought experiences. Using an airplane monitoring paradigm with and without distractors, I also examined pupillary correlates of task conditions and performance. The results indicated that distractors impacted accuracy negatively but facilitated stable responses. Pupil dilation was observed during increased task load, decreased performance, and greater perceived task-focus compared to mind-wandering (MW) in line with predictions of increased arousal. Finally, a tRNS, electroencephalography, and eye-tracking experiment suggested an overall benefit of tRNS on sustained attention during a monotonous task. In addition, participants with low baseline accuracy were predicted to benefit the most, independent of task demands. Pupil size indicated arousal-related differences between MW and task-focus, as well as between response variability during low and high task demand. This work contributes insights into the relationship between sustained attention, MW, arousal, and performance improvements during tRNS. Moreover, it uses this knowledge to highlight the importance of behavioural markers to predict the attentional benefits from tRNS.

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General Introduction

1.1 Thesis Statement

The ability to maintain attention on a chosen stimulus or task is called sustained attention (Ballard, 1996; Esterman & Rothlein, 2019) and is relevant in context of learning and education (K. Godwin & Fisher, 2014; Steinmayr et al., 2010), reading comprehension (Macdonald et al., 2021), memory (deBettencourt et al., 2018), driving performance (Mackenzie & Harris, 2017), and the safety in operator environments (Rees et al., 2017). On a path to improving sustained attention, I am attempting to address several questions that can answer whether brain stimulation, specifically transcranial random noise stimulation (tRNS), is a useful intervention tool and which mechanisms of sustained attention can moderate its efficacy.

1.2 Introduction to Sustained Attention and Vigilance

Sustained attention is defined as the cognitive process by which task focus is maintained over long periods of time (Ballard, 1996; Esterman & Rothlein, 2019; Langner & Eickhoff, 2013; Parasuraman et al., 1989). Thus, task performance is kept accurate and constant, and distractions and thoughts unrelated to the task

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are avoided (Esterman & Rothlein, 2019). Sustained attention is a key mechanism required for higher order cognition such as memory and learning (deBettencourt et al., 2018; K. Godwin & Fisher, 2014; Macdonald et al., 2021; Steinmayr et al., 2010). Vigilance is often used as a synonym for sustained attention and describes the ability to maintain alertness to the environment in general, not bound to a specific task or stimulus (J. F. Mackworth, 1964; N. H. Mackworth, 1948; Schie et al., 2021). Therefore, vigilance is the underlying process that is required when sustained attention is paid to a specific task. It allows to monitor the environment to which attention is directed at the time, and to observe any changes that are relevant to the task goal.

Sustained attention processes are disrupted, for example, in patients with Attention Deficit Hyperactivity Disorder (ADHD). Individuals diagnosed with this neurodevelopmental disorder exhibit symptoms of inattention, hyperactivity, and impulsivity during childhood, which can persist into adulthood (Kessler et al., 2005). The experienced disruptions in maintaining focus present in ADHD are one reason why a great part of the sustained attention literature focuses on performance difficulties and symptomology of ADHD (Johnson et al., 2007; Kessler et al., 2005; Shen et al., 2011).

Early on, Mackworth’s work on vigilance decrement was influential in understanding how humans sustain attention over time. He developed the Mackworth clock test to assess rapid infrequent target detection and was specifically interested in the deterioration of performance over time which was coined the vigilance decrement (J. F. Mackworth, 1964). This decrement was believed to originate from a failure to suppress neural noise due to the reduction of arousal over time (J. F. Mackworth, 1964). Molloy and Parasuraman first studied the vigilance decrement in tasks with different complexity which suggested that vigilance performance deteriorated in simple and multicomplex tasks more than in a single complex task (Molloy & Parasuraman, 1996).

1.3 Sustained Attention Assessments

A range of assessments have shaped the sustained attention literature (Broadbent, 1953; Hasenkamp et al., 2012; Raposo et al., 2023; e.g. Strayer et al., 2023). One of the earliest and most prominent tasks is the Continuous Performance Test (CPT), which requires the participant to respond to targets within a continuous series of simple stimuli, such as single numbers or letters (Rosvold et al., 1956). The CPT was introduced as an assessment of brain injuries in schizophrenia patients and was later adopted for the research of sustained attention (Nuechterlein et al., 1983; Nuechterlein & Dawson, 1984; Rosvold et al., 1956). Different versions have been developed, for example extending the test to assess different modalities (Borgaro et al., 2003; L. Shalev et al., 2011), and to reduce abrupt, stimulus-driven interference by gradually transitioning between images (Esterman et al., 2013; O’Connell et al., 2012). Versions of the latter, also known as gradual CPT (gradCPT) or continuous monitoring task (CMT), are used extensively and have uncovered novel findings about the neural and cognitive correlates of sustained attention (Fortenbaugh et al., 2018; Harty & Cohen Kadosh, 2019; Kondo et al., 2023; Yamashita et al., 2021).

Another frequently used task is the Sustained Attention to Response Task (SART), a Go/No-Go paradigm introduced to assess sustained attention deficits in traumatic brain injury (I. H. Robertson et al., 1997). The original SART is characterised by a stream of digits followed by a mask. Participants are required to respond to all stimuli via rapid button press, except for infrequent targets, when they should withhold their response instead (I. H. Robertson et al., 1997). Performance on the SART is inherently more demanding than on the CPT, and task demands within the SART can additionally be manipulated via the target frequency (Wilson et al., 2016). One advantage over the CPT is the number of available responses, which can be assessed on nuanced changes in speed and accuracy (Manly et al., 1999). However, compared to the CPT, the SART is more susceptible to response inhibition demands and impulsivity (Helton et al., 2008). Accuracy and response times in the SART relate to everyday life cognitive

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failures, attentional failures, symptoms and performance differences associated with ADHD, and with genetic differences associated with sustained attention (Greene et al., 2009; Johnson et al., 2007; Machida et al., 2019; I. H. Robertson et al., 1997; Schepers et al., 2023; Smilek et al., 2010). The SART also showed susceptibility to arousal-related changes during neurofeedback (O’Connell et al., 2008).

Both tasks, the CPT and SART have advantages and relate to sustained attention lapses and decrements in slightly different ways. While gradual, simple tasks are more directed to assess vigilant attention in monotonous environments and performance fluctuations, SART performance reflects sustained attention in more demanding environments and can be manipulated to measure different levels of complexity.

Other behavioural assessments of sustained attention often include self-reported everyday-life experience associated with inattention, other behavioural failures, or symptoms associated with ADHD (Broadbent et al., 1982; Kessler et al., 2005). For example, the cognitive failures questionnaire (CFQ) contains questions on perception, memory, and motor function targeting states of absentmindedness, action failures, and memory deficits (Broadbent et al., 1982). The CFQ has shown to be reliably associated with SART performance in neurotypical and in patient groups (Bridger et al., 2013; Schepers et al., 2023; Smilek et al., 2010). The Adult ADHD Self-Report Scale (ASRS) is more focused on difficulties related to inattention and hyperactivity and has been shown to predict SART task performance, mind-wandering (MW; Gau et al. (2022); Helton et al. (2011)).

1.4 Failures in Sustained Attention and MW

Early sustained attention assessments were centred around the decline in performance over time, measured via linear decreases in accuracy and/or linear increases in response times during repetitive and simple tasks (Langner & Eickhoff, 2013; J. F. Mackworth, 1964). In Luna et al. (2018), the authors disentangled the attention decrement. The authors showed that performing a simple repetitive

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vigilance task resulted in a decrement based on longer and more variable response times, whereas an executive vigilance decrement (requiring to detect infrequent targets), was due to a shift in response bias, meaning that mistakes were more likely avoided at the expense of the overall hit rate. This might suggest that performance measures based on accuracy represent those attention failures related to executive task demands, whereas response fluctuations might represent changes arising from monotony. Indeed, many studies quantify sustained attention performance either based on correct responses, mistakes (omission or commission errors), the sensitivity of detecting a target among noise, or based on response times and response variability without an explicit focus on the performance decrement (Bedi et al., 2023; Egeland et al., 2023; Fortenbaugh et al., 2018; Gallen et al., 2023; Harty & Cohen Kadosh, 2019; N. Shalev et al., 2018; Strayer et al., 2023). In line with O’Connell et al. (2008) lapses of attention, measured via errors were suggested to reflect failures of cognitive control, whereas variability of response times might be indicative of arousal changes over time. The Yerkes-Dodson Law describes performance as an inverted-U relationship (Teigen, 1994; Yerkes & Dodson, 1908), where optimal stimulation leads to best performance, but too little or too much arousal deteriorates performance (Esterman & Rothlein, 2019; Pinggal et al., 2022), see Fig. 1.1.

Next to measures of task performance, failures in sustained attention might result in task disengagement and an increase of spontaneous task-unrelated thoughts, also known as MW. The research has been heavily influenced by studies that investigated the phenomenon of daydreaming since the 50’s (McMillan et al., 2013). Daydreaming refers to the generation of internal thought and encompasses not only the inability to focus on a task, but also positive and creative imagery, as well as negative obsessive thoughts, and rumination. The disengagement from external input is also referred to as perceptual decoupling which is often observed during sustained attention task, yet has been found to be a separate process to the one underlying attention performance (Jin et al., 2020; Unsworth & McMillan, 2014). However, MW usually co-varies with sustained attention performance and is subject

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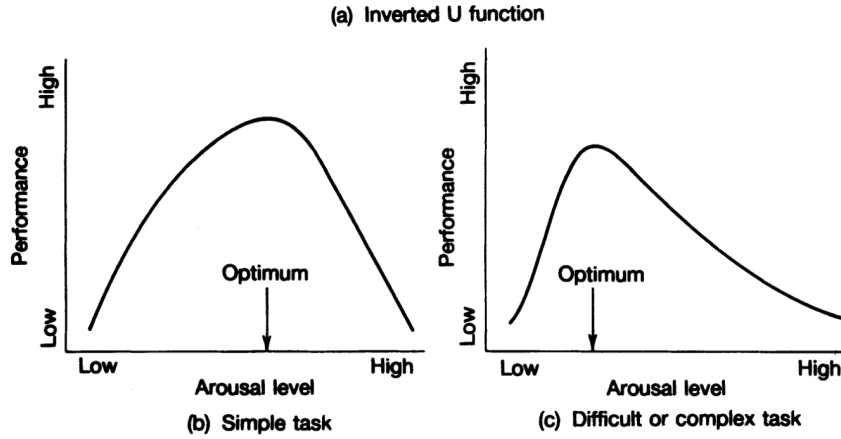


Figure 1.1: Arousal and Performance. Association between arousal and attention performance follows an inverted U-function for simple and complex tasks. Optimal performance in simple and difficult tasks is achieved at moderate levels of arousal. Greater arousal is required to maintain good performance in simple tasks than in harder tasks. Figure reprinted with permission from Teigen, 1994.

to attentional control (C. A. Godwin et al., 2023; Kane et al., 2021; Seli, Cheyne, et al., 2015; Smallwood & Schooler, 2015). Moreover, the relationship between increased task demands and MW is still unclear, with some studies showing that task demand affected the amount of reported MW and other findings did not find evidence for this (Martínez-Pérez et al., 2021; Martínez-Pérez et al., 2023). Theoretically, the interplay between sustained attention and MW over time has been explained by arousal modulating how attention is allocated towards task-related and task-unrelated processes, influenced by motivation and the cost of controlling attention (Esterman & Rothlein, 2019; Thomson et al., 2015).

MW is mostly assessed via experience sampling, for example via thought probes interrupting the task, self-caught MW, and retrospective reports (Kane et al., 2021; Smallwood & Schooler, 2015). While for some studies, MW was distinguished merely based on off-task or on-task thought reports (Baird et al., 2011; Schooler et al., 2011), the importance of distinguishing between different off-task states including MW, internal, and external distractions has been highlighted (Stawarczyk et al., 2011; Unsworth & McMillan, 2014). Similarly, although both induce performance decrements, one importance for MW assessments is the distinction between deliberate and spontaneous MW, where only the latter was related to

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ADHD symptoms (Martínez-Pérez et al., 2021; Seli, Cheyne, et al., 2015; Seli, Smallwood, et al., 2015).

1.5 Neural Activity and Circuitry Underlying Sustained Attention

Brain activity and circuitry associated with sustained attention is concentrated around two mechanisms, bottom-up arousal and top-down cognitive control (Esterman & Rothlein, 2019). Cognitive arousal is modulated by bottom-up processes from the locus coeruleus (LC) which releases norepinephrine (NE), a neurotransmitter relevant to inhibitory and excitatory processes related to the sleep-wake cycle and environmental responsiveness. Moreover, tonic and phasic LC-NE activity has been associated with information processing and target detection (Aston-Jones & Cohen, 2005). Phasic impulses occur selectively following salient, relevant stimuli, and moderate levels of tonic baseline firing are connected with focused attention (Aston-Jones et al., 1999; Aston-Jones & Cohen, 2005). Suboptimal tonic firing is associated with poor performance and task disengagement: lower than optimal tonic firing facilitates inattentiveness and low alertness, while higher levels of tonic LC activity promote behavioural flexibility (Aston-Jones et al., 1999; Aston-Jones & Cohen, 2005).

Projections from the LC innervate frontal and parietal cortices (Alnæs et al., 2014; Aston-Jones & Cohen, 2005; Chandler et al., 2014; Coull, 1998; Melnychuk et al., 2021; Pinggal et al., 2022; Raz & Buhle, 2006). Right fronto-parietal cortices, stimulated by tonic and phasic arousal input, are implied as a top-down component of cognitive control which are involved in maintaining task performance, task switching, and distractor suppression by increasing the signal-to-noise ratio (Cosman et al., 2018; Coull, 1998; Fiebelkorn & Kastner, 2020; Petersen & Posner, 2012; Singh-Curry & Husain, 2009; Sturm & Willmes, 2001; Unsworth & Robison, 2017). For example, sustained attention performance in different modalities has been associated with the right prefrontal cortex (PFC), inferior parietal lobule (IPL),

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and the supplementary motor area (Coull, 1998; Kondo et al., 2023; O’Connell et al., 2008; Raz & Buhle, 2006; Singh-Curry & Husain, 2009).

Task positive areas, such as described here, are active when attention needs to be sustained, and have been shown to anti-correlate with the default-mode network (DMN) activity. High DMN activity is characteristic for states of MW and predicts subsequent lapses of attention, but is also related to stable responses (Esterman et al., 2013; Kucyi et al., 2016). This interplay has been hypothesised to be due to low task demand when MW was captured (Fortenbaugh et al., 2018). MW has also been associated with semantic areas involved in the thought-generating process, while task performance relies more on regions dealing with increased task demand (Jin et al., 2020).

1.6 Physiological Markers of Sustained Attention

In line with the arousal and attentional control component of sustained attention, physiological changes are measured via electroencephalography (EEG) or pupillometry (Oken et al., 2006). The link between LC NE function and pupil dynamics, especially pupil diameter, is well-established (Hou et al., 2005; Joshi et al., 2016). In attention paradigms, pupil dilation has been observed to increase together with increasing visual load in parallel to increases LC activity and parietal areas related to object tracking (Alnæs et al., 2014; Ma et al., 2024). Pupil size was also a predictor of performance and decreased with MW (Grandchamp et al., 2014; Unsworth & Robison, 2016, 2018). In adults with ADHD compared to controls, pupil size indicated lower phasic levels of arousal during a continuous task, but greater pupil size indicated higher tonic arousal during a passive viewing task (Shirama et al., 2020). Similar to pupil size, blink rate also predicted cognitive load (Magliacano et al., 2020). Moreover, deliberate MW resulted in longer and fewer blinks (Benedek et al., 2017; Walcher et al., 2017), longer blinks also occur during MW when reading (Huettenlocher et al., 2016). It is believed that pupil dynamics

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manipulate sensory information in moments of disengagement (Smilek et al., 2010; Unsworth & Robison, 2018).

The literature on children with ADHD brought forward an EEG marker for ADHD symptoms that could be used for diagnostic purposes (Monastra et al., 1999; Saad et al., 2018). The theta/beta ratio (TBR) refers to the ratio between periodic power in slower (theta, ~4-7.5 Hz) and in faster (beta, ~14-30 Hz) frequencies and has since been adopted in non-clinical studies (Angelidis et al., 2016; Clarke et al., 2019; Saad et al., 2018). Associated with underlying arousal-related cortical changes, TBR has been proposed to represent cognitive control and processing capacity, and was associated with sustained attention performance and MW (Harty & Cohen Kadosh, 2019; Melnychuk et al., 2021; Van Son et al., 2019). It has been suggested that synchronised respiratory phases, are coupled with pupillary arousal changes from the LC-NE system and with TBR amplitude, supporting rhythmic top-down attention function (Clayton et al., 2015; Helfrich et al., 2018; Lenartowicz et al., 2013; Melnychuk et al., 2021; Raposo et al., 2023; Van Son et al., 2019).

Although approved by the FDA, TBR has received criticism. For example, for the misguided use of fixed-band measures, especially in clinical samples (Saad et al., 2018). However, another problem with the TBR estimation has been brought forward in more recent studies. The frequency spectrum is characterised by a downward slope, and TBR is usually calculated from the total power in the theta and beta spectrum, hence why the ratio can be confounded by the overall slope of the power spectrum (Donoghue et al., 2020; Finley et al., 2022). It is, however, possible to extract this slope, which has been coined as the aperiodic exponent (AE), or 1/f activity (Donoghue et al., 2020). After extracting the overall slope, the TBR can be fitted on the periodic activity in theta and beta bands (e.g. Del Bianco et al., 2024).

Comparisons of the traditional TBR measure with the AE confirm their overlap and indicate that the AE can be more sensitive for investigating performance and symptom differences between individuals with ADHD and controls than TBR (Dakwar-Kawar et al., 2024; M. M. Robertson et al., 2019). The results show that

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aperiodic slopes are steeper in ADHD groups, and significantly distinguish between the groups when TBR did not (Dakwar-Kawar et al., 2024; M. M. Robertson et al., 2019). Evidence shows that TBR measures decrease with age. Similarly a flattening of the slope has been observed with age, which is in line with ADHD symptoms reducing during adulthood (Finley et al., 2022; Karalunas et al., 2022). The relation between the aperiodic activity and ADHD symptomology can be explained by differences in information processing associated with altered GABAergic and glutamatergic regulation, which underlies the excitation/inhibition (E/I) balance in the cortex (Euler et al., 2024; Ostlund et al., 2021; Van Bueren et al., 2023; Waschke et al., 2021). Moreover, the AE was also predictive of attention performance in a non-clinical sample and cognitive control performance in Go and No-Go tasks (Pi et al., 2024; Waschke et al., 2021), which makes it a promising marker for sustained attention.

1.7 Improving Sustained Attention

The most common treatment for attention difficulties present in ADHD targets the availability of neurotransmitters via psychostimulants, such as methylphenidate, but this can come with adverse effects and risks (Mechler et al., 2022; Peterson et al., 2024). Non-invasive transcranial electrical brain stimulation (tES) such as transcranial direct current (DC) or alternating current (AC) stimulation has been a popular alternative to improving sustained attention showing mixed results on task performance and ADHD symptoms (Clayton et al., 2019; Friehs et al., 2021; Martínez-Pérez et al., 2023; Nawani et al., 2023; Nelson et al., 2014; Wards et al., 2023; Westwood et al., 2023). Compared with magnetic stimulation, the stimulation current is weak and does not generate action potentials, yet has been shown to generate small changes in membrane potentials (Antal & Herrmann, 2016; Van Der Groen et al., 2022).

A more recent form of tES is transcranial random noise stimulation (tRNS) which has demonstrated its benefit for attention improvements. Sustained attention

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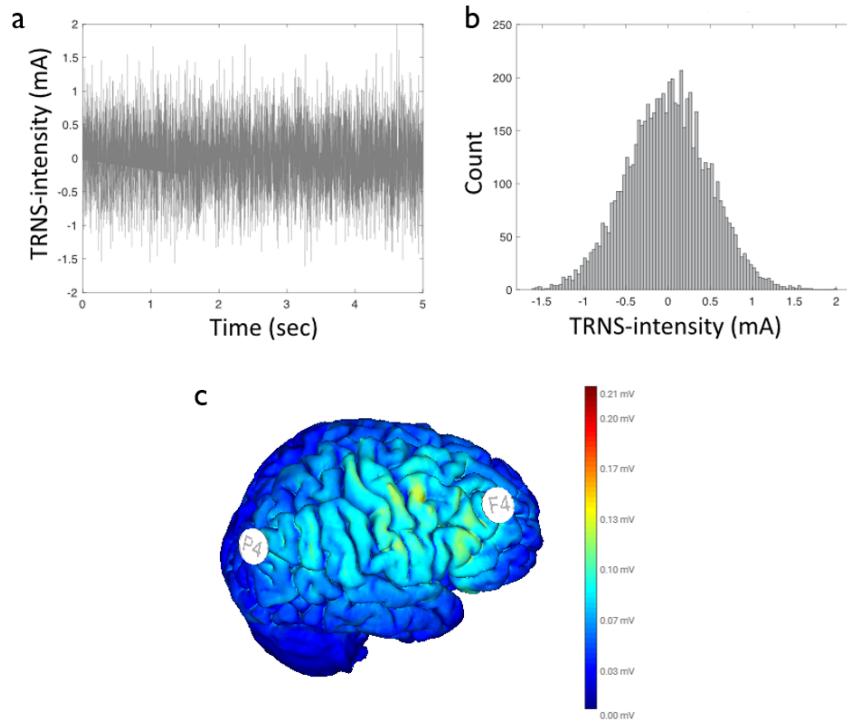


Figure 1.2: tRNS amplitude and frequency distribution. a. During tRNS, amplitudes up to the specified current intensity (mA) from peak-to-peak are applied via the electrodes, here 2 mA. b. The administered current follows a normal distribution centred around 0 mA. c. An example montage and electric field strength over the right fronto-parietal areas (F4 and P4 of the international 10-20 system). The weak current flows bi-directionally between the two electrodes to increase neuronal excitability. Figure panels a and b from Van Der Groen et al., 2022 (open-access).

performance and changes in TBR were observed after 20 minutes of online tRNS in adults (Harty & Cohen Kadosh, 2019), reduced reported symptoms in children with ADHD (Berger et al., 2021; Dakwar-Kawar et al., 2024), and improved attention selectivity (N. Shalev et al., 2018). In combination with training, 25 min of tRNS also improved orientation discrimination and temporal order judgement along with increased connectivity in an attention network (Contò et al., 2021). Furthermore, improvements on motion perception, response inhibition, and arithmetic problem solving have been observed (Moret et al., 2021; Pavan et al., 2019; Sheffield et al., 2020; Van Bueren et al., 2023). The benefit of tRNS has both been shown in monotonous and simple tasks but also in more complex and multi-task procedures (B. Frank et al., 2018; Lema et al., 2021).

There is evidence suggesting that tRNS improves performance more in partic-

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ipants with high TBR or steeper AE (Harty & Cohen Kadosh, 2019; Sheffield et al., 2020; Van Bueren et al., 2023). These results suggest the promising benefit of tRNS on attentional and perceptual processes for those individuals with lower baseline ability.

1.7.1 The Application and Mechanism of tRNS

tES is usually administered via a headgear setup holding the stimulation electrodes in place over the desired area on the scalp and are prepared using saline or electrode gel to ensure connectivity (Reed & Cohen Kadosh, 2018). The difference between tES methods is how the electrical current is administered. During DC stimulation, the directional current flows between one excitatory (anode) and one inhibitory (cathode) electrode. For alternating and random noise stimulation, the anode and cathode periodically reverse allowing the current to flow bidirectionally. In AC stimulation, the frequency range of the current is narrow with the aim to entrain neural activity in the same rhythm and shift their phase (Paulus, 2011; Plas & Hanslmayr, 2020). During tRNS, alternating current is applied in a wide frequency range, see Fig 1.2. High-frequency random noise (100-640 Hz) has shown the largest excitability increases (Laczó et al., 2014; Moret et al., 2019; Terney et al., 2008).

In contrast, tACS induces rhythmic depolarisation of neurons with the aim of altering the ongoing activity patterns of underlying brain regions through frequency-specific modulation (Antal & Herrmann, 2016; Paulus, 2011; Plas & Hanslmayr, 2020). The stimulation delivers a sinusoidal current at a defined frequency to entrain endogenous neural oscillations—synchronising the timing of neuronal firing with the externally applied rhythm. This mechanism allows tACS to influence cognitive functions that are linked to specific oscillatory frequency bands, such as theta or beta rhythms involved in attentional processes (Helfrich et al., 2018; Plas & Hanslmayr, 2020).

The advantages of tRNS over other methods of brain stimulation are that the bi-directional current shows less sensitivity to neurons’ orientation (Fertonani & Miniussi, 2017; Terney et al., 2008), which might facilitate greater changes in

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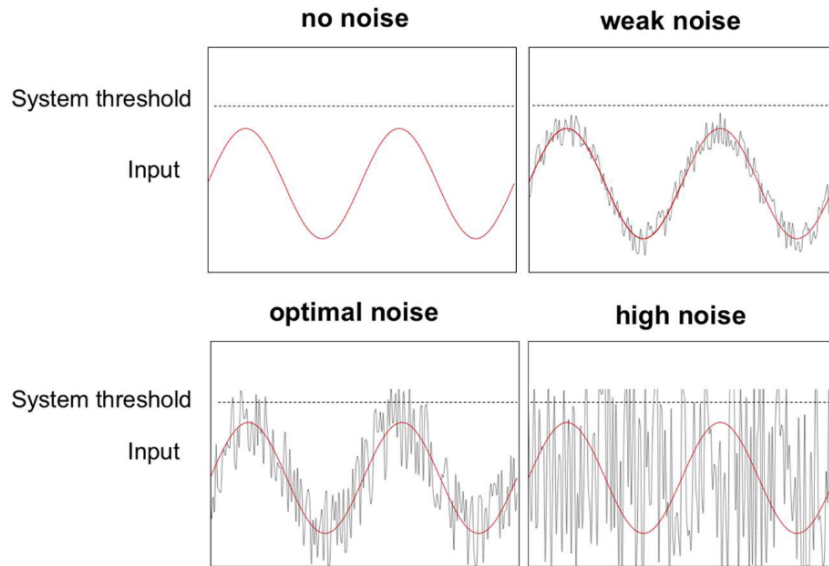


Figure 1.3: Stochastic resonance describes the boosting impact of noise on a subthreshold signal or input (red line), such as the oscillatory activity in the brain (panel 1). The applied weak noise, for example via tRNS (grey line), might push the signal towards the threshold (panel 2) but the optimal dose of noise will enhance the signal to become suprathreshold (panel 3) without masking the information by overwriting the signal with noise (panel 4). Figure from Van Der Groen et al., 2018 (open-access).

excitability and behaviour compared to tDCS (Inukai et al., 2016; Lema et al., 2021). Furthermore, it has been shown that the intervention is less noticeable leading to better blinding and fewer side-effects for the participant (sensations are additionally modulated by electrode size for all tES variations; Fertonani et al. (2015)). However, montage and parameters, such as current amplitude, frequency range, duration, and anatomical differences, all have been suggested to impact the delivery and effectiveness of tES (Krause et al., 2013; Moret et al., 2019; Parkin et al., 2019).

Several explanations for tRNS-related effects on cognition have been brought forward. One possibility is that the induced change in membrane potential facilitates the opening of sodium channels and neuron depolarisation leading to increased synaptic transmission (Antal & Herrmann, 2016; Paulus, 2011; Reed & Cohen Kadosh, 2018).

Another theory describes the phenomenon of noise improving a subthreshold

1. General Introduction

signal (Antal & Herrmann, 2016; Van Der Groen et al., 2022), see Fig. 1.3. According to stochastic resonance, when the optimal amount of noise, which could be visual or electric, is added to a weak signal, the signal strength is increased (Van Der Groen et al., 2022).

Physiologically, neural signalling in the brain depends on excitatory and inhibitory changes in the membrane potential of neurons, regulated by the movement of charged ions into and out of cells within the engaged neural networks (Van Der Groen et al., 2022). The overall balance of these inputs determines the excitability of the brain region involved in the current cognitive process. Applying a weak external electrical current, such as through tRNS, can facilitate the influx of positively charged ions (e.g., Na⁺), resulting in the depolarisation of cortical neurons that are already close to their firing threshold. This increases the likelihood of action potential generation in a state-dependent manner, enhancing activity only in neurons that are receiving intrinsic or extrinsic stimulation. Moreover, the intensity of the applied current is critical. It is thought that an optimal level of noise can selectively boost the responsiveness of target neurons without overwhelming the signal by indiscriminately increasing the firing of less relevant neuronal populations (Van Der Groen et al., 2022).

The effects on visual discrimination and motion perception have been shown to follow the predictions of stochastic resonance when noise is applied (Pavan et al., 2019; Van Der Groen et al., 2018; Van Der Groen et al., 2022; Van Der Groen & Wenderoth, 2016). When low levels of visual noise or tRNS amplitudes are used, no benefit on task performance is apparent, which is the same when noise levels are very high. However, at moderate ranges of visual noise and tRNS, task performance improved in line with an inverted-U shape function (Pavan et al., 2019; Van Der Groen & Wenderoth, 2016).

1.8 Thesis Aim

Sustained attention has been meticulously researched. However, uncertainties remain with regard to the differences between sustained attention markers in context of monotonous and simple tasks compared to difficult tasks. For instance, sustained attention is required both on a long uneventful drive, and when monitoring machines and attending to specific information on a busy display. There are open questions on the association between attention performance and off-task thoughts such as MW, and how these change with task demand. Most importantly, not much conclusive research has been done on how this information can be used to maximise brain stimulation outcomes. Therefore, this thesis aims to investigate the behavioural and physiological correlates of sustained attention and examine how sustained attention can be improved using tRNS. The experiments will test how performance, MW, and other assessments of sustained attention relate to one another, and to EEG and pupil markers of attention, in different sustained attention tasks. Furthermore, I am interested in whether tRNS is a useful tool for improving sustained attention and whether this is subject to task demands. In addition, I am interested in individual differences in tRNS benefits and whether attention measures predict these differences. Some of the questions that I will be addressing are:

1. Which markers of sustained attention predict who will benefit from tRNS (Chapter 2 and 5)?
2. How are behavioural sustained attention measures related to each other during low and high demand search tasks (Chapter 3 and 4)?
3. How do pupillary and cortical markers represent sustained attention (Chapter 4 and 5)?
4. Can sustained attention performance and MW be improved during monotonous and difficult sustained visual tasks (Chapter 5)?

2

The Role of Cognitive Control Markers of Sustained Attention Improvement during Transcranial Random Noise Stimulation

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2. The Role of Cognitive Control Markers of Sustained Attention Improvement during Transcranial Random Noise Stimulation

Abstract

Inconsistencies among research findings have made it challenging to determine the benefits of non-invasive electrical brain stimulation on cognitive performance. One reason for the variation in outcomes might be individual differences in prior brain state. A previous study found that participants who profited from 1 mA transcranial random noise stimulation (tRNS) for improved sustained attention could be identified by a lower theta/beta ratio (TBR) at baseline ([Harty & Cohen Kadosh, 2019](#)). In this chapter, I compared four markers of sustained attention to find whether task performance and self-rated cognitive failures can predict brain stimulation success similarly, or better than TBR in the same sample from Harty & Cohen Kadosh ([2019](#)). Participants completed a continuous monitoring task (CMT) before and during the tRNS intervention with placebo (sham), 1 mA, and 2 mA on three consecutive days.

The results demonstrated that baseline Coefficient of Variation (CoV) and Cognitive Failures Questionnaire (CFQ) ratings moderated response variability during tRNS. Participants with high baseline CoV, or CFQ scores - indicating poorer performance - benefited the most from 1 mA tRNS compared to sham. Individuals with high CoV also improved during 2 mA tRNS compared to sham. Classical and cross-validated model comparisons suggested that no significant additional proportion of the data was explained by TBR, and CoV was the best moderator overall. Changes in resting TBR after tRNS were not explained by behavioural attention markers.

These results suggest that behavioural proxies of sustained attention could identify participants who profit most from brain stimulation.

2. The Role of Cognitive Control Markers of Sustained Attention Improvement during Transcranial Random Noise Stimulation

Sustained attention refers to the process of goal-directed maintenance of attention on a single task over longer periods of time and is subject to moment-to-moment fluctuations (Esterman & Rothlein, 2019; Fiebelkorn & Kastner, 2019; Fortenbaugh et al., 2018; Helfrich et al., 2018; Raposo et al., 2023). To sustain optimal task performance, levels of bottom-up arousal and top-down cognitive control modulate the available attentional resources and allocate them to the current task (Esterman & Rothlein, 2019).

2.0.1 Unravelling the Benefits of Transcranial Random Noise Stimulation

In the past 15 years after its introduction, tRNS has become more and more popular in the brain stimulation intervention literature (Brancucci et al., 2023). Different to other methods of tES, during tRNS, a weak alternating electrical current in a range of high frequencies that mimic neural white noise is applied to the scalp (Antal & Herrmann, 2016; Fertonani & Miniussi, 2017; Harty & Cohen Kadosh, 2019; Paulus, 2011). The currents administered through tRNS are bi-directional and tRNS shows an overall excitatory effect on neural clusters below both electrodes (Fertonani & Miniussi, 2017; Laczó et al., 2014; Van Bueren et al., 2023).

However, the effects of tRNS, like other neurostimulation methods, may be state- and task-dependent and therefore benefit from personalisation (Krause et al., 2013; Lorenz et al., 2017; Lorenz et al., 2019; Van Bueren et al., 2023; Van Der Groen & Wenderoth, 2016). It is expected that baseline ability varies not only between healthy and clinical samples (e.g. attention difficulties in ADHD) but also within these groups, and therefore, a one-size-fits-all approach might not produce the optimal effects.

Furthermore, previous studies hypothesised that the mechanism of adding noise to the brain via tRNS works according to the theory of stochastic resonance (Fertonani & Miniussi, 2017; Van Der Groen et al., 2022). This theory describes the improvement and deterioration of a perceived signal (e.g. a stimulus) when different levels of noise are added. For example, when the optimal amount of noise

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is introduced, processing of the signal is facilitated, but when suboptimal noise is added to a signal, the processing is hindered. In tRNS, optimal levels of electrical noise may lead to increased neural activity in task-positive networks ([Antal & Herrmann, 2016](#); [Battaglini et al., 2023](#); [Van Der Groen & Wenderoth, 2016](#)).

Examples of stochastic resonance in visual stimulus and motion processing in human subjects have been brought forward, showing that global motion processing is optimal at a medium level of surrounding distractors but performance was significantly lower in conditions with more and less distractors ([Battaglini et al., 2023](#)). Similarly, adding a noise mask over a Gabor patch improved the visibility of the grating to a certain degree but worsened it when the intensity of the noise was increased ([Van Der Groen & Wenderoth, 2016](#)). Interestingly, both studies found the same effect of the visual noise when adding electrical noise using tRNS instead. When adding 1 mA tRNS during the motion task, Battaglini et al. ([2023](#)) found that optimal performance was improved when less distractors were present than in the sham condition, but with 2 mA tRNS, there was no clear optimal distractor numerosity for best performance. Van Der Groen & Wenderoth ([2016](#)) showed that when stimuli were displayed at subthreshold level, discrimination improvement during different strength tRNS was improved according to an inverted-U-function, with the most improvement at intermediate mA of tRNS. These studies indicate that tRNS gains are sensitive to prior brain state of participants and could be more beneficial to those with suboptimal performance or neurophysiology before the intervention.

Sustained attention is an ideal target for tRNS since attention networks are modulated by underlying stochastic resonance principles. Fronto-parietal control networks receive input from both tonic and phasic activity in the locus coeruleus (LC), which encode the overall arousal state of the brain according to an inverted U-shape ([Aston-Jones & Cohen, 2005](#); [Unsworth & Robison, 2017](#)). If tonic activity is in the optimal range, better sensitivity for goal-relevant stimuli is achieved through increased phasic activity. However, lower and higher tonic activity lead to task disengagement and suboptimal performance ([Unsworth & Robison, 2017](#)). Hence,

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attention cortices, such as the right prefrontal cortex (PFC) and right inferior parietal lobule (IPL), might benefit from additional noise when the ability to maintain alertness over long stretches of time fails (Kondo et al., 2023).

Within the attention literature, tRNS has shown improvements in cognitive performance and connectivity of relevant attention networks (Contò et al., 2021; Harty & Cohen Kadosh, 2019; Lema et al., 2021; N. Shalev et al., 2018). Specifically, Harty & Cohen Kadosh (2019) found an improved ability to sustained attention over 20 minutes persisting for at least 20 minutes after stimulation with 1 mA of tRNS over the right frontal and parietal cortex. Fronto-parietal stimulation is of interest since sustained attention recruits networks such as the dorsal top-down visuospatial and the frontoparietal control systems enervated by the right lateralised alerting network (Dosenbach et al., 2008; Petersen & Posner, 2012).

Moreover, Harty & Cohen Kadosh (2019) found that participants with high theta/beta (TBR) ratio, indicating low cortical arousal showed increased performance gains compared to participants with a more optimal cortical arousal. This indicates that positive effects of tRNS measured in one sample could be masked by participants who profit less or not at all. Therefore, it is important to identify measures, such as TBR, which can easily and reliably code changes in baseline sustained attention and serve as markers for brain stimulation success.

2.0.2 Quantifying Sustained Attention Skills

TBR, the ratio of slow and fast wave activity, has been associated with sustained attention performance and tRNS-related gains and is often elevated in children with attention deficit disorder (ADHD) (Angelidis et al., 2016). With slower, compared to fast, wave activity being recorded in a resting-state EEG measurement, lower baseline excitation of the cortex is indicated by a high TBR (Van Son et al., 2019). TBR has shown reliable correlations with attentional control in young neurotypical adults over two sessions, and has been hypothesised to represent control processes of underlying arousal states (Angelidis et al., 2016). However, using the TBR as a proxy for sustained attention performance could be

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problematic, with its foundation literature stemming from few clinical studies in children with ADHD and showing less consistent findings in healthy adult samples (Saad et al., 2018).

Therefore, another approach to identifying baseline attention states could utilise behavioural measures of sustained attention performance. In Harty & Cohen Kadosh (2019)'s slow-paced gradual monitoring task, sustained attention skill in healthy adults was measured by Coefficient of variation (CoV), a measure of response variability, which quantifies the intra-individual deviation from mean performance speed. A high score marks participants who deviate more in response times from their mean performance throughout the block (inconsistent response speed), whereas a low score marks less deviation and thereby a more consistent performance throughout the block. Even though participants' mean speed can differ, participants who are overall more consistent in their performance (low CoV) are categorised as more focused compared to participants who zone in and out of the task represented by some faster (focused) and some slower reaction times (inattentive) (Esterman & Rothlein, 2019; Harty & Cohen Kadosh, 2019). Similar to TBR, this score is hypothesised to reflect arousal-based engagement related to oscillatory activity in attention networks and therefore is an excellent candidate to reflect moment-to-moment fluctuations in attention networks at baseline (Esterman & Rothlein, 2019; Fortenbaugh et al., 2018).

Moreover, it is possible that simpler behavioural measures such as self-reported lapses in behaviour and attention during everyday life is sufficient in predicting stimulation outcome. Brain stimulation interventions such as tRNS could largely benefit from personalisation based on markers predicting performance improvements. Baseline behavioural scores, such as performance variability over time, are an excellent prognostic candidate due to their links with brain processes and their time and cost effectiveness compared to electrophysiological measurements.

2. The Role of Cognitive Control Markers of Sustained Attention Improvement during Transcranial Random Noise Stimulation

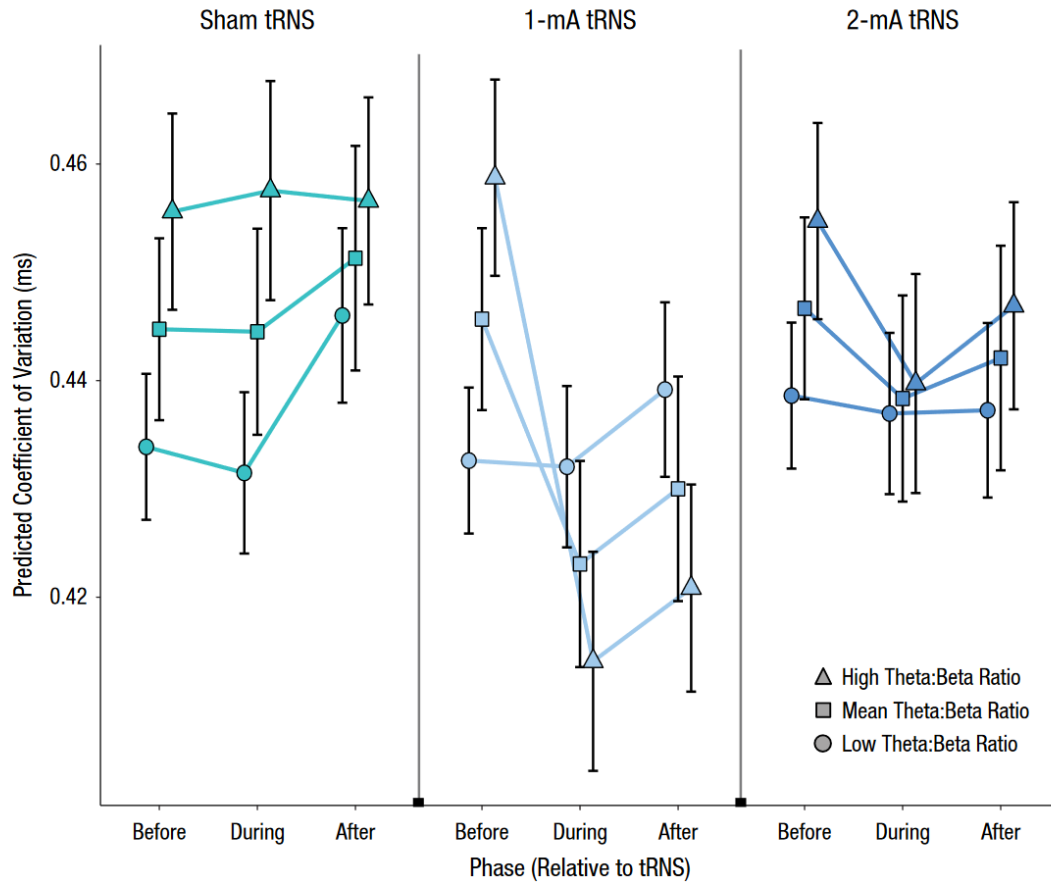


Figure 2.1: Moderating effect of TBR on sustained attention performance. Figure reprinted with permission from Harty & Cohen Kadosh (2019).

2.0.3 The Current Study

This chapter was inspired by Harty & Cohen Kadosh (2019) who found an overall improvement in a sustained attention paradigm after 1 mA tRNS compared to sham stimulation and not 2 mA tRNS but were furthermore able to determine a subgroup of high-responders using a physiological proxy of baseline sustained attention, the TBR (Fig. 2.1). Additionally, TBR was reduced after 1 mA tRNS and not after sham or 2 mA tRNS (Harty & Cohen Kadosh, 2019).

Based on these findings, the current chapter attempted to answer the following research questions:

1. Can differences in behavioural improvements during 1 mA, 2 mA, and sham tRNS be predicted using behavioural baseline measures of sustained attention,

2. The Role of Cognitive Control Markers of Sustained Attention Improvement during Transcranial Random Noise Stimulation

instead of TBR, in Harty & Cohen Kadosh (2019)’s sample?

2. Can changes in post-stimulation TBR be predicted by the same baseline markers from Q1?
3. In case several markers of sustained attention gains are identified in Q1 - Q2, which of the markers fit the respective data best in a direct comparison?

Here, I reevaluated the data from the original study in our lab (Harty & Cohen Kadosh, 2019) where participants detected gradual changes in contrast of a flickering stimulus during 5-minute blocks, first without and then together with tRNS. As behavioural score, variability of response time, measured by CoV, was recorded. In addition, ratings on the Cognitive Failures Questionnaire (CFQ) at baseline and TBR before and after tRNS was administered were assessed.

The aim of the chapter was to confirm whether CoV during stimulation blocks could not only be predicted by pre-stimulation TBR but also by behavioural baseline sustained attention scores. In addition, I aimed to confirm whether changes in TBR after active tRNS were predicted by the same baseline predictors (TBR, CoV, A', CFQ) compared to sham tRNS. To that end, task performance 1) based on response time variability (CoV) and 2) based on accuracy (discriminability measured by A'; Stanislaw & Todorov (1999)) before stimulation were investigated as potential moderators of tRNS improvement. In addition, CFQ was evaluated as a subjective self-rating of sustained attention linking to a real-world representation of sustained attention.

To follow up whether TBR can explain the data beyond the behavioural predictions, I planned to compare all models with significant main or interaction effects of behavioural moderators to the models also containing TBR as a covariate and interaction. In addition, an exploratory cross-validated model comparison was performed to compare all candidate models with interesting effects directly to one another, by fitting them to a partial training data set and validating them in a smaller testing data set. The best model fit was determined by the minimal error between observed and predicted data points. This would allow to determine and quantify differences between all successful moderator variables.

2.1 Methods

2.1.1 Participants

I conducted a secondary analysis on a data set published in Harty & Cohen Kadosh (2019) which included 72 participants (age 19-35, $M = 25.1$, 33 females). All participants gave informed written consent, were reimbursed for their time at the rate of £10/hour or equivalent course credit. Participants were right-handed with normal or corrected-to-normal vision. In addition, standard exclusion criteria for brain stimulation were controlled for, i.e. history of fainting, neurological or psychiatric illness and use psycho-active medications, neurological surgeries including eye surgery and drug or alcohol abuse. In the 24 hours before each session, participants were asked to avoid drinking more than 1 unit of alcohol.

Ethical approval was sought from the University of Oxford Medical Sciences Interdivisional Research Ethics Committee.

2.1.2 Apparatus and Materials

Stimuli

A computerised monitoring task (adapted from O’Connell et al. (2012)) was administered, presenting an annular shape with an inner radius of 3° and an outer radius of 10° of the visual angle flickering at 21.25 Hz. Periodically, the stimulus contrast decreased linearly from its baseline of 65% to 35% of contrast over 1.6 seconds, see Fig. 2.2. This decrease in contrast was considered a target.

Once the stimulus reached 35%, the contrast increased back to baseline within 0.8 s. Between targets, stimuli stayed at baseline contrast for 4 s, 7.2 s, or 10.4 s.

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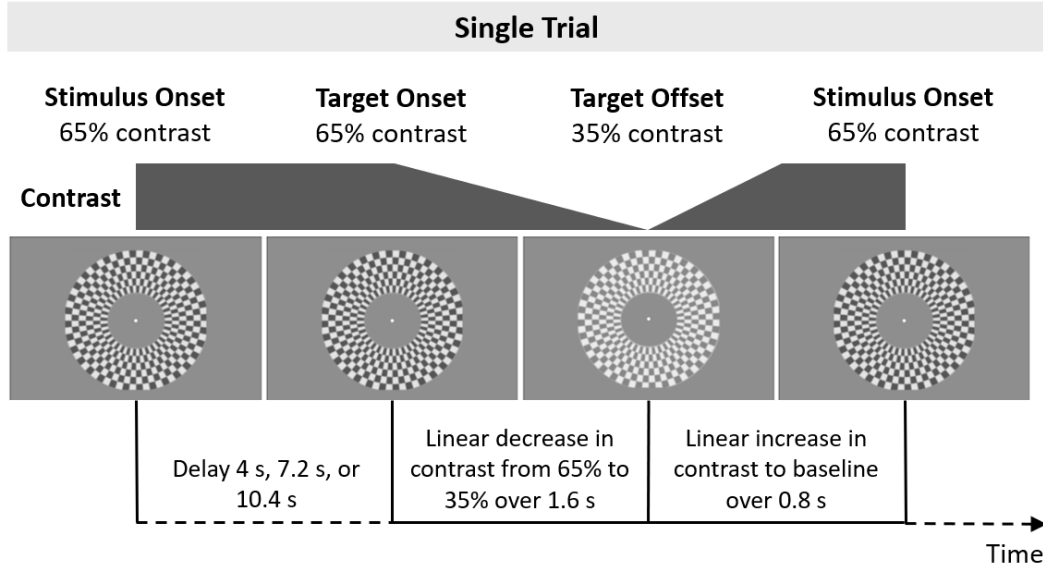


Figure 2.2: Stimulus. A flickering annular stimulus was intermitted by gradual decreases in contrast (targets) from 65 % to 35 % over 1.6 s before returning to 65 % contrast. Targets appeared in randomized intervals of 4 s, 7.2 s, or 10.4 s within one block of 4 minutes. Figure is taken from MSc dissertation (Malin I. Karstens, 2019).

Cognitive Failures Questionnaire (CFQ)

Self-reported failures in perception, memory, and motor actions related to MW and lapses in attention were assessed via CFQ (Broadbent et al., 1982).

EEG Acquisition

EEG resting-state recordings were acquired from 20 channels (international 10-20 system: Fp1, Fpz, Fp2, F3, Fz, Fc1, Fc2, C3, Cz, C4, Cpz, Pz, P3, PO3, PO4, PO7, O1, Oz, O2) and right mastoid references (common mode sense, driven right leg) at 500 Hz sampling rate using the Enobio 20® (Neuroelectrics®). A bluetooth connection was used to transmit the data via the Neuroelectrics Instrument Controller (NIC) software onto a Windows 7 desktop computer. Recordings lasted 4 minutes at baseline with participants observing a fixation cross on a black screen throughout and were instructed to refrain from mental or motoric activities.

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tRNS Administration

Twenty minutes of 1 mA or 2 mA peak-to-peak high-frequency (100-500 Hz, normally distributed amplitudes) tRNS was administered through a StarStim® device (Neuroelectronics®) and using saline-soaked sponge electrodes (25cm²) over the international 10-20 system's F4 and P4 locations. Ramp-up and ramp-down of the current lasted an additional 30 s. During sham stimulation, 1.5 mA tRNS was applied for 30 s with additional ramp up and down of 30 s.

Brain Stimulation Side-Effects Questionnaire

To assess blinding and side-effects of the tRNS, participants filled out a questionnaire adapted from (Fertonani et al., 2010). First, participants reported whether they believed they had received (a) real (active) stimulation, (b) placebo (sham), or (c) they did not know which kind of stimulation they received. Next, participants rated experiencing “itching”, “pain”, “burning”, “warmth/heat”, “fatigue/decreased alertness”, “flashing lights (other than the stimulus)” on a 10-point Likert scale. In case of mild (2-3), moderate (4-6), or severe (7-10) reported sensations, a follow up questionnaire assessed the subjective effect that the sensation had on the performance rated on a scale from 1 to 5, and the duration of the sensation in minutes from 1 to 5. Results of the side effects and perceived sensations are reported in Harty & Cohen Kadosh (2019).

2.1.3 Procedure

Continuous Monitoring Task (CMT)

Experimental Sessions. In this within-subject study, all participants completed the same set of questionnaires and tasks on three consecutive days at the same time of day.

In the beginning of the first day, the CFQ was administered followed by a short task practice of the CMT (14 targets) with verbal feedback.

In each session, eight CMT blocks (25 targets, 4 minutes each) were completed. Participants were instructed to monitor a flickering annular stimulus and to detect

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targets as soon as a change in contrast was noticed, without making any guesses. Responses were given via right-handed button press on a response-box. No feedback was provided throughout the task.

Four task blocks were administered without stimulation as baseline, followed by four task blocks with simultaneous tRNS. On each day, a participant completed one of three double-blinded tRNS conditions (sham stimulation, 1 mA, 2 mA) in randomised order. Side-effects of the stimulation were assessed after all stimulation blocks via self-report. Four-minute resting-state EEG was recorded before and after the stimulation portion of the session. Throughout the measurement, participants were instructed to relax and fixate on the centre of a black screen.

Attention Measures

CFQ scores. The total CFQ score of all 25 items on a 5-point scale was calculated, where a higher total score indicated stronger tendencies for failures across multiple domains, such as attention and memory, in daily life.

Discriminability (A'). A non-parametric estimate of discriminability as formulated in signal detection theory was used to quantify performance in the CMT (Pallier, 2002). A' can take values of up to 1 (perfect performance); a value of 0.5 signals chance performance.

Coefficient of Variation (CoV). Behavioural performance was evaluated using the CoV (Harty & Cohen Kadosh, 2019) which represents the standard deviation in RT (SD_{RT}) to target appearances controlled for mean RT (M_{RT}) per task block: $CoV = \frac{SD_{RT}}{mean_{RT}}$. Valid responses occurred 150 ms after target onset and before the target contrast reverted back to baseline at 1600 ms after onset. A stimulation score (CoV_s) was formulated using the mean CoV from 4 task blocks when online tRNS was applied. Baseline CoV (CoV_{bl}) is defined as the mean CoV over the first 4 non-stimulation task blocks.

Theta/Beta Ratio (TBR). The TBR was reported as calculated in the original paper due to the unavailability of the raw EEG data (Harty & Cohen Kadosh, 2019). Excessive packet loss (above 10%) was found for 2 participants

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who were consequently excluded from the data analysis. Noisy channels were interpolated with spherical spline interpolation after visual inspection. All data was re-referenced averaging all electrodes, excluding F3 and P3, which were placed opposite the stimulation-only electrodes. Two-second epochs were examined for excessive noise such as eye and face movements and excluded if they at any point exceeded ± 100 V. Participants with more than 50% rejected epochs, were excluded ($N = 1$). 69 participants contributed between 151 and 208 epochs to be transformed via Fast-Fourier transform and high-pass filtered at 1.5 Hz. TBR was calculated for each midline region (frontal, central, parietal, and occipital) by dividing relative theta (4-7.5 Hz) by relative beta power (14-30 Hz) at Fz, Cz, Pz, and Oz respectively, and subsequent log-transformation. TBR_{pre} defined TBR recorded before the tRNS task blocks and TBR_{post} defined TBR recorded after the tRNS blocks.

Data Preprocessing

All analyses were performed in R (Version 4.3.0) using custom scripts.

To ensure a robust analysis, outliers in CoV were identified excluding values deviating more than 3 standard deviation from the mean. A total of 2.9% of blocks by 2 participants were identified as outliers and removed. After outlier removal, only complete cases were retained for further analysis ($N=67$).

Data Analysis

Data Availability. Data for the full sample was made available from Harty & Cohen Kadosh (2019) including personal information such as age, but missing raw EEG data and information on the sex reported by participants.

Linear Models. I performed moderation analyses to predict changes in CoV during stimulation by different baseline attention measures: 1) TBR (replicating the effect from Harty & Cohen Kadosh (2019) due to slight changes in the model formulation and for comparisons), 2) CoV_{bl} 3) CFQ, and 4) A'. CoV_s was entered as the dependent variable. To control for baseline performance, CoV_{bl} was entered as covariate in all models. The same procedure was repeated using TBR

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after stimulation (TBR_{post}) as outcome. To control for baseline TBR, TBR_{pre} was entered as covariate in those models. In all analysed models, subjects were entered as random effect to account for inter-individual differences in performance. Mixed-effect models were fitted using the *lme4* package from R. All models were initially formulated as full models with the respective predictor as random slope and then reduced in R by estimating explained variance of the random effect and confirming whether the reduced model performs significantly better in a Chi² test. All continuous predictor variables were centred to avoid adverse effects of multicollinearity between interaction terms resulting in all GVIF^{(1/(2*df))} <2, which is below conservative thresholds used in the literature (Fox & Monette, 1992; Zuur et al., 2010).

Posthoc slope comparisons were performed in R using *emmeans* (emmeans package) with Tukey correction for pair-wise comparisons for any model showing interaction effects for different conditions.

Model Comparison. Model fit was compared individually between all significant models with CoV, CFQ, and A' as predictors against the model including TBR as an interaction, to examine whether performance and questionnaire-based predictors fitted the data better than TBR. Comparisons were performed via Chi² test and the Bayesian Information Criterion (BIC) was reported as an additional indication of model fit while penalising for higher number of parameter in models.

Cross Validation. An exploratory model comparison approach using cross validation was used to directly compare all models with significant interaction effects irrespective of nested and non-nested predictors. All models were compared based on least predicted error, see a full list of models in Tab. 2.1 (predicting CoV_s). The simplest model contained only tRNS condition (1 mA, 2 mA, sham) as fixed predictor.

To compare models, I ran a repeated 5-fold cross-validation in R. Data was partitioned into a training data set (4 folds=~80%: 156 observations, 52 participants) and a testing data set with the remaining data (1 fold=~20%: 39 observations, 13 participants). The cases were split such that data from one participant in all

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three tRNS conditions was allocated to the same data set and fold. I then run the cross-validation returning the prediction error, or root mean square error (RMSE), between the training and testing data set for all nine models.

RMSE was chosen to compare models since it is a measure of how well the model fits the data. When models had a similar error, adjusted R^2 was used to compare whether there were differences between the proportion of variance the models explained.

Within the training data set each of the 4 folds was held out as a validation data set once and model errors were averaged for the 4 comparisons ($RMSE_{train}$). Then, models fitted on the full training data were used to predict the dependent variable in the testing data set and RMSE between predicted and observed values were reported ($RMSE_{test}$). Since RMSE fluctuated with different data partitions, the cross validation was repeated for 100 seeds and the mean RMSE ($mRMSE_{train}$, $RMSE_{test}$) was reported together with the 95% confidence interval (CI).

Model summaries and 95% CIs for the predictors were generated using bootstrapping (1000 simulations), and R^2 .

2.2 Results

2.2.1 Sample

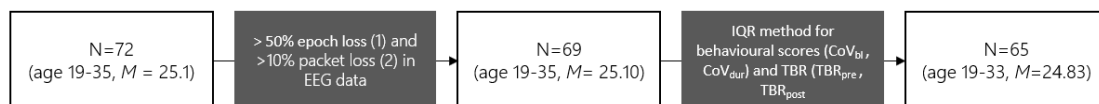


Figure 2.3: Participant exclusion procedure. Participants were excluded based on EEG data quality and outliers in relevant scores.

Of the initial 72 participants, EEG data of three individuals was excluded due to excessive epoch loss (1) and packet loss (2), see Harty & Cohen Kadosh (2019). Additionally, 2.9% of the remaining data was excluded due to outliers in behavioural or EEG data resulting in a sample of $N=67$ (Age: $M= 24.91$, $SD= 4.4$). The exclusion

2. The Role of Cognitive Control Markers of Sustained Attention Improvement during Transcranial Random Noise Stimulation

procedure and final sample details are visualised in Fig. 2.3. The distribution of sex was unavailable for this final data set.

2.2.2 Changes in Task Performance During Brain Stimulation

Resting TBR Moderated Performance during tRNS (Replicated)

I replicated the effect of TBR_{pre} in predicting performance score during stimulation only at 1 mA tRNS compared to sham ($adjR^2 = 0.57$). The model $CoV_s \sim tRNS * TBR_{pre} + CoV_{bl} + (1 | \text{subject})$ showed a main effect of tRNS condition, indicating that 1 mA compared to sham stimulation resulted in lower CoV, and a significant main effect of CoV_{bl} indicating that baseline performance positively predicted performance during stimulation (see all model results in Tab. A.1). Furthermore, the model showed a significant interaction between TBR_{pre} and 1 mA tRNS vs. sham ($\beta = -0.042$, $SE = 0.01$, $t(201) = -2.9$, $p = 0.004$), indicating differences in responding to 1 mA tRNS compared to sham tRNS between participants with low and high baseline TBR, see Fig. 2.4.

Post hoc comparisons revealed that compared to sham stimulation, the slope of predicted CoV during 1 mA tRNS was significantly reduced ($\beta = 0.04$, $p = 0.014$). There was no evidence for a significant difference in predicted CoV between 2 mA tRNS and sham stimulation ($\beta = 0.01$, $p = 0.8$) or between 1 mA and 2 mA tRNS ($\beta = -0.03$, $p = 0.083$).

Baseline CoV Moderated Performance during tRNS

When testing whether baseline CoV could replace TBR and moderate the effect of stimulation ($CoV_s \sim tRNS * CoV_{bl} + (1 | \text{subject})$) a main effect of tRNS condition was found (see all model results in Tab. A.2). This indicated that 1 mA compared to sham stimulation resulted in lower CoV. There was also a significant main effect of CoV_{bl} indicating that baseline performance positively predicted performance during stimulation. Moreover, the model showed significant interactions between CoV_{bl} and 1 mA tRNS ($\beta = -0.435$, $SE = 0.11$, $t(195) = -4.09$, $p < .001$) and

2. The Role of Cognitive Control Markers of Sustained Attention Improvement during Transcranial Random Noise Stimulation

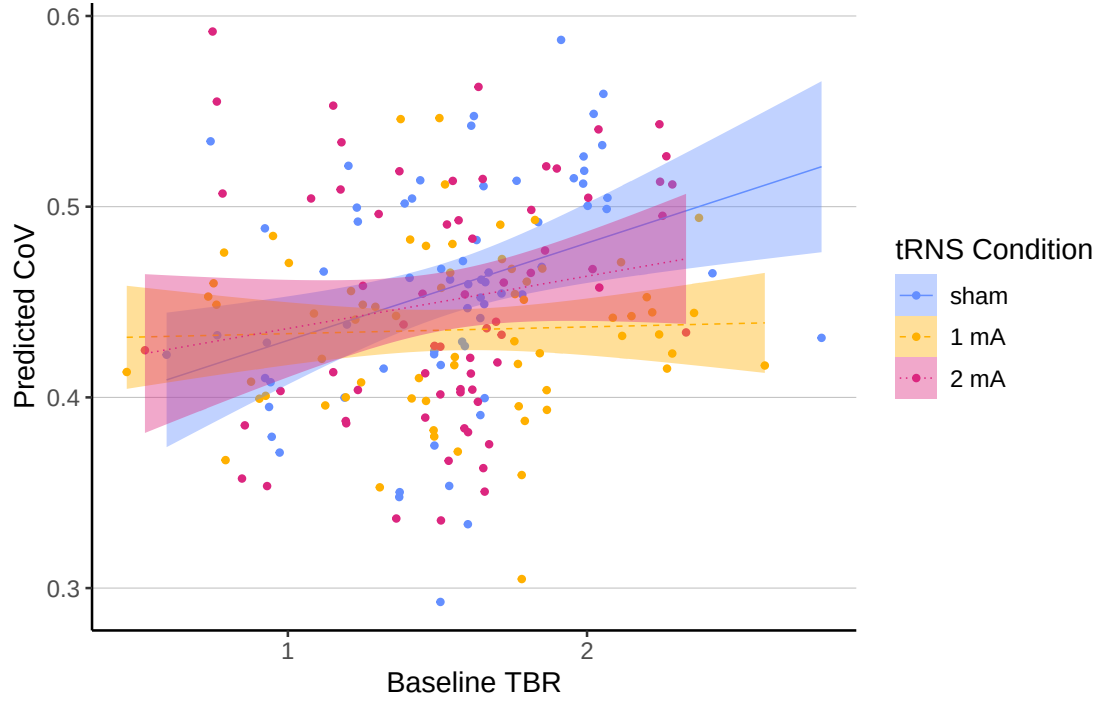


Figure 2.4: Resting state TBR before tRNS predicted CoV during tRNS. The figure displays the significant interaction ($p=.004$) between baseline TBR and tRNS condition. Compared to sham stimulation, 1 mA tRNS significantly reduced CoV in participants with high TBR at baseline, indicating greater benefit from the stimulation. Data points of participant's performance in each condition are displayed in the respective colour. The shaded areas depict the 95% confidence interval of the estimates.

between CoV_{bl} and 2 mA tRNS ($\beta = -0.262$, $SE = 0.1$, $t(195) = -2.54$, $p = 0.012$), indicating predicted differences in stimulation CoV between participants with low and high baseline CoV during both tRNS conditions (1 mA and 2 mA) compared to sham stimulation (see Fig. 2.5). For higher CoV measured at baseline, scores during 1 mA and 2 mA improved more and vice versa ($adjR^2 = 0.58$).

Post hoc comparisons revealed a significantly reduced slope of predicted CoV during tRNS compared to sham stimulation, for 1 mA ($\beta = 0.43$, $p = 0$) and 2 mA ($\beta = 0.26$, $p = 0.033$). There was no evidence for a significant difference in predicted CoV between 1 mA and 2 mA tRNS ($\beta = -0.17$, $p = 0.186$).

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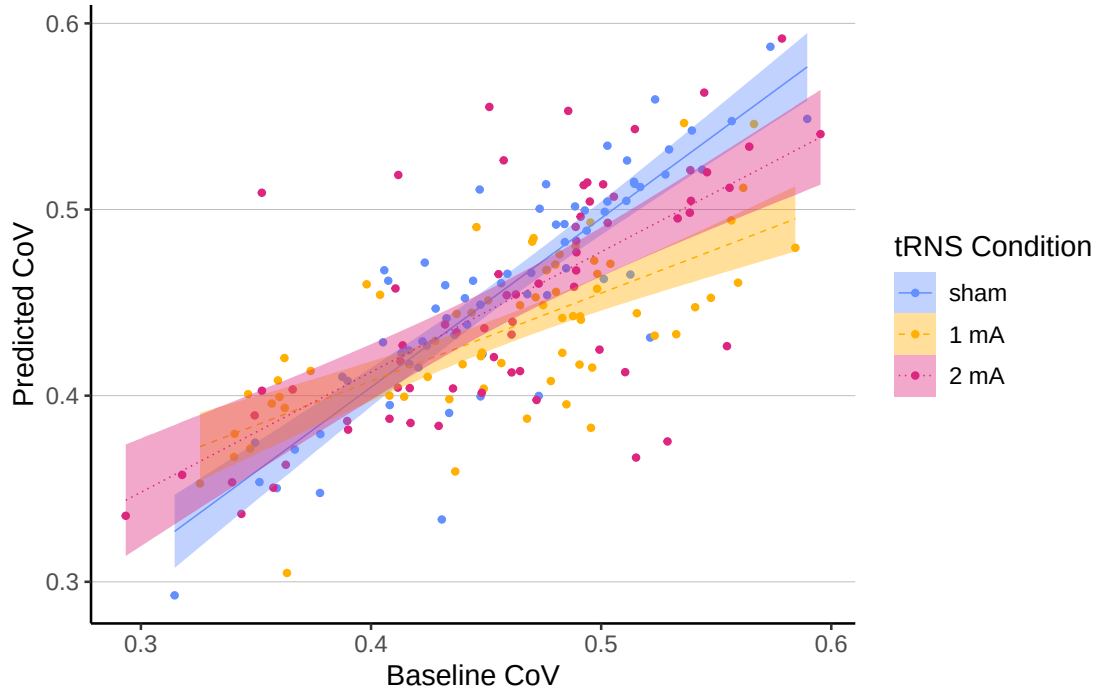


Figure 2.5: Baseline CoV predicted CoV during tRNS. The figure displays the significant interactions between baseline CoV and tRNS condition indicating better performance during 1 mA ($p < .001$) and 2 mA ($p = .012$) tRNS for participants with high baseline CoV compared to sham stimulation. Data points of participant's performance in each condition are displayed in the respective colour. The shaded areas depict the 95% confidence interval of the estimates.

Self-reported Attention Moderated Performance during tRNS

Similar to resting TBR, CFQ predicted performance during stimulation only at 1 mA tRNS compared to sham but not during 2 mA compared to sham ($\text{adj}R^2 = 0.58$). As in both models before, $\text{CoV}_s \sim \text{tRNS} * \text{CFQ} + \text{CoV}_{bl} + (1 | \text{subject})$ showed both main effects of tRNS condition, indicating that 1 mA compared to sham stimulation resulted in lower CoV, and of CoV_{bl} , indicating that baseline performance positively predicted performance during stimulation (see all model results in Tab. A.3). Finally, the model also showed a significant interaction between CFQ and 1 mA tRNS compared to sham ($\beta = -0.001$, $\text{SE} = 0$, $t(132.46) = -3.53$, $p = < .001$), indicating differences between participants with low and high CFQ scores in response to 1 mA tRNS compared to sham stimulation but not 2 mA, see Fig. 2.6).

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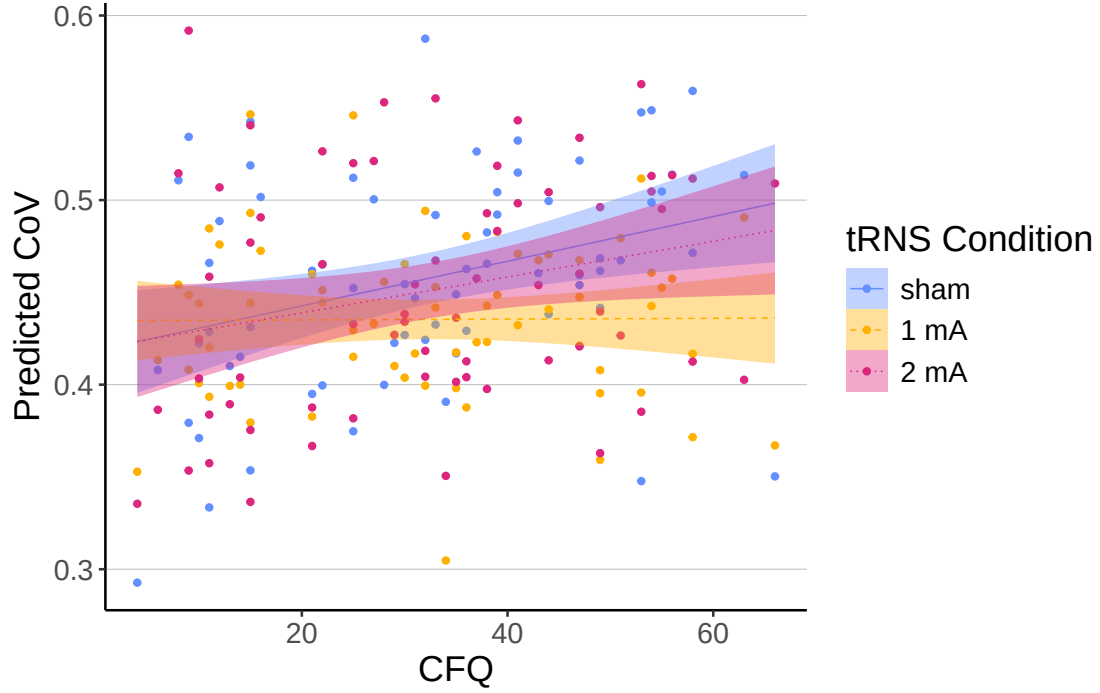


Figure 2.6: CFQ score predicted CoV during tRNS. The figure displays the significant interaction between CFQ and tRNS condition. Better performance was predicted during 1 mA tRNS ($p < .001$) for participants with high ratings on the CFQ, compared to sham stimulation. Data points of participant's performance in each condition are displayed in the respective colour. The shaded areas depict the 95% confidence interval of the estimates.

Post hoc comparisons showed a significantly reduced slope of predicted CoV during tRNS compared to sham stimulation for 1 mA ($\beta=0$, $p=0.002$) and there was a significant difference in predicted CoV between 1 mA and 2 mA tRNS ($\beta=0$, $p=0.005$). A significant difference between sham stimulation and 2 mA was not supported by the data ($\beta=0$, $p=0.005$).

No Moderation of Discriminability on Performance during tRNS

In contrast to the other attention outcomes, baseline A' did not predict CoV during stimulation ($\text{adj}R^2 = 0.53$). As in the models before, $\text{CoV}_s \sim \text{tRNS} * \text{A}' + \text{CoV}_{bl} + (1 | \text{subject})$ showed both main effects of tRNS condition and of CoV_{bl} (see all model results in Tab. A.4). However, no interactions between baseline A' and tRNS condition, for 1 mA or 2 mA were significant.

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A follow up analysis showed no significant effects or interactions ($\text{adj}R^2 = 0.09$) when instead of CoV during stimulation, A' during stimulation was predicted using baseline A' scores ($A' \sim \text{tRNS} * A' + \text{CoV}_{\text{bl}} + (1 | \text{subject})$), see Tab. A.5

Performance Prediction Model Comparison

Since baseline CoV and CFQ responses could both predict stimulation performance measured by CoV, as found for TBR before stimulation in Harty & Cohen Kadosh (2019), I compared the model fit of these models before and after adding baseline TBR as covariate and interaction.

For CoV, the initial model ($\text{CoV}_s \sim \text{tRNS} * \text{CoV}_{\text{bl}} + (1 | \text{subject})$) with $\text{BIC} = -722.88$ was not significantly improved by adding TBR_{pre} as covariate ($\text{BIC} = -721.78$, $X^2 = 4.2$, $p = 0.04$) or as interaction term ($\text{BIC} = -699.8$, $X^2 = 4.53$, $p = 0.476$), indicating that baseline CoV alone predicted the stimulation performance best.

Similarly, the initial model ($\text{CoV}_s \sim \text{tRNS} * \text{CFQ} + \text{CoV}_{\text{bl}} + (1 | \text{subject})$) with $\text{BIC} = -715.81$ was not significantly improved by adding TBR_{pre} as covariate ($\text{BIC} = -715.19$, $X^2 = 4.69$, $p = 0.03$) or as interaction term ($\text{BIC} = -697.24$, $X^2 = 8.57$, $p = 0.128$), indicating that baseline CFQ alone predicted the stimulation outcome best.

Cross Validated Model Comparison

One limitation of model comparison using Chi^2 tests and probabilistic model selection such as BIC is that only nested models can be compared to one another. To overcome this shortcoming, an exploratory cross validated model comparison was performed attempting to compare model fit of the previously tested models directly. The null model (the most simple model containing only stimulation as a predictor) and a model only containing a main effect of baseline CoV as control were introduced in the comparison in addition to the models containing main effects and interactions for the three baseline predictors (CoV, TBR, CFQ).

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The cross-validated model comparison (see Tab. 2.1) indicated that CoV_{bl} in interaction with tRNS condition alone (Model 4: adjusted $R^2 = 0.58$) predicted the stimulation performance best in the training data ($\text{mRMSE}_{\text{train}} = 0.0369$, 95% CI = [0.0366, 0.0372] and testing data set ($\text{mRMSE}_{\text{test}} = 0.0371$, 95% CI = [0.036, 0.0383]). It is important to note that in the testing data set, the upper 95% CI of Model 4 included all other model estimates, except for the models only including stimulation as a predictor (Model 1) and without interaction (Model 2), indicating that TBR and CFQ in interaction with tRNS condition and CoV_{bl} as covariate as well as the baseline model with only CoV_{bl} as main effect fitted the data closely as well. However, it is expected to find larger margins around the estimates due to the much smaller amount of data in the testing set.

These results suggest that all baseline predictors show some explanatory power of the stimulation-related gains in the sustained attention task during 1 mA compared to sham. However, the minimal error for model fit was predicted for CoV baseline confirming the traditional model comparison outcome.

Table 2.1: Model Comparison

Model	Training data			Testing data		
	Estimate	CI95%		Estimate	CI95%	
1. $\text{CoVs} \sim \text{tRNS} + (1 \text{subj})$	0.0566	0.0562	0.0569	0.0556	0.0543	0.0569
2. $\text{CoVs} \sim \text{tRNS} + \text{CoV}_{\text{bl}} + (1 \text{subj})$	0.0381	0.0378	0.0384	0.0384	0.0373	0.0394
3. $\text{CoVs} \sim \text{tRNS} * \text{TBR}_{\text{pre}} + \text{CoV}_{\text{bl}} + (1 \text{subj})$	0.0378	0.0375	0.0381	0.0381	0.0369	0.0392
4. $\text{CoVs} \sim \text{tRNS} * \text{CoV}_{\text{bl}} + (1 \text{subj})$	0.0369	0.0366	0.0372	0.0371	0.0360	0.0383
5. $\text{CoVs} \sim \text{tRNS} * \text{CFQ} + \text{CoV}_{\text{bl}} + (1 \text{subj})$	0.0375	0.0372	0.0378	0.0379	0.0368	0.0390

Notes. Model estimates of average mRMSE and 95% CIs over 100 repetitions for training and testing data set.

tRNS = sham, 1 mA, 2 mA, subj = subject number.

2.2.3 Changes in TBR During Brain Stimulation

Resting TBR Moderated Post-Stimulation TBR

The first tested model $\text{TBR}_{\text{post}} \sim \text{tRNS} * \text{TBR}_{\text{pre}} + (1|\text{subject})$ revealed a main effect of tRNS condition, indicating that 1 mA compared to sham and 2 mA

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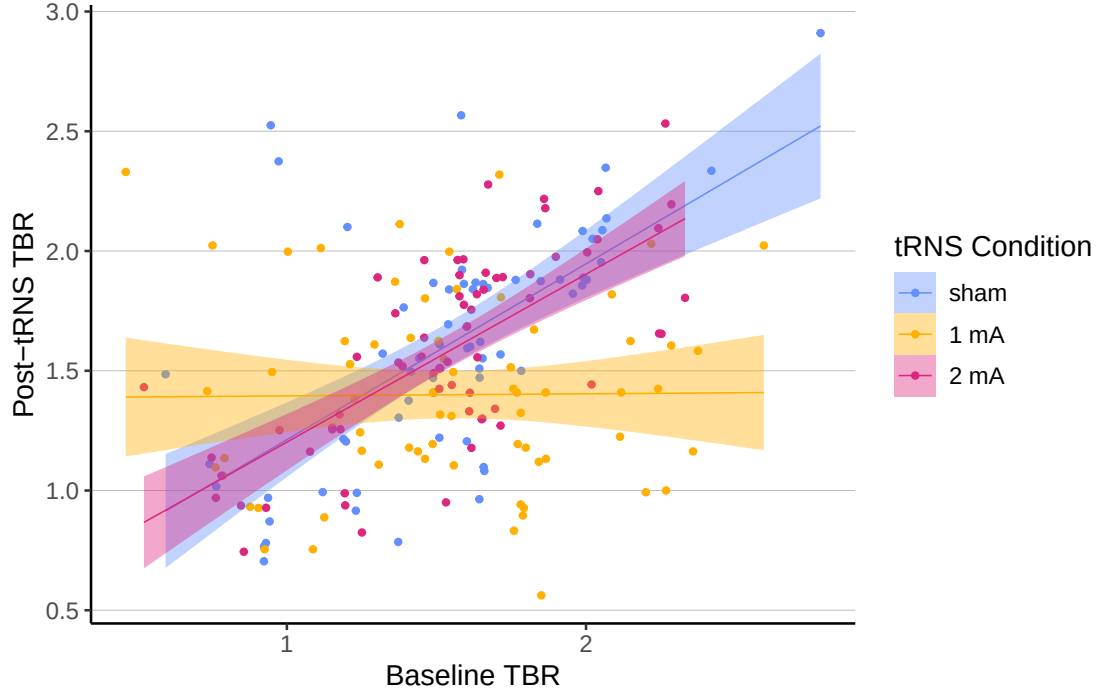


Figure 2.7: Resting state TBR before stimulation predicted a change in TBR. The figure displays the significant interaction ($p < .001$) between baseline TBR and tRNS condition indicating reduced TBR after 1 mA tRNS compared to sham stimulation. Data points of participant's performance in each condition are displayed in the respective colour. The shaded areas depict the 95% confidence interval of the estimates.

stimulation resulted in lower TBR. There was also a significant main effect of TBR_{pre} indicating that baseline TBR predicted TBR_{post} during stimulation, see Tab. A.6). Finally, the model showed a significant interaction between TBR_{pre} and 1 mA tRNS compared to sham ($\beta = -0.042$, $SE = 0.015$, $t(201) = -2.9$, $p = 0.004$) indicating that participants with higher TBR at baseline showed a significantly reduced TBR after stimulation with 1 mA which was not the case for 2 mA tRNS, see Fig. 2.7) ($adjR^2 = 0.33$).

Post hoc comparisons showed a significantly reduced slope of predicted TBR after tRNS compared to sham stimulation for 1 mA ($\beta = 0.72$, $p = 0$) and there was a significant difference in predicted CoV between 1 mA and 2 mA tRNS ($\beta = -0.69$, $p = 0$). A significant difference between sham stimulation and 2 mA was not supported by the data ($\beta = 0.03$, $p = < .001$).

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No Moderation of Baseline Performance on Post-Stimulation TBR

In contrast to baseline TBR, baseline CoV did not predict post-stimulation TBR reduction ($\text{adjR}^2 = 0.21$). The model $\text{TBR}_{\text{post}} \sim \text{tRNS} * \text{CoV}_{\text{bl}} + \text{TBR}_{\text{pre}} + (1 + \text{CoV}_{\text{bl}} | \text{subject})$ revealed a main effect of tRNS condition, indicating that 1 mA compared to sham and 2 mA stimulation resulted in lower TBR, and of TBR_{pre} indicating that baseline TBR predicted TBR_{post} during stimulation, see Tab. A.7). However, no interactions between TBR_{pre} and 1 mA or 2 mA tRNS were significant.

No Moderation of Self-reported Attention on Post-Stimulation TBR

Similarly, CFQ did not predict post stimulation TBR reduction ($\text{adjR}^2 = 0.2$). The model $\text{TBR}_{\text{post}} \sim \text{tRNS} * \text{CFQ} + \text{TBR}_{\text{pre}} + (1 + \text{TBR}_{\text{pre}} | \text{subject})$ only revealed a main effect of tRNS condition, indicating that 1 mA compared to sham and 2 mA stimulation resulted in lower TBR and of TBR_{pre} indicating that baseline TBR predicted TBR_{post} during stimulation, see Tab. A.8).

No Moderation of A' on Post-Stimulation TBR

As with the previous predictors, A' did not predict any changes in TBR after stimulation ($\text{adjR}^2 = 0.25$). As in the models before, $\text{TBR}_{\text{s}} \sim \text{tRNS} * \text{A}' + \text{CoV}_{\text{bl}} + (1 | \text{subject})$ showed a main effect of tRNS condition, indicating that 1 mA compared to sham stimulation resulted in lower TBR. No other main effects or interactions were significant, see Tab. A.9).

Since only the model with baseline TBR, but no other behavioural predictor showed a significant effect on changes in TBR after tRNS, no model comparison was performed.

2.3 Discussion

First, the study revealed that not only pre-stimulation TBR, but also baseline response variability (CoV) and CFQ scores moderated response variability in a sustained attention task during tRNS. Participants with poor attention indicated by higher TBR, CoV, and CFQ score performed better during 1 mA compared to

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sham stimulation, as shown by a larger reduction in CoV during stimulation. In addition, high baseline CoV also predicted better outcome during 2 mA compared to sham. However, task performance A' could not be confirmed as a significant predictor of tRNS improvements.

Second, classic model comparison revealed that the behavioural moderators (CoV and CFQ) predicted the performance outcome best as the mixed effect models did not significantly improve when baseline TBR was entered as main effect and interaction. An exploratory cross-validated model comparison revealed that out of all predictors, CoV showed an advantage over TBR and CFQ, and simpler models, with minimal error in model fit.

Third, while baseline responses successfully predicted stimulation success measured by performance, only baseline TBR moderated changes in TBR at 1 mA compared to sham tRNS. CoV, CFQ, and A' did not moderate changes in TBR during stimulation.

The original study suggested that the TBR in healthy adults could potentially be used to predict stimulation effects on sustained attention performance. However, I could show that this moderator is not exclusive to this cognitive marker but can also be achieved when using response variability and self-rated sustained attention in the same data set. This could indicate that TBR was a proxy of general sustained attention in the sample and participants who struggled more, were found to profit more from the intervention.

In line with the literature, the results suggested performance improvements through online tRNS compared to sham stimulation ([Van Der Groen et al., 2022](#)). The current data showed effects on sustained attention performance, especially during 1 mA tRNS. This is in line with previous studies who found excitatory effects around 1 mA ([Battaglini et al., 2023](#); [Van Der Groen et al., 2022](#); [Van Der Groen & Wenderoth, 2016](#)). Moreover, beyond the differences in effects for 1 mA predicted by TBR before the stimulation, baseline CoV revealed performance improvements for those participants with sub-optimal performance also during 2 mA tRNS. While performance improvements after 2 mA tRNS are equally reported

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in some studies (Contò et al., 2021; Lema et al., 2021), replication issues between tRNS studies are not uncommon (Dondé et al., 2019; Pavan et al., 2019). Not only are there differences in behavioural tasks between brain stimulation studies, Krause & Cohen Kadosh (2014) also note that anatomical, physiological, and functional differences between individuals can impact the replicability of the results in this field. For other studies, it is possible that inconsistent reporting and parameters such as electrode size and material, amplitudes, frequency range, duration, online vs. offline stimulation, cause varied effects and possibly masking effects (Reed & Cohen Kadosh, 2018). The current results align with this notion and highlight that differences in prior skill level and engagement need to be taken into account and could potentially mask any improvements of a subgroup within the full sample.

The most prominent result of the study was that during 1 mA and 2 mA participants with poorer performance improved more than participants with better sustained attention at baseline. One alternative explanation for this effect could be regression to the mean, meaning that participants with outlier performance at baseline are statistically more likely to have an outcome closer to the mean than before, meaning participants whose performance had more room for improvement, showed greater success (Barnett et al., 2005). However, since the performance in the sham condition did not change in the same participants, it is more likely that tRNS showed the most benefit when performance was sub-optimal, but less or no effect when performance was near optimal before the intervention (Van Der Groen et al., 2018; Van Der Groen & Wenderoth, 2016). In addition, A' was not found to be a useful marker of tRNS success, which could suggest that rather than marking general proficiency in the CMT, TBR, CoV and CFQ tap into a more specific process within sustained attention linked to the temporal lapses within the attention networks involved in task performance (Fortenbaugh et al., 2018).

Importantly, when comparing all moderators to one another, the model including baseline CoV as interaction with tRNS condition was preferable in predicting performance improvement compared to models including TBR or CFQ. Notably, several other models had overlapping estimates with the confidence interval of

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the model with CoV in the smaller testing set, indicating that these predictions showed potential compared to the less complex models without baseline predictors. These results have to be interpreted with caution since the testing set of data contained fewer data points and the estimates have larger error margins. It is possible that we see this pattern due to over-fitting, where the model fitting the training data was over-fitted and diverts somewhat from the testing data. However, the overall model results using the full data predicted a similar improvement by all baseline markers, and standard comparisons (X^2 , BIC, adjusted R^2) were in line with the cross-validation results.

It appeared that TBR, behavioural performance in the CMT, and the CFQ in the current study showed very similar outcomes in line with previous research (Angelidis et al., 2016; Harty & Cohen Kadosh, 2019; Schepers et al., 2023; Van Son et al., 2019). However, I could not confirm that baseline markers of sustained attention other than baseline TBR (Harty & Cohen Kadosh, 2019), predicted a reduction in TBR after the stimulation. It is also noteworthy, that the variance explained by TBR_{pre} predicting TBR_{post} was overall smaller than the variance explained when predicting CoV_s the same attention markers, indicating that performance could be more effective prognostic marker and outcome measure in the CMT.

2.3.1 Benefits of Performance Markers Compared to TBR

Overall, the results indicated that a behavioural score of reaction time variability can be used to identify participants who will benefit from stimulation above others, and could lead to better predictions than baseline resting-state TBR and questionnaire responses. Using markers of sustained attention could improve brain stimulation approaches by providing a method of personalising stimulation before the intervention starts (Van Bueren et al., 2021) and providing reference measures in closed-loop interventions (Lorenz et al., 2017), as well as potentially tracking effects on baseline sustained attention in long-term experiments.

The results support the notion that behavioural attention lapses could mark underlying processes of maintaining attention in a non-stimulating task (Flehmig et

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al., 2007). One possible explanation could be that CoV reflects moment-to-moment fluctuations of activity in brain areas related to sustained attention (Fortenbaugh et al., 2018). It has also been hypothesised that response variability is sensitive to the interplay between gradual decreases in arousal and frontal control leading to a decrement of readiness for sustained attention (Esterman & Rothlein, 2019; O’Connell et al., 2008). Individual differences in arousal-based innervation of excitability in sustained attention cortical networks could be a possible explanation of performance improvements through the excitatory effects of tRNS in fronto-parietal networks in the current study (Brancucci et al., 2023; Maness et al., 2022; O’Connell et al., 2008). Maintaining an excitation/inhibition (E/I) balance in the cortex has been shown to moderate the effect of tRNS, benefitting those with lower E/I (Van Bueren et al., 2023). Participants with suboptimal engagement of relevant brain regions might profit more from increased excitation over those areas which is supported by literature of children and adults with ADHD, and macaques (Dutra et al., 2016, 2016; A. C. Snyder et al., 2016). Those with close to optimal cortical excitability, as reflected by lower response variability are expected to not profit as much or at all from the stimulation (Krause et al., 2013; Reed & Cohen Kadosh, 2018)

Potential problems when using TBR as prognostic marker could have been overall data quality and manual data cleaning procedures which is less of a problem when evaluating behavioural performance based on reaction times. In addition, the TBR has been criticised as a reliable marker of attention difficulties since the literature is mainly built on samples of children diagnosed with ADHD, which could be an issue since the frequency spectrum often shows a shift. Therefore, some measurements of theta activity might include part of the alpha peak when not adjusted (Saad et al., 2018). This leads to over-estimation of the theta-beta ratio. While TBR is a consistent marker found in samples of children and adults with ADHD, it is still unclear how intra-individual differences, for example responders and non-responders of stimulant medicine in ADHD patients are reflected in TBR

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(S. M. Snyder & Hall, 2006), and whether other measures might be more optimal (Dakwar-Kawar et al., 2024; M. M. Robertson et al., 2019).

More recently, attempts have been made to separate the true oscillatory activity from the aperiodic activity (the exponent underlying the entire EEG power spectrum). Adolescence with ADHD show a flattened exponent, reflective of an E/I imbalance in the brain, which was also related to Go/No-go performance (Arnett et al., 2022; Karalunas et al., 2022). Importantly, in Van Bueren et al. (2023), the aperiodic activity predicted improvements during tRNS in a learning task, suggesting that the moderation via TBR could be confounded with aperiodic characteristics of the power spectrum.

2.3.2 Stochastic Resonance

The current study was inconclusive in confirming the best parameters for participants with poor baseline attention skill. CFQ and TBR selectively predicted improvements during 1 mA, but not during 2 mA compared to sham, which is in line with findings supporting the stochastic resonance hypothesis for tRNS (Battaglini et al., 2023; Van Der Groen & Wenderoth, 2016). However, CoV at baseline predicted improvements at 1 mA and 2 mA compared to sham with no significant difference between the real tRNS conditions. It could be hypothesised that individuals with especially poor performance respond to a wider range of stimulation intensities, since the subthreshold brain state generally profits from added noise, also when the noise intensity diverts from the optimum. Participants with moderate performance, however, might only profit from optimal stimulation but not from a range of noise frequencies, as their brain activity might already be close to the threshold and increased currents could mask any further improvements.

2.3.3 Limitations

Since the data set was already completed before analyses begun, one limitation of the study was the measures available to analyse. Only CFQ was assessed as a baseline report of sustained attention in daily life, which has been associated

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with accuracy in sustained attention to response tasks but was less associated with response time (Smilek et al., 2010). For example, links between TBR and an attentional control scale (ACS) showed very good test-retest reliability in young female participants (Angelidis et al., 2016). Future studies should consider additional self-reported measures, such as the ACS or the Adult ADHD Self-Report Scale assessing everyday-life behaviours related to ADHD symptoms in healthy participants (Kessler et al., 2005).

Furthermore, although the cross-validation results largely agreed with traditional model comparisons, it was apparent that such measures might require more data to give meaningful and strong predictions with agreement between training and testing data sets.

The results indicated that CoV might represent the fluctuations of attention during the CMT more closely than the accuracy-based performance score. However, it is noteworthy that A' performance in this sample was close to ceiling level which means there was less variability in the scores than for CoV. Therefore, CoV might be a good score to use in context of very monotonous but simple tasks but it is possible that similar moderation could be achieved with A' in more effortful tasks.

2.3.4 Implications and Conclusion

In summary, the results revealed that not only TBR but also response variability successfully predicted a subgroup of participants with lower performance who profit more from real tRNS compared to sham. In addition, baseline TBR and performance both predicted the stimulation-related reduction in TBR. Self-reported behaviour related to attention also predicted performance gains but not change in TBR after stimulation. Overall, response variability was closely associated with the cortical marker of sustained attention and was estimated to predict stimulation improvements as well or better than TBR.

The current study had several important implications, namely identifying the close relationship between CoV and TBR which extended to stimulation-gain-related predictions that could be applied in future studies when identifying par-

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ticipants with higher probability to benefit from sustained attention interventions. Specifically, CoV has advantages over TBR in that behavioural assessment compared to a cortical marker involves reduced costs associated with the assessment and less need for manual pre-processing. This would make it more suitable for the use in personalisation systems ([Lorenz et al., 2017](#); [Van Bueren et al., 2021](#)).

3

The Effects of Task Complexity on Behavioural Indices of Sustained Attention and Mind-Wandering

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3. The Effects of Task Complexity on Behavioural Indices of Sustained Attention and Mind-Wandering

Abstract

Sustained attention is shaped by the interaction between subcortical arousal and top-down control processes, both crucial for goal-directed attention and performance, as measured by laboratory tasks. Although mind-wandering (MW) is a separate cognitive process, it frequently co-occurs with lapses in performance, reflecting behavioural outcomes. A common method to manipulate arousal and cognitive control is by adjusting task demands and complexity. This chapter aimed to examine the interplay between task complexity, arousal, and cognitive control, using behavioural performance markers and MW in an online airplane control task (ACT). In Study 1, higher coefficients of variability (CoV) were observed in longer task blocks of the monotonous condition, indicating poorer performance. However, self-reported trait attention, MW, and off-task thoughts were not significantly associated with performance. Study 2 confirmed an inverse relationship between hit rate and CoV, reinforcing a non-significant trend observed in Study 1, indicating higher hit rates in the absence of distractors. In contrast, performance in monotonous trials showed greater CoV compared to the more complex visual task. Overall, these findings suggest that the ACT effectively captured differences in task complexity through performance markers, though no direct connection to MW or off-task thoughts was identified. Future research should investigate direct links between physiological markers of arousal and cognitive control using the ACT.

3. The Effects of Task Complexity on Behavioural Indices of Sustained Attention and Mind-Wandering

Sustained attention is defined as the prolonged maintenance of goal-directed focus on an activity or objective (Boukrina & Barrett, 2017; Huang et al., 2023; Langner & Eickhoff, 2013; Strayer et al., 2023). This competence is predictive of learning outcomes in school (Gallen et al., 2023).

3.0.1 Arousal and Cognitive Control

Sustained attention performance is affected by subcortical arousal in interplay with cortical control processes (Esterman & Rothlein, 2019). On the one hand, maintaining focus is believed to be facilitated by bottom-up phasic and tonic arousal originating in the locus coeruleus with noradrenergic projections innervating fronto-parietal attention networks (Alnæs et al., 2014; Aston-Jones & Cohen, 2005; Chandler et al., 2014; Coull, 1998; Melnychuk et al., 2021; Pinggal et al., 2022). On the other hand, moment-to-moment goal-directed attention is modulated by top-down activity in frontoparietal areas supported by the frontoparietal and cingulo-opercular control system maintaining moment-to-moment task performance, task switching, and suppressing irrelevant distractors (Cosman et al., 2018; Petersen & Posner, 2012). Evidence for a close link of arousal and cognitive control to sustained and selective attention can be measured via electroencephalography (EEG) markers, pupil diameter, or psychopharmacology (Angelidis et al., 2016; Coull, 1998). For example, the slope of the EEG power spectrum, also called aperiodic exponent or 1/f activity, has been suggested to mark the cortical excitation/inhibition balance (Ostlund et al., 2021; Van Bueren et al., 2023) and is sensitive to anaesthetic or stimulant arousal manipulation but also to top-down attentional processes and has clinical relevance for patients with ADHD (Dakwar-Kawar et al., 2024; Gyurkovics et al., 2022; Pani et al., 2022; Pertermann et al., 2019; M. M. Robertson et al., 2019; Waschke et al., 2021).

Behaviourally, sustained attention is assessed via errors, response time variability, or mind-wandering (MW) reports during prolonged experimental tasks that have been associated with activity changes in sustained attention networks and the default mode network (Contò et al., 2021; Corbetta & Shulman, 2002;

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Esterman et al., 2013; Esterman & Rothlein, 2019; Kondo et al., 2023; Raposo et al., 2023; Unsworth & Robison, 2018) and perceived real-world sustained attention (Smilek et al., 2010). To capture moment-to-moment lapses, continuous and monotonous go/no-go paradigms with rapid stimulus display, e.g. Sustained Attention to Response Task (SART) or gradually shifting images, e.g. gradual Continuous Performance Task (gradCPT) in visual display have been administered widely (Kondo et al., 2023; Martínez-Pérez et al., 2021; Martínez-Pérez et al., 2023). Tasks targeting arousal processes usually involve low frequency of targets and less complexity, whereas higher demand and high frequency targets are believed to tap into executive control processes of attention (Martínez-Pérez et al., 2021; Martínez-Pérez et al., 2023).

Together, this suggests that variations in task complexity and performance may reflect changes in the brain’s underlying arousal and cognitive control states underlying sustained attention (Coull, 1998; Ma et al., 2024; Martínez-Pérez et al., 2023; Thomson et al., 2015).

3.0.2 Sustained Attention and MW

Lapses of attention can co-occur with task-unrelated thoughts, also known as MW, which are often reported via subjective self-report administered during behavioural tasks (C. A. Godwin et al., 2023; Kane et al., 2021). These thought probes usually distinguish between on-task and off-task thoughts but can further be categorised by stimulus dependency and task-relatedness to disentangle task-related and external distractions from internal task-unrelated thoughts (Stawarczyk et al., 2011; Unsworth & Robison, 2016, 2018).

Previous literature suggests some functional overlap between sustained attention failures and MW reports associated with anti correlated activity in the default mode and attention-related networks (Esterman et al., 2013; C. A. Godwin et al., 2023; Kane et al., 2021; Kucyi et al., 2016). Although markers related to arousal and cognitive control are shared (Unsworth & Robison, 2018; Van Son et al., 2019), the underlying brain networks were found to be distinct (Jin et al., 2020). However,

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on the behavioural level, a close relationship between task performance and MW has been observed, showing worse accuracy and greater variability in reaction times when thoughts are disengaged and better performance when less MW is reported (C. A. Godwin et al., 2023; Stawarczyk et al., 2020). Furthermore, both subjective task focus and sustained attention performance have previously been found to be interrupted by sleepiness (Stawarczyk et al., 2020). Despite these similarities, MW and attention lapses have been found to differently be affected by goal setting (Strayer et al., 2023), underlining the complex relationship.

MW can occur intentionally and unintentionally, varying based on time and task, and differing in the content of the thoughts involved (Martínez-Pérez et al., 2021; Seli, Cheyne, et al., 2015; Seli et al., 2017; Stawarczyk et al., 2011). Specifically, unintentional MW has been associated with poor task performance (Kane et al., 2021) and symptoms of attention deficit hyperactivity disorder (ADHD) in healthy adults (Seli, Smallwood, et al., 2015). Seli, Cheyne, et al. (2015) found that task-unrelated thoughts mediate the relationship between low task motivation resulting in lower task performance. This is important since in adolescence, low motivation in pupils with ADHD compared to their peers without ADHD predicted academic success in school (Smith et al., 2020).

Despite the undesirable effects that unintentional MW can have when we try to stay focused, both intentional and unintentional MW have been shown to negatively impact task performance (Seli, Cheyne, et al., 2015). Moreover, it has been suggested that patterns of MW were affected by task complexity, demonstrating more unintentional MW reported in a cognitive control SART task and more intentional MW during a more monotonous performance task (Martínez-Pérez et al., 2021). The authors also found a steady increase of unintentional MW during a task requiring more cognitive control, whereas MW only increased at the beginning of the monotonous task and remained stable later (Martínez-Pérez et al., 2021).

This suggests that while MW is a distinct process from inattentiveness, both are closely intertwined and often triggered by similar situations and environments. As a result, the two processes are not always easily distinguishable based on behavioural

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measures alone. Both the presence and intention to mind wander along with factors such as task motivation and sleepiness are crucial considerations when assessing the relationship between sustained attention and MW.

3.0.3 The Current Chapter

The primary aim of this chapter was to explore how behavioural performance and MW differ in an online paradigm. To achieve this, I adapted a simulated air traffic controller task (Nelson et al., 2014), from here onwards referred to as airplane control task (ACT) to create two distinct conditions: a monotonous, low-visual-load condition that was expected to require optimal arousal to maintain sustained focus over time, and a high-demand version with distractor stimuli, designed to engage cognitive control processes while maintaining the same motor demands and task instructions. Task performance was assessed using trial accuracy and coefficient of variation (CoV) over task blocks.

Furthermore, I used thought probes to distinguish MW from task-related and unrelated distractions, evaluating not only the simple on-task vs. off-task distinction but also a more refined comparison between MW and distraction states. Additionally, I assessed how MW varied across task conditions, factoring in participants' intention to mind wander, motivation, and sleepiness. To examine how performance and MW shift over shorter and longer time periods, and to prevent the anticipation of thought probes, I introduced varying block durations (Stawarczyk et al., 2011; Unsworth & McMillan, 2014).

Finally, I aimed to test the transferability and generalisation of effects from this online paradigm to real-world outcomes, measured as self-reported trait attention (Broadbent et al., 1982; Kessler et al., 2005). Few studies to date have applied online sustained attention tasks, addressing media multitasking Ralph et al. (2015), or ageing Fortenbaugh et al. (2015), however, this is the first study to investigate sustained attention and MW during monotone and demanding computerised tasks.

3.1 Study 1

3.1.1 Preregistered Hypotheses

Firstly, I hypothesised that CoV as a main effect and in interaction with task complexity would predict how focused participants rated themselves to be after each task block. 1.1 I expected that better performance in the ACT would predict more on-task ratings overall, and in the non-distractor condition compared to distractors. 1.2 The same prediction was made for MW reports, where better performance was expected to predict less MW specifically in the non-distractor condition.

Secondly, I was interested in the associations of sustained attention in a laboratory task with reports of sustained attention in daily life via questionnaires. 2.1 I predicted average performance variability by the Cognitive failures questionnaires (CFQ). 2.2 I also predicted average performance variability by the Adult ADHD self-report scale (ASRS). The expected results would show that participants with less every-day attention difficulties were predicted to have a more stable performance (lower CoV) in the ACT.

Lastly, I predicted MW by the same two questionnaires as in (2.). 3.1 These models also included the intentionality to mind wander and it was expected to find an interaction, where attention scores from CFQ and 3.2 ASRS are predictive of MW to a stronger degree, the more spontaneous MW is reported and less when MW is reported to be more deliberate on average.

3.1.2 Methods

The study was preregistered ([10.17605/OSF.IO/UFYPR](https://osf.io/UFYPR)) for the monotone task condition (no distractors) and ([10.17605/OSF.IO/384CB](https://osf.io/384CB)) for the demanding task condition (distractors). The experiment featured two task conditions of the ACT, one replicated from a previous paper which was preregistered individually as a replication study to examine the effects of MW and task performance in an online setting. The other task condition adapted the original task to pilot the effects of distractors in the same search task and was preregistered separately as a preliminary

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novel design. Since the task conditions were administered together, the analysis was performed as one study.

Participants

For the current online study, a sample of healthy, young adults was recruited via Prolific which estimated a pool of 5767 eligible registered users. Participants were eligible if they were between the ages of 18 and 35, right-handed with normal or corrected-to-normal vision. English was required to be their first language, and participants must have spent most time before the age of 18 in the UK. Only healthy individuals, specifically without diagnosed ongoing mental health conditions, Autism Spectrum Disorder, Mild Cognitive Impairment, or dementia were eligible. In addition, only subjects with a good record of study participation on Prolific, namely previous approval rate of 90% or higher and a minimum of 50 submissions were recruited.

Fifty participants completed the session and reported good effort and data quality. All participants gave informed consent prior to the study and were reimbursed for their time at the rate of £7.50/hour. Ten additional participants returned the study before completion without payment and one additional participant did not finish the study before the time limit without payment. Four additional participants experienced technical difficulties after spending considerable time and effort in the study and were reimbursed, but no data was obtained. One person reported their data not of good quality and was excluded but reimbursed. Ethical approval was granted via Medical Sciences Interdivisional Research Ethics Committee (R76911/RE001).

Apparatus and Materials

The experiment was built in PsychoPy (V 2021.1.4) and uploaded to Pavlovia.org. The online study was conducted in full screen on participants' personal computer or laptop via Internet browser, 40 participants completed the experiment on Windows,

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8 on a MacIntel system and 2 on other systems. Mean frame rate was 61.92 (SD=18.92). The experimental session took approximately 40 minutes.

Stimuli. Stimuli were adapted from an air traffic controller task (Nelson et al., 2014). Participants were presented with static stimuli resembling an airplane radar that appeared in rapid succession on the screen (see Fig. 3.1). In each trial, participants saw 4 black triangular shapes representing airplanes, one in each quadrant of the circular radar. Either all airplanes were travelling in the same direction, clockwise or anti-clockwise (congruent), or one of the four airplanes travelled opposite the other 3 airplanes, clockwise or anti-clockwise (incongruent). Half of the blocks featured only stimuli with four distractors spaced out between the four airplanes, the other half was presented with additional distractor stimuli. Distractors were black bird shapes of similar size as the airplanes. Participants were instructed to respond to frequent congruent stimuli (89%) by pressing ‘b’ and to press ‘space’ for infrequent incongruent stimuli (11%) on their keyboard. Sub-blocks were counter-balanced and randomised.

Thought Probes. A shortened version of the multi-dimensional experience sampling (MDES) was administered between task sub-blocks to retrospectively gain insight into the extent and content of thoughts reported during the task block. Questions were rated on a discrete scale between 1 and 7 and addressed the amount of on- and off-task thoughts and the intentionality, marking more off-task thoughts and more spontaneous thoughts lower on the scale compared to more on-task thoughts and deliberate MW (Poerio et al., 2017).

MW Probe. In addition, on- and off-task thoughts were rated by a single item together with the experience sampling. The probe required a choice between five types of thoughts: 1) being totally focused on the task, 2) task-related interferences, 3) external distractions, stimulus-independent, 4) zoning out/MW, and 5) Other (Stawarczyk et al., 2011; Unsworth & McMillan, 2014). This rating was to control for off-task thoughts not classified as MW.

Stanford Sleepiness Scale. Sleepiness was assessed as a subjective single-item scale on the degree of perceived sleepiness at a specific moment in time rated

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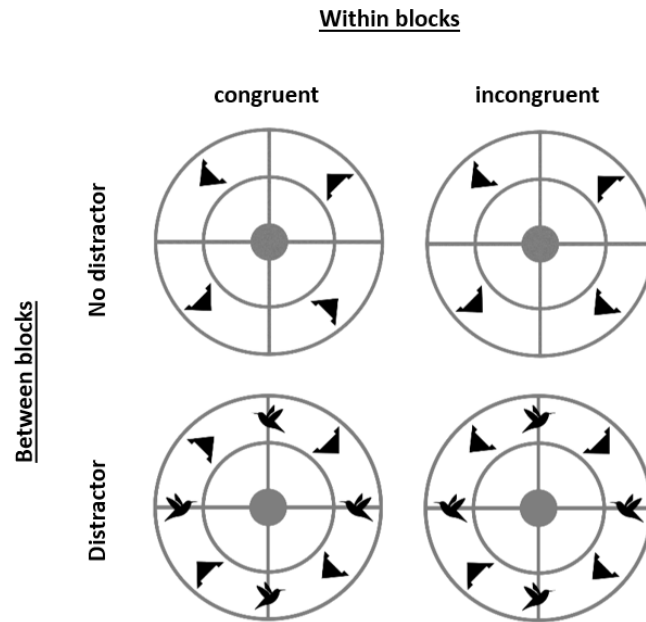


Figure 3.1: Stimuli. Examples of the airplane radar stimuli including 4 airplane shapes on a radar background. Within blocks, airplanes were either oriented in the same direction either clockwise or anti-clockwise (congruent, 89%), or one airplane travelled opposite the others either clockwise or anti-clockwise (incongruent, 11%). Between blocks, the distractor condition was manipulated.

between 1-“Feeling active and vital; alert; wide awake” and 7-“Almost in reverie; sleep onset soon; lost struggle to remain awake” (Herscovitch & Broughton, 1981; Hoddes et al., 1972). Sleepiness was assessed before the task and between blocks.

Motivation. With a single-item scale we assessed task motivation between 1-“not motivated at all” and 7-“very motivated” before the task and with each MW probe. Participants were asked to report “How motivated were you to perform well on the task?” (Unsworth & McMillan, 2013).

Cognitive Failures Questionnaire (CFQ). Self-reported failures in perception, memory, and motor actions related to MW and lapses in attention were assessed via CFQ (Broadbent et al., 1982). The total CFQ score consists of 25 items on a 5-point scale, where a higher total score indicates stronger tendencies for difficulties in daily life.

Adult ADHD Self-Report Scale. The ASRS was assessed using 18 items

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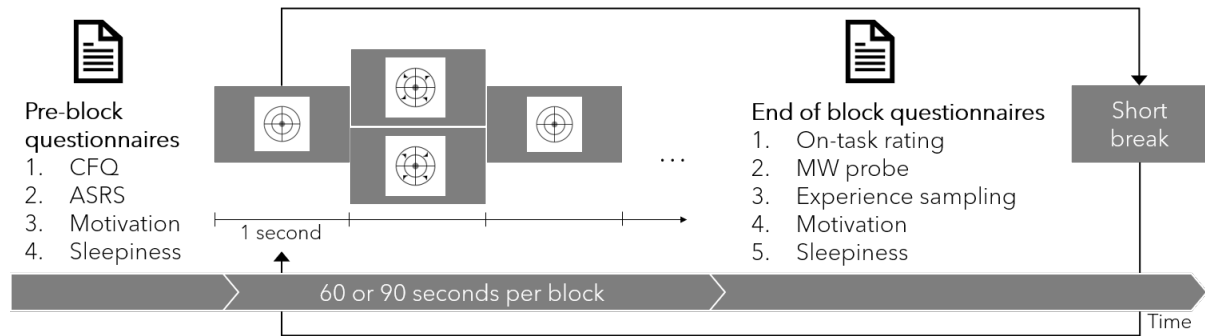


Figure 3.2: Procedure. During the session, participants first completed the CFQ and ASRS questionnaires, followed by rating their motivation and sleepiness before the 8 ACT blocks began. A block contained congruent (89%) and incongruent trials (11%) for which participants pressed the respective keys on their keyboard (F and J). Task blocks were either without or with distractor items in each trial and lasted either 60 or 90s (randomised). After each task block, participants rated on-task behaviour, categorised their thoughts in the MW probe, gave more details through the experience sampling, and rated their motivation and sleepiness in the previous block.

rated on a 5-point scale. The ASRS questionnaire was used to assess individual differences in daily behaviour related to ADHD in a healthy sample. Specifically, the sub scale of inattention (ASRS IA) computed from the six first questions (part A) was reported in this study (Kessler et al., 2005).

Data Quality Items. Using data quality items, the continued effort of online participants to complete the experiment to the best of their abilities was assessed to determine data that had to be excluded. The first exclusion criterion was when participants reported data quality as bad at the end of the study. Secondly, quality assessment items that were not part of the questionnaires and scales and were added during the experiment instructing the participant to rate these items as “7”. One control question was placed as item 23 within the CFQ questionnaire form, and another one was placed within the thought probes at the end of each block.

Procedure

The study was advertised via Prolific and hosted on Qualtrics (Information sheet, consent, demographics, CFQ and ASRS questionnaires) and on Pavlovia (ACT, MW sampling, motivation, and sleepiness). After reading the study information, participants gave consent online. All participants performed the same set

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of tasks and questionnaires, see Fig. 3.2. First CFQ and ASRS questionnaires were filled out, followed by a practice of the ACT and MW reports. The ACT practice was split into a slow practice of 20 trials with 6 s per stimulus and feedback (sets of 5 trials with and without distractors) and a practice of 75 trials at expected speed with 1 s per stimulus without feedback (sets of 9/10 trials with and without distractors). Practice for the MW probe encompassed 10 example thoughts that had to be categorised correctly, see Tab. B.1. Next, participants reported their motivation and sleepiness at baseline and then completed 8 blocks of the ACT. The blocks were randomised to either feature distractor stimuli in each trial or no distractors at all and to either be 60s (30 stimuli) or 90s (45 stimuli) long. Immediately after each ACT block, thought content and MW probes, motivation and sleepiness ratings were taken. Thought probes always began with the on-task rating followed by the MW probe, followed by the remaining items rating thought content, motivation, and sleepiness. Participants were given the option of a short break. At the end of 8 blocks, participants were thanked for participation and automatically redirected to prolific for completion and payment of the study. A completion code was displayed in case the redirection did not work. Participants were reimbursed upon experimenter approval via prolific.

Data Analysis

All analyses were performed in R (Version 4.3.0) using custom scripts.

Outliers and Exclusion. For the ACT, individual blocks were excluded where less than 40% of stimuli had been responded to or hit rate deviated more than 3 SD from the mean in any individual block. A valid button press occurred between 150ms and 1000ms after stimulus onset.

Attention Measures. Sustained attention was quantified using self-rated scores from every-day life questionnaires and task performance.

Hit Rate. The hit rate during the ACT was calculated by dividing the number of correct timely responses by the total number of stimuli in a given block.

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Coefficient of Variation (CoV). In this study we use the CoV as an approximation for sustained attention fluctuations (Harty & Cohen Kadosh, 2019). The CoV reflects response time variation over time and is calculated for all correct responses in each task block (60s or 90s) and reflects the standard deviation (SD) of response time controlled for mean response time: $CoV = \frac{SD_{RT}}{mean_{RT}}$.

Linear Models. Mixed effect models were fit using the lmer function from *lme4* package from R when predicting continuous dependent variables, and using glmer for generalised linear models (binomial and poisson). Ratings on a scale from 1 to 7 were treated as continuous predictors in the mixed models since the distance between rating values could be assumed to be equal. All continuous predictor variables were centered to avoid adverse effects of multicollinearity (increase in type 2 errors due to correlation between covariates) between continuous interaction terms resulting in all GVIF^{(1/(2*df))} <2, or VIF <3 which are conservative thresholds used in the literature (Fox & Monette, 1992; Zuur et al., 2010). A type-III test was run for each model to examine the significance of joint effects for all the variables in the model using F-statistics for continuous predictors and Chi-square statistics for generalised linear models. This is more suitable for complex models than reporting the fixed effects calculated for each effect independent of the other variables in the model. All models were initially formulated as full models with ID as random effect, and the respective predictors as random slopes. The models were then reduced in R by estimating the explained variance of the random effects and slopes and confirming whether the reduced model was not significantly different from the initial model using a Chi² test (*anova* package). In case of a remaining singular fit, the model complexity was further reduced, by eliminating random effects, slopes and fixed effect interactions according to least variance explained. Model performance was reported via R² statistics (adjusted for linear and generalised linear models and conditional for mixed effect models). Post hoc effects and trends were reported using *emmeans*.

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3.1.3 Results

Sample

The final sample included 43 participants (age 19-35, $M = 27.37$, $SD = 4.6$, 24 female). Of the initial 50 completed data sets, 4 participants were excluded due to failing more than 60% of the data quality checks (total 9 questions). Furthermore, 3 participants that responded to less than 75% of total trials throughout the experiment were excluded.

Performance and Task Manipulation

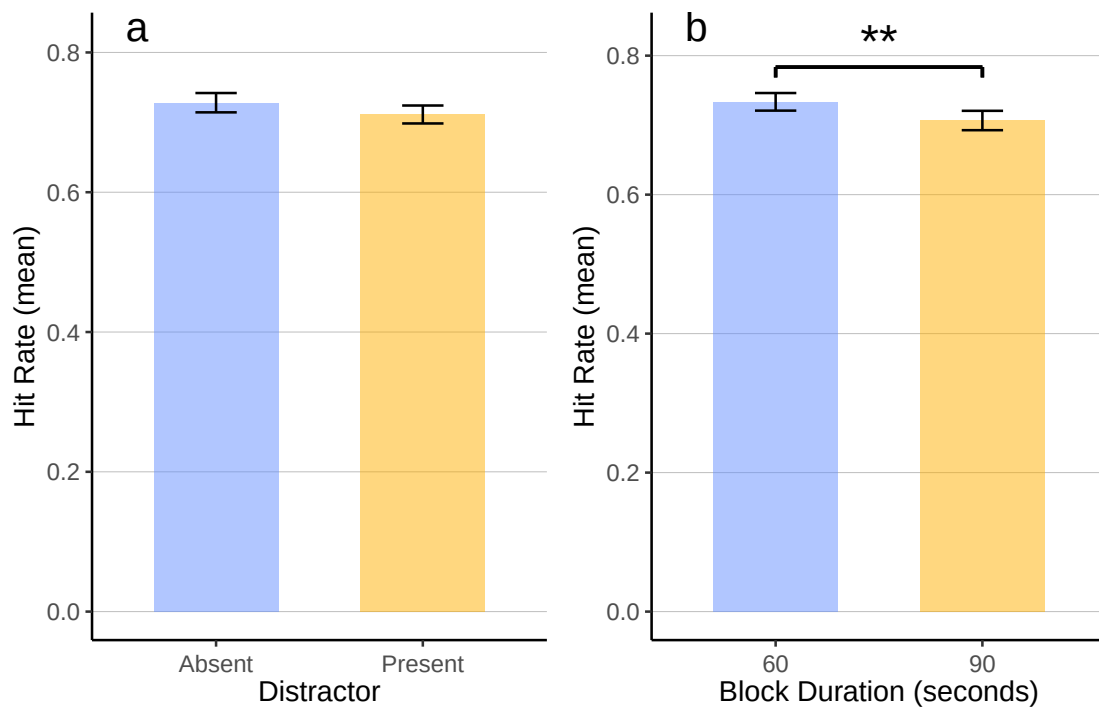


Figure 3.3: T-test results. a. Mean hit rate did not significantly differ in blocks with distractor absent compared to blocks with distractor present. b. Mean hit rate in shorter blocks (60s) was significantly greater than in longer blocks (90s). Error bars signifying standard error of the mean. Significance marked by **: $p < .01$.

Data of 21 experimental blocks (6.1%) from 10 participants were removed due to low total responses given (<40%) or low performance (hit rate deviated more than 3 SD). Out of the included participants, no additional participant was excluded

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for 4 or more excluded blocks throughout the session. Participants mean hit rate was 70% ($SD=16$) and CoV was $M=0.19$ ($SD=0.1$). Details on the distribution of response times and hit rate can be found in Fig. B.1

As shown in Fig. 3.3 b, performance in shorter blocks ($M=0.73$, $SD=0.17$) was significantly better than in longer blocks ($M=0.71$, $SD=0.18$), $t(42)=2.57$, $p=0.007$, $d=0.39$ suggesting that a difference of 30 s in block duration had an verifiable impact on performance.

Hit rate was higher in the non-distractor condition ($M=0.73$, $SD=0.18$) compared to the distractor condition ($M=0.71$, $SD=0.17$) but the difference was not significant, although it showed the expected trend ($t(42)=1.42$, $p=0.082$, $d=0.22$), indicating that the distractor condition designed as more demanding was not different enough to the visually more monotone non-distractor condition (see Fig. 3.3 a).

Table 3.1: Correlating Sustained Attention Measures

Variable	CoV	Hit Rate	On-task Rating	Motivation	Sleepiness	ASRS (IA)	CFQ
CoV	1.00						
Hit Rate	-0.13	1.00					
On-task Rating	-0.40**	0.06	1.00				
Motivation	-0.40**	0.06	0.82***	1.00			
Sleepiness	0.41**	-0.03	-0.71***	-0.67***	1.00		
ASRS (IA)	-0.00	-0.10	-0.15	-0.27	0.33*	1.00	
CFQ	0.11	-0.13	-0.21	-0.28	0.27	0.82***	1.00

Notes. Spearman correlation coefficients between all mean outcome measures.

Significance is marked as ***: $p < .001$, **: $p < .01$, *: $p < .05$.

For later analyses, we correlated the main outcome variables (see Tab. 3.1). In this sample, participants' CoV correlated negatively with how well they rated their task focus, motivation and positively with sleepiness, indicating most stable performance co-occurred when participants were on-task, motivated and feeling most awake. Motivation and sleepiness, as well as ASRS IA and CFQ scores,

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correlated highly with one another. In addition, ASRS IA correlated significantly with sleepiness scores. However, there were no other significant correlations between questionnaire scores and task-scores, or -ratings or hit rate and other experimental measures.

For correlating variables in the following mixed effect models, I'm using centered variables to reduce multicollinearity.

Preregistered Analyses

First, I examined whether task performance could predict participants' subjective ratings of being focused on the task and rating their thoughts as MW (Hypotheses 1.1 and 1.2). Then, I used everyday life questionnaires (CFQ and ASRS IA) to predict mean task performance (Hypotheses 2.1 and 2.2) and mean rating of MW (Hypotheses 3.1 and 3.2) in interaction with the intention to mind wander.

Task Ratings vs. Task Performance. Since the preregistered mixed model resulted in a singular fit, the random effects were removed and a generalised linear model was fit using a poisson distribution. The results (see Tab. B.2) suggested a significant main effect of motivation ($p = <.001$) with a slope of $\beta = 0.09$ ($SE = 0.02$, $95\%CI = [0.05, 0.13]$, adjusted $R^2 = 0.53$), see Fig. 3.4. Contrary to the prediction, there was no significant effect of CoV, although it followed the expected trend ($p = 0.101$).

Furthermore, I ran the same model predicting MW including random slopes for CoV, distractor, and block duration. However, the reduced model only including one random effect of subject over fitted the data and was further reduced as a generalised linear model without random effects. Apart from a main effect of motivation ($p = <.001$) with a slope of $\beta = -1.63$ ($SE = 0.31$, $95\%CI = [-2.25, -1.01]$, and a main effect of sleepiness ($p = <.001$) with a slope of $\beta = 0.92$ ($SE = 0.26$, $95\%CI = [0.42, 1.42]$, see Fig. 3.5), no predictors were significant when predicting participants' MW reports ($R^2 = 0.58$). Contrary to the prediction, CoV did not predict the amount of MW during task blocks ($p = 0.57$), see Tab. B.3.

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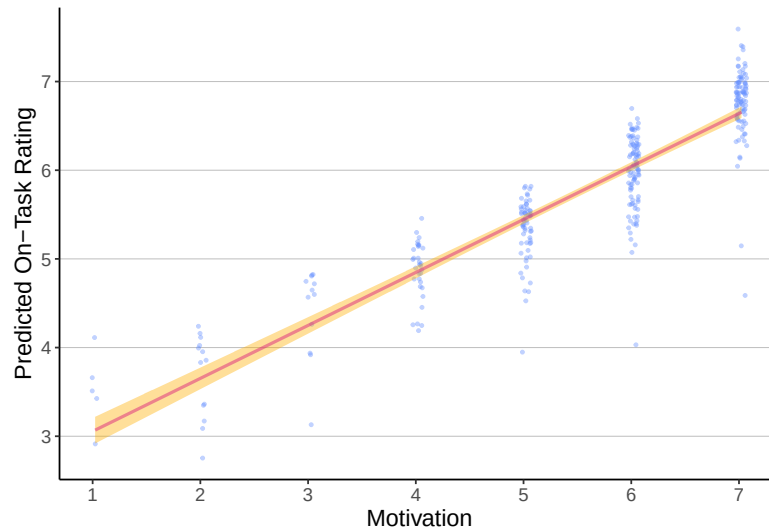


Figure 3.4: Task motivation rated between 1 and 7 (1 = not motivated, 7 = completely motivated) predicted participants' ratings on how well they perceived themselves to be focused on the task, on a scale from 1 to 7 (1 = completely off-task, 7 = completely on-task), $p < .001$. The shaded area represents the 95% confidence interval of the estimates. Predicted task focus values are displayed in blue.

Task Performance and Rating vs. Questionnaires. To examine whether the ACT paradigm reflects attention skill in daily life, CFQ (adjusted $R^2 = 0.39$, see Tab. B.4) and ASRS IA responses (adjusted $R^2 = 0.4$, see Tab. B.5) were used to predict mean response variability during the task. In both models, the only significant effect on CoV were sleepiness ratings during the task suggesting that self-perceived attention skills extracted from the CFQ ($p = < .001$) with a slope of $\beta = 0.05$ ($SE = 0.01$, $95\%CI = [0.03, 0.07]$) and the ASRS IA ($p = < .001$) with a slope of $\beta = 0.05$ ($SE = 0.01$, $95\%CI = [0.03, 0.07]$) did not predict performance on the ACT in this sample.

To examine whether MW during the ACT reflected attention skill in daily life, CFQ (adjusted $R^2 = 0.41$, see Tab. B.6) and ASRS (IA) scores (adjusted $R^2 = 0.37$, see Tab. B.7) were used to predict mean MW ratings during the task. In both models, the effect of questionnaire on MW was not significant, suggesting that the amount that participants reported themselves to mind wander during the ACT was not significantly predicted by self-perceived attention in every day life. However, the intention to mind wander predicted the amount of MW in the model including

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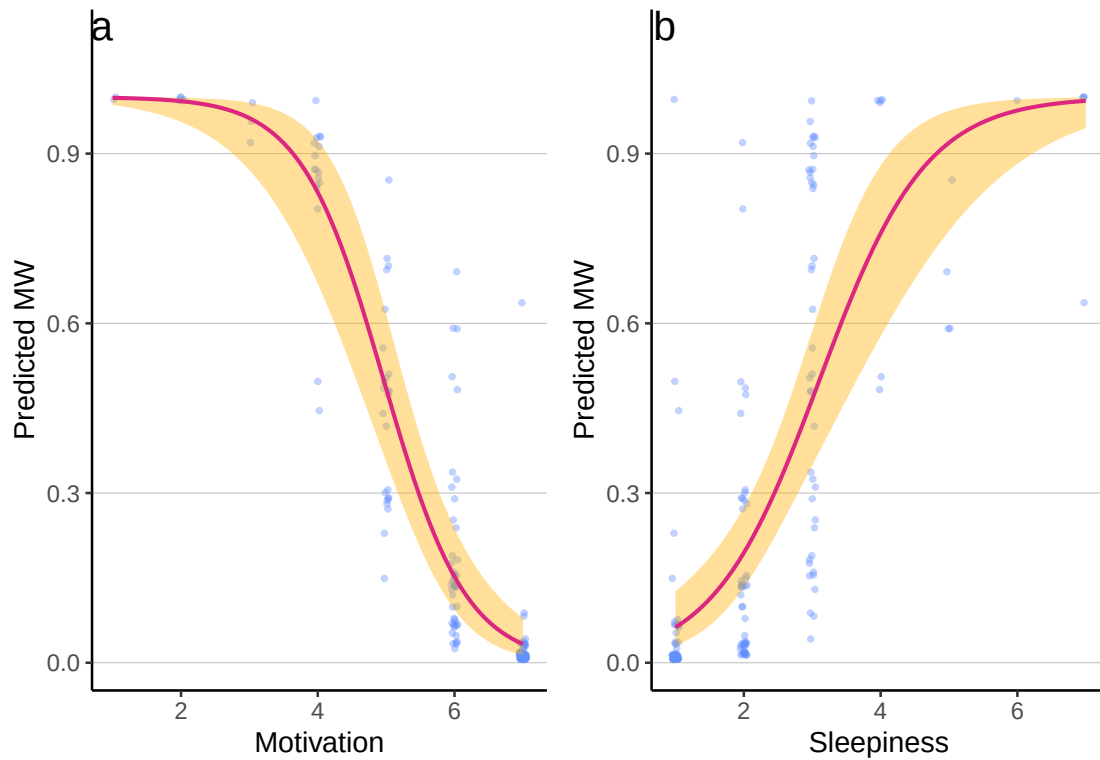


Figure 3.5: MW rating (0 = totally focused on the current task, 1 = zoning out/MW) was predicted by motivation a) and sleepiness b) in this generalised linear model. a. Higher motivation during the previous task block predicted less MW ratings than on-task ratings. b. In contrary, greater sleepiness predicted more MW ratings than on-task thoughts. The shaded areas represent the 95% confidence interval of the estimates. Predicted MW values are displayed in blue.

ASRS IA ($p = 0.025$) with a slope of $\beta = -0.1$ ($SE = 0.04$, $95\%CI = [-0.2, -0.01]$), but not in the model including CFQ ($p = 0.052$) with a slope of $\beta = -0.09$ ($SE = 0.04$, $95\%CI = [-0.18, 0.001]$), indicating that high levels of MW were associated with a reduced intention to mind wander. No effects of motivation or sleepiness were significant in either model.

Exploratory Analyses

MW Intention. To explore further, whether the effect of MW intention on MW ratings was significant without the influence of CFQ or ASRS (IA), the previous regression model was reformulated as a mixed effect model including only MW intention, motivation and sleepiness (adjusted $R^2 = 0.65$, see Tab. 3.2). Random slopes were reduced to avoid over-fitting. Here, the intention to mind wander also

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predicted the amount of MW ($p = <.001$). This indicated that whether thoughts were more spontaneous or more deliberate had an impact on the amount that MW.

Table 3.2: MW Predicted by Intention to Mind Wander

model term	Chi-square	df	p
MW Intention	33.71	1	<.001
Motivation	32.21	1	<.001
Sleepiness	0.78	1	0.378

The Table shows the joint test for the mixed model mean
MW report $\sim$ MW intention + motivation + sleepiness+ (1|
subject) predicting MW by intention to mind wander.

Hit Rate. I explored the effects of the task conditions on hit rate to understand whether task manipulations, i.e. block duration and distractor condition could predict a change in accuracy (conditional $R^2 = 0.67$). The full model was reduced to avoid random slopes with 0 variance and a singular fit. The result showed no significant main effect of distractor ($p = 0.054$) on hit rate, see Tab. B.8. This result indicated that the difference in accuracy between distractor and non-distractor blocks was too small to be found significant in this sample.

Response Variability. Next, I explored the effects of the task conditions on CoV to understand whether responses would become more variable with or without distractors, in longer or shorter blocks or with time on task (conditional $R^2 = 0.71$), see model results in Tab. B.9.

Main effects of block duration ($p = 0.017$) with a mean CoV of 0.17 ($SE = 0.01$, $95\%CI = [0.15, 0.19]$) in shorter blocks compared to longer blocks with a mean CoV of $M = 0.18$ ($SE = 0.01$, $95\%CI = [0.16, 0.2]$), and a main effect of sleepiness ($p = <.001$) with a slope of $\beta = 0.02$ ($SE = 0$, $95\%CI = [0.01, 0.03]$) were significant, see Fig. 3.6. Additionally, the interaction between block duration and distractor condition was significant ($p = 0.031$), see Fig. 3.7. Mean CoV in non-distractor blocks was higher in longer blocks $M = (0.19, SE = 0.01, 95\%CI = [0.17, 0.21])$ compared to shorter blocks $M = (0.17, SE = 0.01, 95\%CI = [0.15, 0.19])$, but similar

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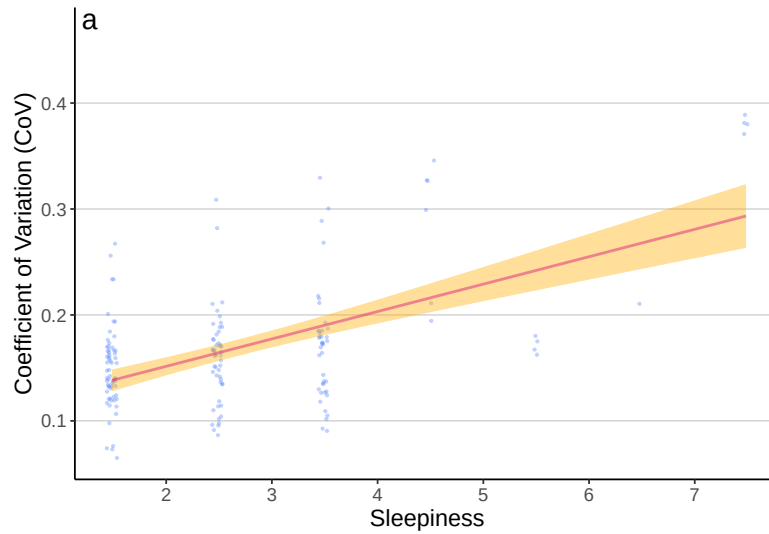


Figure 3.6: Sleepiness rated between 1 and 7 (1 = feeling active/vital/alert, 7 = sleepy/woozy/fighting sleep) predicted CoV during the task, with higher variability in responses when sleepiness was rated high ($p < .001$). The shaded areas represent the 95% confidence interval of the estimates. Predicted CoV values are displayed in blue.

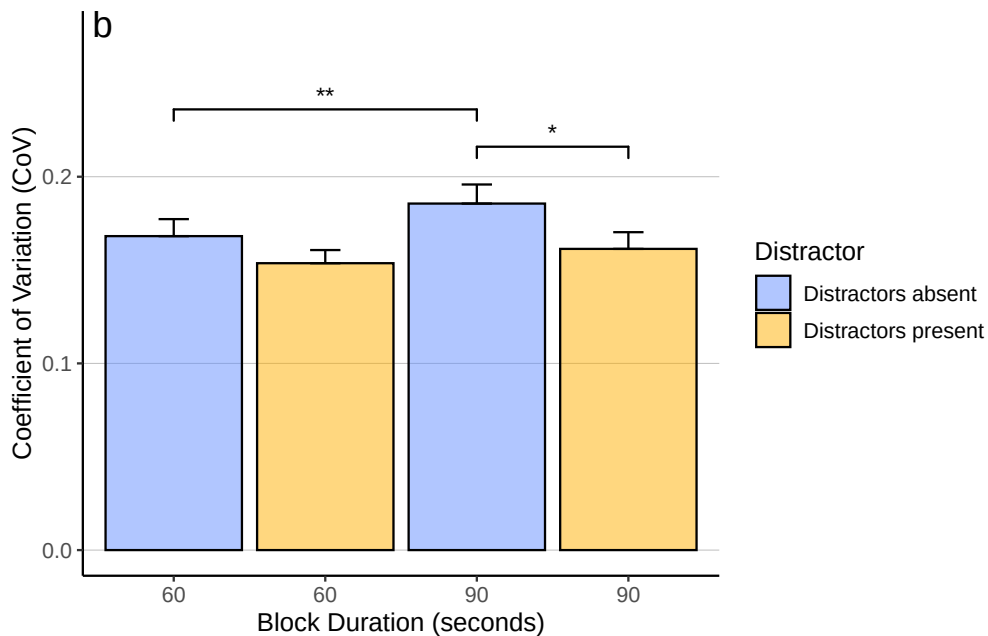


Figure 3.7: There was an interaction of block duration (60s or 90s) and distractor condition (absent or present) when predicting CoV during the task. CoV was higher in longer, non-distractor blocks compared to shorter, non-distractor blocks. CoV was also higher in non-distractor blocks compared to distractor blocks but only for long blocks (90s). Error bars signifying standard error of the mean. Significance marked by **: $p < .01$, *: $p < .05$.

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in distractor blocks for short $M=(0.17)$, $SE= 0.01$, $95\%CI= [0.15, 0.19]$) and long blocks ($M=0.17$, $SE= 0.01$, $95\%CI= [0.15, 0.2]$). This result demonstrated that when distractors were absent, performance was better in shorter than longer blocks. When blocks were longer, performance was better in more complex blocks.

3.1.4 Summary Study 1

An exploratory analysis revealed that an interaction between the duration of blocks and the distractor condition predicted a difference in response variability. CoV was worse in longer compared to shorter non-distractor blocks. Most importantly, performance was worse in non-distractor blocks compared to distractor blocks but only for blocks lasting 90s. In addition, CoV was predicted by sleepiness. These effects were not mirrored by hit rate. Although a t-test revealed more accurate responses in shorter (60s) compared to longer blocks (90s), the main effect was not significant in the exploratory mixed effect model. There was a trend of better hit rate in non-distractor compared to distractor blocks, but there was no significant difference in a t-test or the exploratory moderation analysis. This indicated that accuracy of performance was not significantly affected by the task manipulation. Compared to hit rate, these result could indicate that CoV was more sensitive to capture differences in performance on the task in an unexpected direction. The discrepancy could suggest that the ACT with and without distractors was similarly difficult to accurately respond to but it was more difficult to respond consistently when no distractors were present.

Differently to the predictions, MW reports were not predicted by task manipulation or performance, sleepiness and motivation but motivation was a significant predictor for how task-focused (including task-related and external distractions) participants rated themselves during task blocks. In addition, exploratory results showed that spontaneity of thoughts was predictive of MW. However, the CFQ and ASRS (IA) did not predict task performance or whether participants were MW during the task.

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The current study was the first to adopt the SART-like airplane task to compare continuous performance in monotone and complex search environments directly to one another. Yet, differences between all task conditions were relatively small, and there were no effects of block, suggesting no improvement or decline of performance over time in the relatively short task. It is possible that randomising the distractor and non-distractor blocks might have had a stimulating impact on participants' ability to stay on task.

3.2 Study 2

In Study 2, I planned small adjustments to increase the differences in experimental conditions while keeping the task short enough for online participants to stay motivated to complete it. The study was carried out to replicate the results of the first study in a new sample. The visual stimuli were altered to make the airplanes and birds more difficult to distinguish in the distractor condition. Blocks were administered for a longer time to increase the amount of trials and the chances for off-task thoughts including MW. Furthermore, blocks for each condition were administered sequentially, only randomising whether participants started with 4 distractor or 4 non-distractor blocks. This change was made to increase any effects of condition across blocks. The effect of order was added as an additional covariate in all relevant analyses.

3.2.1 Preregistered Hypotheses

In this online study we planned to replicate the results of Study 1, using the same online attention task, with minor adaptations, in a new sample of healthy adults. There were three main hypotheses regarding hit rate, CoV and on-task rating.

1. Performance measured by hit rate was expected to be more accurate when distractors were absent compared to when they were present in the ACT. Study 1 showed a non-significant decrease in performance with introduction of distractors, although with a p-value close to significance, which was expected

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to be amplified by the introduction of more similar airplane stimuli to the distractor shapes. Furthermore, more data collected via longer blocks was predicted to show a significant difference when predicting hit rate. Similarly, it was expected to find significantly better performance in shorter (90s) than in longer blocks (180s) due to the sustained attention component.

2. Based on the results of Study 1, response variability was predicted to be lower in longer compared to shorter blocks and CoV was expected to show an interaction between distractor and non-distractor blocks such that response variability is greater during the more monotonous task condition. I also expected to see an effect of block showing an increased CoV over time on task.
3. On-task ratings were predicted to decrease with larger CoV during the ACT and with time-on-task based on changes made to the task. Time-on-task was increased overall in this replication study using longer task blocks and was expected to have an impact on the reported task focus. In Study 1, CoV was not significantly predictive of the rating but had a p-value relatively close to significance.

3.2.2 Methods

Methods of Study 2 are largely identical to Study 1 with few minor adaptations as outlined in this section. The study was preregistered ([10.17605/OSF.IO/2A6S8](https://osf.io/2A6S8)) on [<https://osf.io/2a6s8>](https://osf.io/2a6s8).

Participants

The recruitment and inclusion process was identical to Study 1. A total of 74 participants from an estimated pool of 2,874 eligible registered users completed the online study. All participants gave informed consent prior to the study. Ethical approval was granted via Medical Sciences Interdivisional Research Ethics Committee (R76909/RE001).

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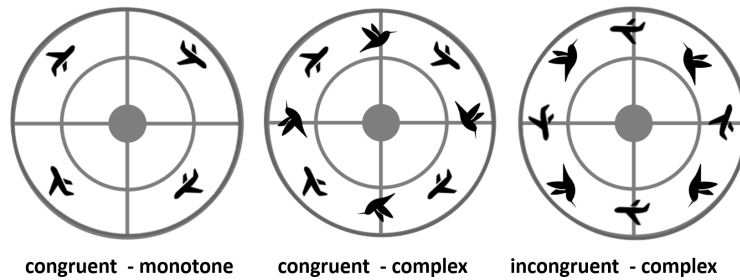


Figure 3.8: Stimuli. Examples of the adapted airplane radar stimuli including 4 airplane icons on a radar background either flying in the same direction (congruent - 89%) or one plane deviating from the flight direction (incongruent - 11%). Left: Monotone blocks only displayed 4 airplanes without distractor birds and at a stable position of the airplanes (no airplane at 12 o'clock). Centre and Right: Complex trials featured the 4 airplanes with distractors in between airplanes and randomised positioning (airplanes/birds at 12 o'clock).

Apparatus and Materials

The experiment was built in PsychoPy (V 2021.1.4) and uploaded to Pavlovia.org. The online study was displayed in full screen on participants' personal computer or laptop via Internet browser and took approximately 40 minutes. 29 participants completed the experiment on Windows, 12 on a MacIntel system and 4 on Linux. Mean frame rate was 63.62 ($SD= 31.08$).

Stimuli. Stimuli from Study 1 were visually refined by exchanging the triangular abstract airplane shape with a more life-like airplane icon, similar to the birds used as distractors. Different to Study 1, the positions of the distractors and airplanes in the distractor condition were alternating and evenly spaced with either an airplane or a bird icon positioned on 12 o'clock of the radar. Congruency, randomisation and responses remained the same as in Study 1.

Questionnaire items. All other materials (CFQ, ASRS, thought and MW probes, sleepiness, motivation, and data quality assessments) were the same as described in Study 1.

Procedure

The experimental session structure remained the same with exception of practice trials, block order randomisation, and block duration. Practice trials in the

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ACT were shortened to a slow practice of 10 trials with 6 s per stimulus and feedback (sets of 5 trials with and without distractors) and a practice of 45 trials at expected speed with 1 s per stimulus without feedback (sets of 22/23 trials with and without distractors). Block order was not fully randomised, but 4 consecutive non-distractor blocks and 4 consecutive distractor blocks were presented for each participant with starting block randomised instead. Block duration was increased from the previous 60s and 90s, to 90s (short; 45 stimuli) and 180s (long; 90 stimuli).

Data Analysis

The analysis was performed using mixed effect models and linear models as described in Study 1. To correct for any effects of block order, the starting blocks were entered as covariate in models investigating task manipulations.

3.2.3 Results

Sample

Out of the 74 collected participants, 2 reported insufficient data quality or did not pass the data quality checks, a further 25 responded to less than 75% of total trials. In addition, 2 participants had more than 4 out of 8 task blocks excluded since less than 40% of trials were available or hit rate deviated by more than 3 standard deviations. The final sample included 45 participants (age 19-35, $M = 27.8$, $SD = 4.46$, 29 female).

Performance and Task Manipulation

Data of 65 experimental blocks (18.06%) from 31 participants were removed due to low total responses given ($<40\%$) or low performance (hit rate deviated more than 3 SD). Participants' mean hit rate was 80% ($M = 0.8$, $SD = 0.11$) and CoV was $M = 0.19$ ($SD = 0.1$). As shown in Fig. 3.9 a), hit rate was significantly higher ($t(42) = 1.7$, $p = 0.049$, $d = 0.26$) in the non-distractor condition ($M = 0.81$, $SD = 0.11$) compared to the distractor condition ($M = 0.79$, $SD = 0.12$) indicating that the distractor condition in Study 2 was, as designed, more demanding than the non-distractor condition.

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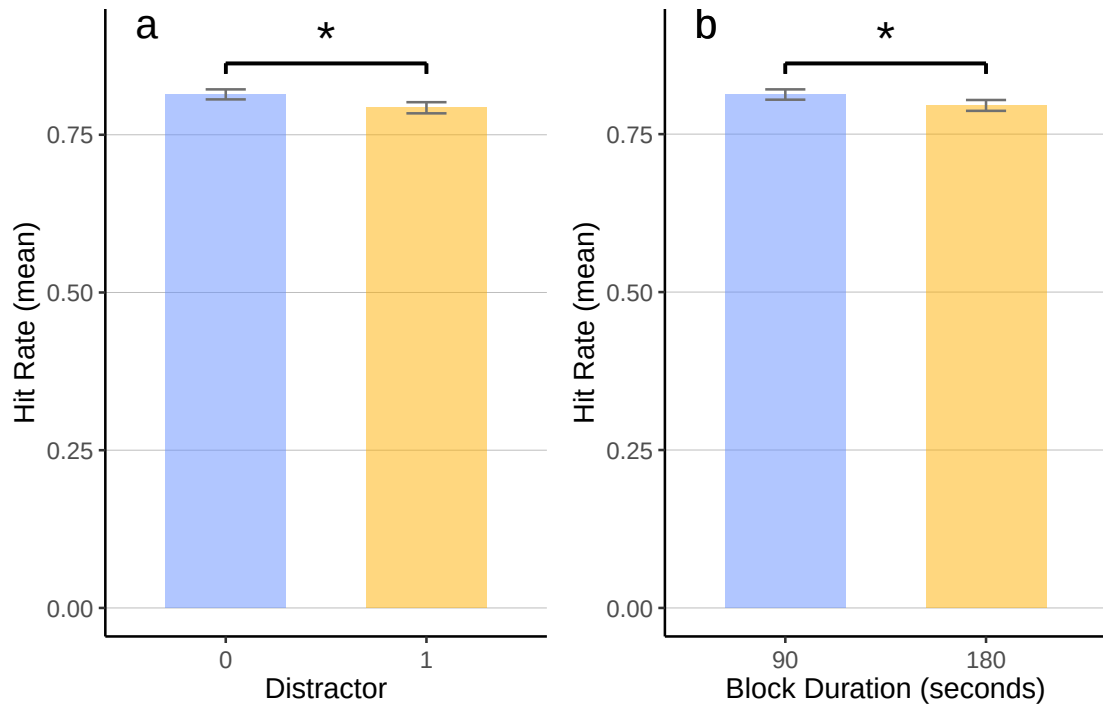


Figure 3.9: T-test results. a. The mean hit rate was significantly greater in blocks with distractor absent than in blocks with distractor present. b. The mean hit rate in shorter blocks (90s) was significantly greater than in longer blocks (180s). Error bars signifying standard error of the mean. Significance marked by *: $p < .05$.

Details on the distribution of response times and hit rate can be found in Fig. B.2

As in Study 1, performance in shorter blocks ($M = 0.81$, $SD = 0.11$) was significantly better than in longer blocks ($M = 0.8$, $SD = 0.12$), $t(44) = 2.31$, $p = 0.013$, $d = 0.52$ (see Fig. 3.9 b).

Table 3.3: Correlating Sustained Attention Measures

Variable	CoV	Hit Rate	On-task Rating	Motivation	Sleepiness	ASRS (IA)	CFQ
CoV	1.00						
Hit Rate	-0.37*	1.00					
On-task Rating	-0.04	0.11	1.00				
Motivation	-0.05	0.20	0.47***	1.00			
Sleepiness	-0.11	-0.07	-0.20	-0.71***	1.00		

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Table 3.3: Correlating Sustained Attention Measures

Variable	CoV	Hit Rate	On-task Rating	Motivation	Sleepiness	ASRS (IA)	CFQ
ASRS (IA)	0.17	-0.03	-0.10	-0.38**	0.44**	1.00	
CFQ	0.02	0.04	0.09	-0.23	0.38**	0.65***	1.00

Notes. Spearman correlation coefficients between all mean outcome measures.

Significance is marked as ***: $p < .001$, **: $p < .01$, *: $p < .05$.

Several of the main outcome variables were correlated with one another (see Tab. 3.3), which was taken into account by centering variables in later linear models to reduce multicollinearity. Performance in the ACT measured by CoV and hit rate correlated, but on-task ratings correlated with motivation. Motivation and sleepiness were correlated as well as ASRS (IA) with CFQ scores. In addition, sleepiness was correlated with both questionnaire ratings (ASRS IA, CFQ), but motivation only with ASRS (IA) scores.

Preregistered Analyses

To examine the hypotheses, mixed effect models predicted hit rate (Hypothesis 1), CoV (Hypothesis 2), and on-task ratings (Hypothesis 3) by distractor, block duration and block. I additionally predicted on-task ratings by CoV in the same model.

Hit Rate. I predicted that block duration and distractor condition would affect hit rate in the ACT. Task block was not predicted to affect hit rate initially, but was added into the tested model to account for any variability explained by block, especially since blocks were longer than in Study 1 and not randomised in order.

The model (conditional $R^2 = 0.69$) revealed main effects of distractor ($p = 0.001$) and block with block 1 serving as the reference ($p = < .001$) on hit rate, see Tab. B.10. There was also an interaction of block with block duration ($p = 0.004$). As seen in Fig. 3.10, hit rate was higher in non-distractor blocks with a mean of $M = 0.83$ ($SE = 0.01$, $95\%CI = [0.81, 0.85]$) than in distractor blocks ($M = 0.8$, $SE = 0.01$, $95\%CI = [0.77, 0.82]$). The interaction between blocks and block duration

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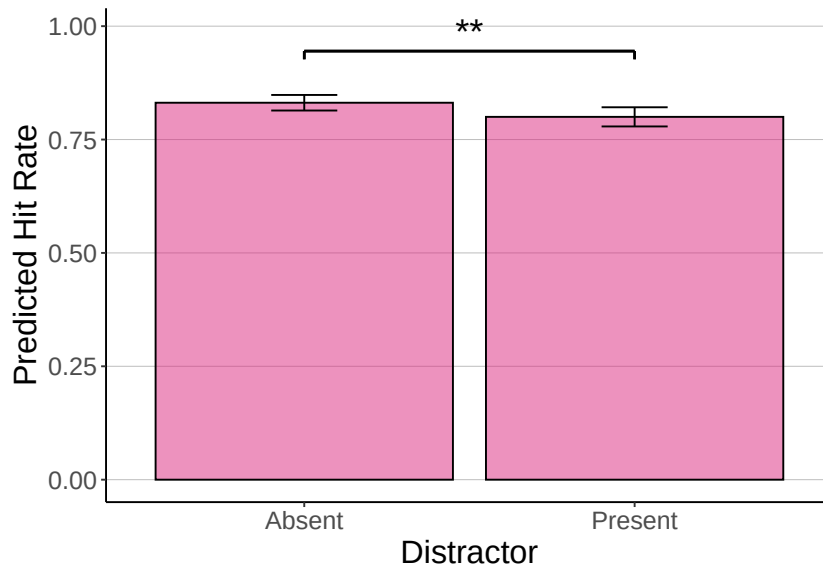


Figure 3.10: Distractor condition significantly predicted hit rate in the task ($p = .001$). The figure shows a higher predicted hit rate when distractors were absent compared to when they were present. Error bars represent the standard error of the mean estimates. Significance marked by **: $p < .01$.

revealed significantly better performance in shorter (90s) blocks 2 and 6 compared to the longer block (180s), and worse performance in the shorter compared to longer block 5, Fig. 3.11. Since block 5 was the first block with the new distractor condition it is possible that participants had more time to adapt and learn the new condition and hence perform overall better in the longer block. A drop in performance in block 2 and 6 for only long blocks after each new condition was introduced (blocks 1 and 5) might be due to on-setting boredom and fatigue after sufficient practice of the new condition.

Response Variability. As shown in Tab. B.11 there was main effect of distractor ($p = <.001$) when predicting performance measured by CoV (conditional $R^2 = 0.79$).

Opposite to the direction of hit rate, CoV was higher (indicating worse performance) in non-distractor blocks with a mean of $M = 0.19$ ($SE = 0.01$, 95%CI = [0.17, 0.21]) compared to distractor blocks ($M = 0.17$ ($SE = 0.01$, 95%CI = [0.15, 0.19])), see Fig. 3.12. This result replicated Study 1, showing that in blocks of 90s or longer, participants are less accurate when predictors are present but at

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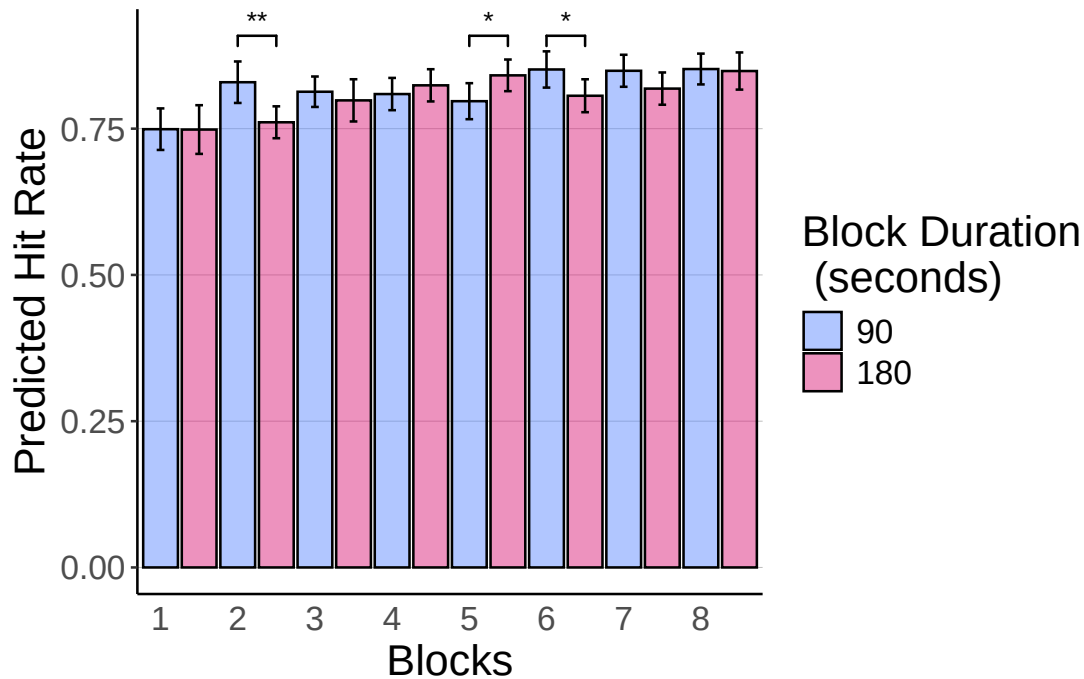


Figure 3.11: There was an interaction ($p = .031$) of block duration (90s or 180s) and blocks (1 to 8). In block 2 and 6, predicted hit rate was higher for shorter compared to longer blocks. However, in block 5, hit rate was greater for longer block compared to the shorter ones. Error bars signifying standard error of the mean. Significance marked by *: $p < .05$, **: $p < 0.01$.

the same time have a more stable performance with distractors compared to the more monotone version of the task.

On-Task Behaviour. I investigated the effect of CoV and blocks on On-task ratings in the ACT in the same mixed model.

Contrary to the predictions, on-task ratings were not predicted by blocks or CoV (conditional $R^2 = 0.7$), see Tab. B.12. There was only a main effect for motivation ($p = < .001$) with a slope of ($\beta = 0.21$ (SE = 0.04, 95%CI = [0.13, 0.28])), see Fig. 3.13.

3.2.4 Summary Study 2

More participants and task blocks had to be excluded but the average hit rate was better in Study 2. As predicted, t-tests revealed significant differences between shorter (90s) and longer task blocks (180s), as well as between distractor and non-

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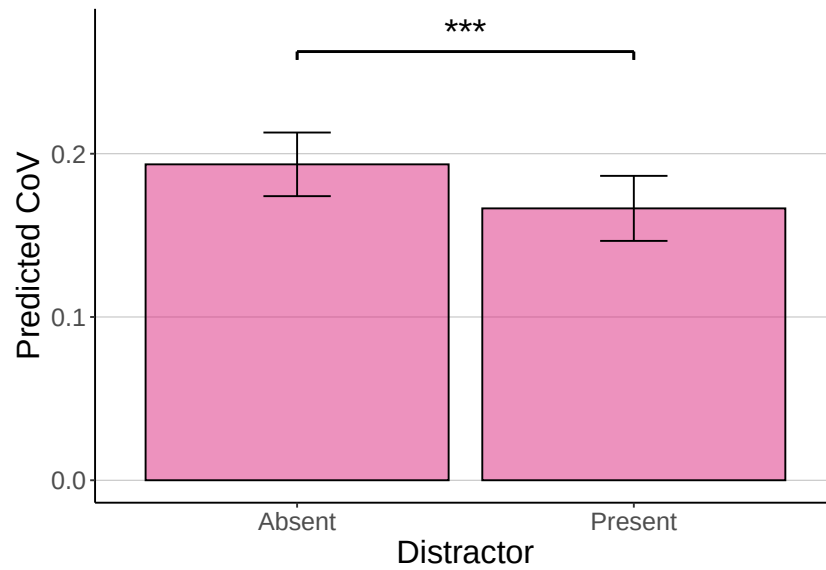


Figure 3.12: Distractor condition significantly predicted CoV in the task ($p < .001$). The figure shows a higher predicted CoV when distractors were absent compared to when they were present. Error bars represent the standard error of the mean estimates. Error bars signifying standard error of the mean. Significance marked by ***: $p < .001$.

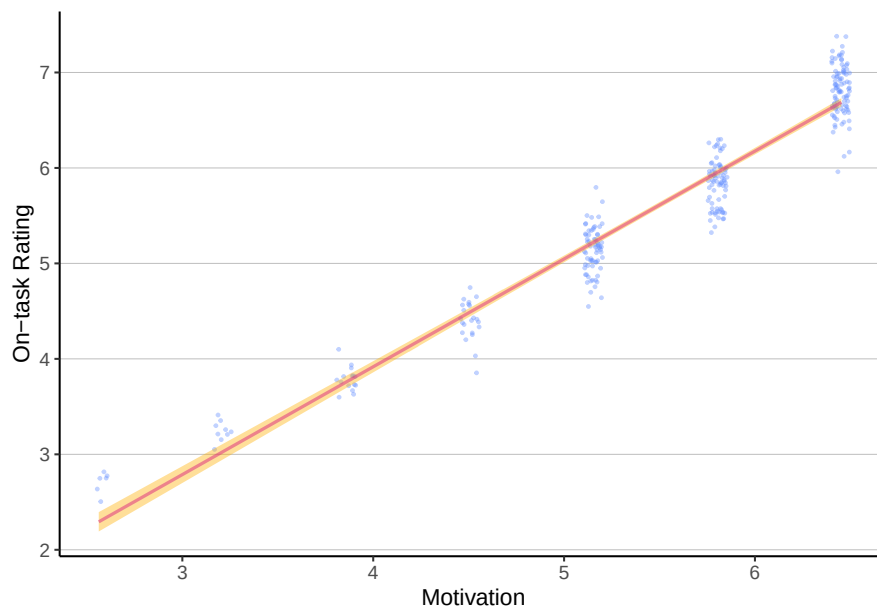


Figure 3.13: Task motivation rated between 1 and 7 (1 = not motivated, 7 = completely motivated) predicted participants' ratings on how well they perceived themselves to be focused on the task, on a scale from 1 to 7 (1 = completely off-task, 7 = completely on-task), $p < .001$. The shaded area represents the 95% confidence interval of the estimates. Predicted task focus values are displayed in blue.

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distractor blocks, where the mean hit rate was better in short blocks and blocks without distractors. This main effect of task complexity was confirmed in the mixed model as expected. Further analysis predicted an interaction between task duration and block, hit rate was better in shorter blocks 2 and 6 compared to longer blocks. In contrast, lower hit rate was predicted for the shorter block 5 compared to the longer one. Since for all participants, the task complexity changed after the first 4 blocks, these results indicated that task switching impacted performance at the beginning of the block but evened out when participants had longer time to practice in block 5. However, blocks 2 and 6 were more accurate when performed for a shorter time, compared to the longer block condition. It is possible that the first block of each condition was sufficient to adapt performance, and that if the following block was longer, participants required more effort to keep up performance than when it was shorter.

Although, CoV and hit rate were significantly correlated across both task conditions, the results of CoV suggested a similar trend to Study 1, confirming that in blocks of 90s or longer, CoV was significantly higher when no distractors were present compared to the more demanding distractor condition, confirming an opposite effect of the task complexity on CoV compared to hit rate. The effect of block was not significant and there was no interaction with block duration, indicating no significant difference between blocks lasting 90s and blocks of 180s.

Different to the expectation, on-task rating was not predicted by blocks or CoV, but as in Study 1 by motivation only, suggesting that ratings depended on how motivated participants felt to perform the task. Since motivation was retrospectively rated together with other questions and probes after each block, it is possible that the subjective impression of how well a participant performed had an impact on how they rated their task-focus and motivation for the preceding block.

3.3 Discussion

Overall, the results from Study 2 mirrored those of Study 1 in a comparable sample. In both studies, hit rates were numerically lower in blocks containing distractors compared to those without, although the t-tests and mixed effect models only reached significance in Study 2. These findings suggest that the more complex task condition impaired participants' performance in the ACT when the stimuli and block durations were modified for Study 2. Furthermore, there was an advantage of hit rate for shorter blocks compared to longer blocks (60s vs. 90s in Study 1; 90s vs. 180s in Study 2). However, as a main effect in the moderation analysis, this was only significant in Study 2. Furthermore, an interaction with block revealed a more complex relationship, where performance detriments in longer blocks may be attributed to task switching costs.

Interestingly, in both studies for blocks lasting 90s or longer, response variability was higher when distractors were present compared to the non-distractor condition, contrasting the effect on hit rate. While accuracy was higher in the less complex condition, response times were more inconsistent, indicating poorer performance, than when distractors were displayed.

Both studies revealed that motivation predicted on-task ratings but not task performance. Sleepiness was only a predictor for CoV in Study 1. Furthermore, questionnaires assessing real-world sustained attention did not demonstrate any predictive value for performance in the online task or the occurrence of MW during the task in Study 1 and were not assessed in Study 2.

Overall, the chapter demonstrated that intricate differences in behavioural scores of sustained attention were differentiated and replicated in two online studies.

3. The Effects of Task Complexity on Behavioural Indices of Sustained Attention and Mind-Wandering

3.3.1 Behavioural Representation of Arousal and Cognitive Control

I found some evidence for better accuracy for the less complex task condition, compared to the distractor condition, which is consistent with Alnæs et al. (2014) who found correctly identified targets decreased with higher attentional load, and with Martínez-Pérez et al. (2023) where task demand was manipulated via the proportion of go-trials. However, one difference is that in the current studies, the amount of stimuli and responses did not increase with higher task complexity, but only the amount of visual elements on the screen distracting from the targets. In contrast, Molloy & Parasuraman (1996) demonstrated faster response times along with more false alarms in a simple task compared to more complex task conditions, indicating a shift in speed accuracy trade-off. Participants of the current studies were instructed to respond as accurately as possible within the 1 s time-window when stimuli were visible. One possibility is that in distractor trials, participants shifted their decision threshold for an accurate response due to the limited time resulting in less accurate button presses.

The distributions of response time and hit rate are not directly indicative of a speed-accuracy trade-off, which assumes that slower responses are more accurate and faster responses are less accurate. In this study, participants responded more quickly and achieved higher hit rates without distractors compared to distractor trials. CoV indicated greater stability of responses during the distractor search which could have resulted from a narrower distribution of response times, however, the response time distributions in both task conditions appear to have a similar width. Both distributions were negatively skewed, but less in the simple vs. distractor search. The shift towards the upper bound of response times in the distractor condition might have driven the accuracy to lower, as less responses might have been made within the response interval, in line with the greater skewness. If this affected CoV values, it would be expected that less responses lead to greater variability in the distractor search, but the opposite was found here. However, kurtosis indicated less variability for most response times which might have affected

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CoV. This suggests that increased task difficulty led to slower responses and time pressure may have prevented accurate responses in more trials. Although the pattern of reaction times is not in line with a speed-accuracy trade-off, some variability in CoV might have been explained by the difference of the spread in response times around the mean.

Overall, CoV and hit rate were significantly correlated in Study 2, suggesting that more accurate responses were associated with stable response times. This is in line with previous literature, which showed more commission and omission errors during phases of higher response variability (Esterman et al., 2013). In addition, Fortenbaugh et al. (2015) found that response variability and sensitivity (an accuracy-based score) in a gradCPT measured a common latent variable in a large online sample. These results were shown in a gradual and monotonous task with longer response intervals than in the current design.

When analysing the effects between monotone and complex task blocks, I found that in contrast to hit rate, CoV was more stable during the complex task in my studies. The opposing results of hit rate and CoV could indicate that responding accurately and consistently were two separate processes within the ACT when comparing low to high demand conditions.

This assumption is consistent with current theories of arousal. For example, it is possible that a more visually engaging task facilitated consistent performance, since higher energetic arousal (correlated with autonomic arousal; Thayer (1990)) can boost performance Matthews & Davies (2001). While a group with higher arousal showed reduced reaction times compared to those with lower arousal, the effect of arousal on sensitivity was specifically in a more difficult task, indicating that when stimuli were more degraded, those with lower levels of arousal performed worse on the task than those with higher arousal level (Matthews & Davies, 2001). The authors concluded that for higher levels of stimulus degradation, low energetic arousal impacted performance due to increased attentional complexity, while task demands stayed the same.

3. The Effects of Task Complexity on Behavioural Indices of Sustained Attention and Mind-Wandering

It is possible that through the addition of distractors in the ACT, monitoring the airplanes required a more complex search strategy, not only increasing attentional monitoring but also cognitive control requirements. In line with this, Demeter et al. (2011) found that a visual distractor increased attentional control demands which were hypothesised to be separate from motivation or arousal-related changes.

Together this suggests that the ACT paradigm revealed behavioural changes based on task complexity, consistent with underlying arousal and cognitive control demands. In support of this notion, Kondo et al. (2023) suggested that continuous performance tasks demand not only maintenance of accurate performance but also control processes to maintain a speed-accuracy trade-off associated with fronto-parietal attention network activity. Here, response variability benefited when the task was more visually complex, contrasting previous literature that suggested a link to cognitive control and response inhibition processes (Johnson et al., 2007; Kondo et al., 2023; Stevenson et al., 2011). My results suggested that hit rate was affected more by the increased control demands and reflected a potential shift in speed-accuracy trade-off when distractors were present, resulting in worse performance than when the task was less visually complex. In support of these results, O’Connell et al. (2008) argued that lapses of attention, measured via errors could reflect failures of cognitive control, whereas variability of response times co-occurred with changes in arousal over time.

3.3.2 Linking Cognitive State and Trait Attention

Task performance and task focus, as well as MW specifically were not associated with each other in the current studies which is in line with Walker & Trick (2018) who found that MW was not related to SART performance but predicted only by sleep duration in the previous night. While a potential link between sustained attention and MW has been suggested, my results support the idea that these processes are distinct (Jin et al., 2020).

Furthermore, I could not replicate an interactive effect between task complexity and unintentional MW that was found in Martínez-Pérez et al. (2021). MW

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was not predicted by other behavioural measures or task manipulations. However, thought probes including off-task thoughts (MW and distractions) revealed more on-task thoughts when motivation was higher in both studies, which stands in contrast with Strayer et al. (2023) who found that setting a specific goal, improved performance but did not affect task-unrelated thoughts.

Since motivation was assessed together with thought probes, it is possible that participants were biased in their responses reporting to be more motivated when they believed to have been more focused. Yet, this is unlikely since on-task reports were not associated with better task performance and reports of sleepiness did not follow the same pattern as motivation. Sleepiness, predicted CoV in Study 1 but not in Study 2 which could indicate a weak effect that did not replicate with more available data and overall longer task blocks. A previous study found that SART performance was less affected by fatigue when go frequency was low, compared to the more difficult high-go version, and in line with my results, task unrelated thoughts were not predicted by sleepiness (Stevenson et al., 2011).

There was no indication that the ACT performance or thought probes reflected everyday ratings of cognitive failures and ADHD symptoms. A reliable association between SART performance and CFQ responses has been proposed (Smilek et al., 2010), but Schepers et al. (2023) only found this effect in a sample of employees and not in students, which is consistent with the current results.

Overall, there was no evidence for an association between ACT performance and subjective ratings of every-day life attention, as well as MW, motivation, and sleepiness reported after the task blocks. Ratings of task-focused thoughts was predicted by the motivation to perform the task.

3.3.3 Limitations and Future Research

The ACT paradigm that was adapted for the current online studies has similarities with SART paradigms and, differently from gradual monitoring tasks, has been suggested to be less monotonous through the abrupt onset and offset of discrete trials that tap into alertness component of sustained attention (Esterman et al.,

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2013). In addition, a component of response inhibition has been proposed to play a role in many go/no-go paradigms (Stevenson et al., 2011). However, in order to distinguish the two complexity conditions, for the monotone task there were regular and predictable timing of trial onsets and location of stimuli, whereas in the more difficult condition, distractors were introduced to make the target search more difficult and stimuli were in unpredictable locations in Study 2. This was supported by the result indicating difference in accuracy between these conditions. One advantage of the design is that it administered high and low demand conditions within the same task. Many environments that require sustained attention, for example surveillance and air traffic control, demand the monitoring of complex data and busy visual displays which is mimicked in the current studies (Donald, 2008). Future research should investigate direct links between performance on the ACT and markers of cognitive control and arousal.

The paradigm was run entirely online and for that reason conservative with the length of task blocks, and only data that passed intermittent attention checks and were self-reported as good quality were analysed here. Greater effects might be confirmed in a lab-based study with longer block durations. Yet, the interaction between block duration and complexity which was present in blocks of 60s vs. 90s, was eliminated after 90s, indicating that the effects of task condition on response variability remained stable for blocks of 90s or longer. Since no relationship of performance with MW or off-task thoughts could be confirmed, future studies might consider less frequent task probes to allow for more task disengagement.

Another effect of shorter time on task in combination with task complexity might have been that general arousal levels were high during both task versions which might have reduced MW overall. States of arousal measured via pupil dynamics have been linked to changes between task focus, MW, and distractions (Unsworth & Robison, 2018).

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3.3.4 Conclusion

The current studies demonstrated differences in task performance during more monotonous compared to complex environments in an online paradigm. While the absence of distractors improved accuracy, the opposite was true for response variability. More consistent responses were facilitated by the presence of distractors in longer blocks. However, task performance did not predict the amount of MW or off-task thoughts reported to have occurred during the task.

4

Eye-Dynamics Capture Sustained Attention and Mind-Wandering

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4. Eye-Dynamics Capture Sustained Attention and Mind-Wandering

Abstract

Maintenance of sustained attention requires optimal arousal levels, which depend on locus coeruleus (LC) noradrenergic projections in conjunction with top-down attentional control. A commonly found marker of these mechanisms has been pupil dynamics, such as pupil dilation and eye blinks. Sustained attention demands can be manipulated via varying difficulty and monotony. Suboptimal sustained attention is characterised by less accurate and more variable responses. In addition, task disengagement leads to thoughts focused externally, leading to distractions or internally, which is also called mind-wandering (MW).

Here, I used a single task design to examine the relationship between sustained attention performance, MW, and pupil markers of arousal and cognitive control under varying task demands. Healthy young adults (N=39) completed the Cognitive Failures Questionnaire (CFQ), Adult ADHD Self-Report Scale (ASRS) and an airplane control task (ACT) to measure sustained attention with distractors present and absent. To capture level of task focus, attentional state, and level of sleepiness and motivation to perform well on the ACT, I recorded pupil size, the number and duration of eye blinks during the ACT. In addition, I also included thought probes after ACT blocks to quantify MW.

Distractors increased task demands along with a decrease in accuracy and reduced response variability. Smaller pupil size was predictive of higher accuracy and marked reduced task demand in the ACT. Interestingly, pupil size could distinguish between different attentional states, with smallest pupil size during MW compared to focused thoughts. Higher CFQ scores were associated with longer eye blinks during the ACT.

The results indicated that the ACT taps into arousal and attentional control demands which were approximated by pupil markers. The study also supported that sustained attention and MW rely on separate mechanisms, as they were affected differently by task demands.

4.0.1 Performance and Pupil Markers of Arousal and Cognitive Control

Voluntarily maintaining sustained attention on one task for a prolonged time is regulated by underlying processes of arousal and cognitive control (Coull, 1998; Ma et al., 2024; Martínez-Pérez et al., 2023; Thomson et al., 2015). Behaviourally, visual sustained attention performance can be measured via a variety of cognitive tasks, such as Psychomotor Vigilance Task (Dinges & Powell, 1985; Martínez-Pérez et al., 2021; Unsworth & Robison, 2018), gradual onset, continuous performance tasks (gradCPTs; e.g. Esterman et al. (2013); Kondo et al. (2023)), and gradual monitoring tasks (e.g. O’Connell et al. (2008) and Harty & Cohen Kadosh (2019)), simple choice reaction-time tasks (Lema et al., 2021; Strayer et al., 2023), Go/No-Go paradigms such as the Sustained Attention to Response Task (SART; e.g. Schepers et al. (2023); Martínez-Pérez et al. (2023); Bedi et al. (2023)), and spatial attention task with distractor stimuli (Raposo et al., 2023; N. Shalev et al., 2018). To tap into arousal and attentional control mechanisms specifically, task demands have been adapted by, for example, displaying distractors, manipulating the Go compared to the No-Go trial frequency (Martínez-Pérez et al., 2023; Wilson et al., 2016), or adjusting the congruency of stimuli and adding cues (Lema et al., 2021).

With failures in sustained attention performance, indicated by lapses in accuracy and/or variable response times, thoughts are often found to disengage from the current task. This resulted in internally focused thoughts, namely mind-wandering (MW), or externally focused thoughts linked to environmental distractions (C. A. Godwin et al., 2023; Kucyi et al., 2016; Unsworth & Robison, 2018). Despite this behavioural overlap between sustained attention lapses and thought disengagement, the underlying mechanisms have been described independent from one another (C. A. Godwin et al., 2023; Strayer et al., 2023). MW is mostly assessed using self-report via thought-probes interrupting a sustained attention task (e.g. Martínez-Pérez et al. (2023); Poerio et al. (2017); Stawarczyk et al. (2011)). However, other methods, such as self-caught MW reporting, and retrospective reports have also been used (Smallwood & Schooler, 2015).

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Sustained attention performance has been demonstrated to be affected by task demands and arousal levels. Increased attention control demands, for example via the presence of distractors or less frequent targets, decreased task performance (Demeter et al., 2011; Martínez-Pérez et al., 2023), in line with the previous chapter. In contrast, MW, although it was reported more in a monotonous task with higher arousal demands compared to a cognitive control task (Martínez-Pérez et al., 2021), did not decrease when attention control demands were increased (Martínez-Pérez et al., 2023). Drug-induced central nervous system stimulation targeting dopamine and noradrenaline concentrations resulted in more accurate and faster performance. In contrast, a non-stimulant drug targeting the same neurotransmitters and a drug decreasing arousal resulted in poorer performance compared to placebo (Pinggal et al., 2022). The authors also found that alpha power activity, a proxy for arousal, predicted task errors and slow reaction times, indicating that arousal increased to sub optimal levels hindered task performance in line with an inverted U-shape relationship between alpha power or task performance and arousal.

Another marker tracking arousal levels relative to noradrenergic activity in the locus coeruleus (LC), are pupil dynamics, especially pupil size (Alnæs et al., 2014). Pupil size increases with higher levels of arousal, physical and mental effort, and task demand such as a larger number of objects to track and difficult compared to easy maths problems (Alnæs et al., 2014; Pan et al., 2022; Zénon et al., 2014). Pre-trial pupil size also increased after lapses compared to accurate trials, decreased over blocks, and could distinguish different attentional states, see Fig. 4.1. Pupil diameter was larger than overall baseline when participants were distracted from the task by external sources and smaller when they reported MW or inattentiveness (Unsworth & Robison, 2016). In Unsworth & Robison (2018), tonic pre-trial pupil size was confirmed to mark MW in both, an arousal and a control demanding task, showing smaller pupils when participants reported MW compared to being focused on either task. Stawarczyk et al. (2020) found similar results along with more and longer blink duration when MW during the SART, however, the significant effects were fully explained by sleepiness ratings in their

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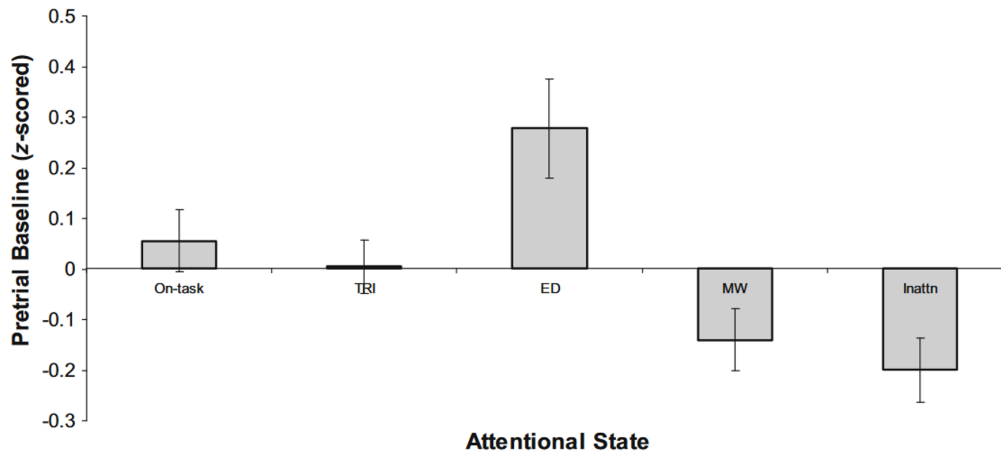


Figure 4.1: Pre-trial pupil size distinguished different attentional states. From Unsworth & Robison (2016), figure reprinted with permission. On-task = on-task thoughts, TRI = task-related interference; ED = external distraction; MW = mind-wandering; Inattn = inattentive/nonalert

sample. This indicated that ocular markers might represent loss of task focus more generically than tracking a specific MW state, which could be related to a drowsiness-induced low arousal state (Stawarczyk et al., 2020). Yet, other studies also found a link between MW and more frequent and longer eye blinks (D. J. Frank et al., 2015; Grandchamp et al., 2014).

4.0.2 The Current Chapter

In this chapter, I aimed to confirm whether the behavioural online results from Chapter 3 can be replicated in a lab-based study using the same sustained attention task. In this ACT, participants monitored the flight path of four airplanes on a radar without and with distractor stimuli present and responded to frequent congruent and infrequent incongruent trials via respective button presses. Participants attended one in-person study session in which they first filled out the Cognitive Failures Questionnaire (CFQ) and the Adult ADHD Self-Report Scale (ASRS), and then completed four 5-minute blocks of the ACT while their pupil dilation and eye blinks were recorded.

Using pupil dynamics as a proxy for underlying changes in arousal and effort,

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I investigated how changes in eye dynamics, namely pupil size, blink rate, and blink duration were affected by task difficulty (distractor condition) and whether pupil dynamics were associated with changes in sustained attention performance, self-reported attention, cognitive failures, task focus, and MW.

4.0.3 Research Questions

Based on the literature and previous chapters, the following questions were addressed:

1. Are behavioural attention markers replicable between an online and a lab-based study? The presence of distractors was expected to decrease both hit rate and CoV as in the previous chapter, indicating reduced accuracy but an increase in stable performance compared to task blocks when distractors are absent. Significant results were not expected for task focus and MW ratings. Questionnaires, although associated with sustained attention performance in previous studies (e.g. [Harty & Cohen Kadosh, 2019](#)), had not shown significant predictions for hit rate or CoV in the previous chapter but the analysis was repeated here to confirm in an lab-based setting with a larger data set.
2. Do different ACT conditions affect pupil markers of arousal and effort? Pupil size was expected to be larger when distractors are present compared to when they are absent and to decrease over blocks.
3. Is performance on the ACT associated with changes in pupil markers of arousal and effort? Pupil size, eye blinks and blink duration were expected to vary with performance. Specifically, a smaller pupil was expected with better hit rate and with less MW. Pupil size was also expected to be highest with internal distractions reported during the task. The effects of pupil dynamics on CoV, and questionnaires was explored.

4.1 Methods

4.1.1 *Participants*

A sample of healthy, young adults was recruited via posters in Oxford University buildings, student and public recruitment schemes hosted by the University, local social media groups, and word-of-mouth.

The eligible age was 18-35, and participants were required to have normal or corrected-to-normal vision (contact lenses or glasses), be right-handed, and fluent English speakers. Only healthy, non-pregnant individuals, specifically without diagnosed neurological or psychiatric conditions, history of migraines or fainting, previous head trauma, neurosurgical procedures, hearing problems, metallic implants, or drug treatments could take part. Participants were not eligible if they consumed alcohol or drugs (regularly, or more than 3 units during the 24h prior to the study), caffeine (more than 1 cup of coffee/ tea in the hour before the study), or if they reported less than 6 hours of sleep in the previous night.

Forty participants completed the study session and one additional participant took part but did not complete the session since the eye tracker could not be calibrated correctly. After the session, the time was reimbursed with £10/ hour paid via bank transfer, or corresponding study credits. Ethical approval was granted via Medical Sciences Interdivisional Research Ethics Committee (R82513/RE002).

4.1.2 *Apparatus and Materials*

The experiment was displayed on a computer monitor in a sound-proof experimental booth with the researcher present. Participants were seated at a table with their chin stabilised approximately 50 cm away from the display (28.5 degrees horizontally, 24.6 degrees vertically). The room was lit by a ceiling light. The task was presented on Windows 7 in Matlab (Version R2019a) using the Psychophysics Toolbox 3 ([Brainard, 1997](#)) and custom scripts.

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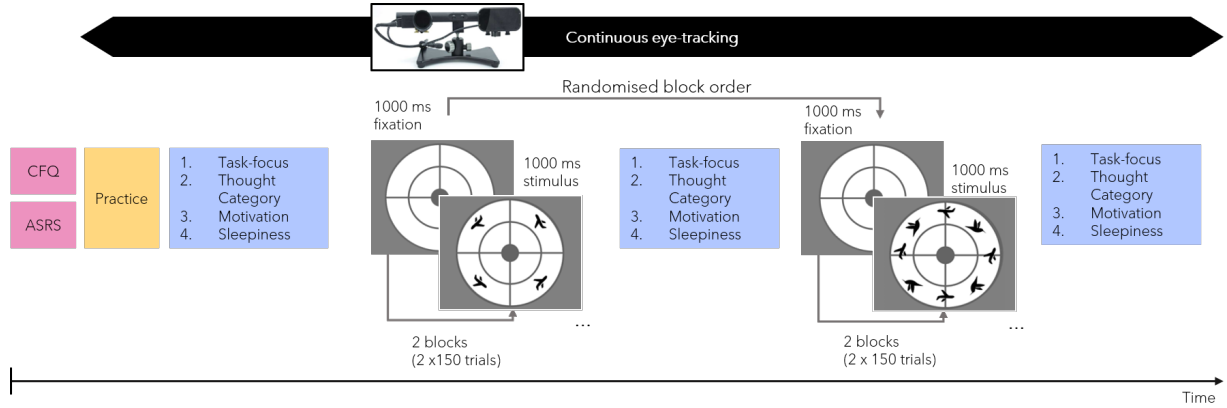


Figure 4.2: Procedure. During the session, participants first completed the CFQ and ASRS questionnaires, followed by rating their motivation and sleepiness before the task blocks began. A block contained congruent (89%) stimuli which required the space bar to be pressed and incongruent stimuli (11%) for which participants withheld their response. Task blocks were either without or with distractor items in each trial and lasted 300 s. After each task block, participants rated on-task behaviour, categorised their thoughts in the MW probe, gave more details through the experience sampling, and rated their motivation and sleepiness in the previous block.

Task parameters for the ACT, as well as thought probes for task focus, motivation, and sleepiness, the MW probe, and CFQ and the ASRS inattention subscale (ASRS IA) questionnaires, were reproduced as described in Chapter 3 (Study 2).

Eye-tracking. A desktop-mounted Eyelink 1000-Plus (SR Research, Ontario, Canada) with chin-rest collected monocular eye dynamics data at a sampling rate of 500Hz from the dominant eye. For most participants, a 9-point calibration was run using customised coordinates (20% horizontal, 35% vertical) to cover specifically the stimulus display area of the screen. Participants 7-14 were run with a 9-point calibration using customised coordinates (50% horizontal, 75% vertical), and participants 1-6 were recorded using the default 5-point calibration (binocular).

4.1.3 Procedure

All participants performed the same tasks and questionnaires, see Fig. 4.2. Participants received the study information after signing up and at least 48 hours before the session. On arrival, the study information was given and, if no further questions remained, participants gave their consent to participate. Next, questionnaires including personal information, CFQ, and ASRS were presented. In the experimental

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booth, the eye-tracker was adjusted and calibrated for a short test-recording. Then, participants received instructions for the session and completed practice trials for the MW probes (practice items reported in Chapter 3) and the ACT. First, 20 slow practice trials were performed with fixation lasting 1000ms, stimulus display lasting 5000ms, and feedback was given. Out of these, the first 10 trials were non-distractor trials, and the last 10 showed distractors in addition to the stimuli, 4 out of 10 trials were critical target trials. Then, participants practiced 45 trials (including 5 critical targets) each, first without and then with distractors at normal speed (1000ms fixation, 1000ms stimulus) and without visual feedback. Verbal feedback was given by the experimenter when necessary to correct, or encourage performance. Before the task started, participants reported their motivation and sleepiness at baseline and then completed 2 sets of 4 blocks with 150 trials each of the ACT. Each block lasted approximately 5 minutes (300 s). The starting condition for the first 2 blocks was randomised between participants, however due to a partial failure in the randomisation at the start of the study, 26 participants started without distractor blocks and only 14 started with distractor blocks. Immediately after each ACT block, thought content and MW probes, motivation and sleepiness were rated and reported. Between blocks, a timed 1-minute break allowed participants to drink, rest their eyes and neck while remaining seated. Responses were recorded using right and left index fingers on a response box with two buttons labelled ‘R’ and ‘L’. The association between left and right buttons and critical and safe trials was randomised between participants.

4.1.4 Data Analysis

All analyses were performed in R (Version 4.3.0) using custom scripts. Outliers, exclusion criteria, and calculation of performance (hit rate, CoV, CFQ, ASRS) were the same as in the previous chapters, as was the method for all linear models. Motivation, sleepiness, and task-focus (On-task rating) were rated between 1 and 7 and analysed as ordinal variables.

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MW vs. task focus. MW probe ratings were analysed as a binary comparison, taking only ratings into account when participants reported to be task-focused and reports of MW, while excluding any ratings for task related or unrelated distractions, and ratings falling in the “other” category.

Thought categories. In a multinomial model, all 4 thought probe categories (on-task, task distractions, external distractions, and MW), excluding “other” were analysed.

Eye blinks. The number of eye blinks and blink duration were recorded by the EyeLink On-line Parser. An extra 100ms of data around detected eye-blinks was removed. Mean eye blinks was based on all eye blinks during the entire task block, mean trial eye blinks took only blinks during the stimulus display into account (200ms-1000ms after stimulus onset), and mean pre-trial blinks were calculated from blinks during the fixation display (200ms-1000ms after fixation onset). Blink duration for all included eye blinks were extracted as recorded by the Eye-Link in ms.

Pupil size. Pupil sizes were Z-scored per participant based on all 4 blocks. Mean pupil size was calculated including any pupil size data not marked as eye blinks in the aforementioned procedure. Pupil sizes were averaged over the pretrial period (200-1000 after fixation onset). I also extracted pupil size from the entire block, and the trial period only (200-1000 after stimulus onset).

4.2 Results

4.2.1 *Sample*

Out of 40 complete data sets, 11 blocks of 6 participants were excluded because 60% or more of the responses were missing. Out of those, 4 blocks belonged to the same participant and their data were therefore excluded from the study. The final sample included 39 participants (age 18-35, $M = 22.54$, $SD = 5.39$, 29 female).

4.2.2 *Behavioural Effects*

First, I compared the behavioural results from the previous chapter to the current outcomes and tried to replicate the effects of performance and task focus.

Participants mean hit rate was 79% ($SD=9$), mean response times were 710 ms ($SD=100$), and CoV was $M=0.19$ ($SD=0.09$). Overall sleepiness was reported 2.81/7 ($SD=0.98/7$), and motivation 5.53/7 ($SD=1.05/7$). Task focus out of 7 was rated on average with 4.94 ($SD=1.11$).

Hit Rate. Based on the results in Study 2 of the previous chapter, I predicted a main effect of distractor and block, with hit rates being higher in non-distractor blocks and improving with time on task.

As predicted, the model (conditional $R^2=0.86$) revealed main effects of distractor ($p<.001$) and block ($p<.001$) on hit rate, see Tab. C.1. As seen in Fig. 4.3a, hit rate was significantly higher in non-distractor blocks with a mean of $M=0.81$ (95%CI= [0.78, 0.85]) than in distractor blocks ($M=0.77$, 95%CI= [0.74, 0.81]).

Hit rate was higher in blocks 2 ($M=0.8$, 95%CI= [0.77, 0.84], $p<.001$), 3 ($M=0.81$, 95%CI= [0.78, 0.85] $p<.001$), 4 ($M=0.84$, 95%CI= [0.8, 0.87] $p<.001$) compared to block 1 ($M=0.72$, 95%CI= [0.68, 0.75]), and in block 4 compared to block 2 ($p=0.004$), see Fig. 4.3b.

CoV. Opposite to hit rate, CoV was expected to indicate less stable performance in the non-distractor condition, which was confirmed (conditional $R^2=0.84$) by a main effect of distractor on CoV ($p=0.019$), see Tab. C.2. CoV was higher (indicating worse performance) in non-distractor blocks with a mean of $M=0.19$ (95%CI= [0.17, 0.21]) than in distractor blocks ($M=0.18$, 95%CI= [0.16, 0.2]), see Fig. 4.3c.

Task-Focus. In the previous chapter, there were no effects of task on on-task ratings except for a main effect of motivation.

In the current analysis (conditional $R^2=0.54$), see Tab. C.3, motivation was replicated to predict task focus ratings ($p=0.004$) with a trend of $\beta=0.36$ (95%CI= [0.12, 0.6]), see Fig. C.1a. In addition, a main effect of sleepiness was significant ($p=$

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0.017) with a trend of $\beta=-0.33$ (95%CI= [-0.6, -0.06]), see Fig. C.1b. I also found a significant interaction between distractor and block ($p= 0.031$), see Fig. 4.3d.

There was a significant difference between distractor ($M= 4.17$, 95%CI= [3.46, 4.88]) and non-distractor blocks ($M= 5.34$, 95%CI= [4.82, 5.86]) in block 2 ($p= 0.01$), indicating that task focus was reduced when distractors were present compared to when they were absent. In block 3, the difference between distractor ($M= 5.02$, 95%CI= [4.48, 5.56]) and non-distractor blocks ($M= 4.13$, 95%CI= [3.41, 4.84]) was reversed ($p= 0.05$).

MW. In the previous online study (Study 1), MW was not significantly predicted by task parameters, but by motivation. In the current in-person study, I ran a simplified logistic regression to ensure convergence. The model did not predict significant changes in MW between different task conditions, blocks, or based on motivation ratings, see Tab. C.4.

Only a main effect of sleepiness on MW was significant, ($p= 0.023$) with a trend of $\beta=0.79$ (95%CI= [0.06, 1.53]), see Fig. C.2.

Questionnaires. CFQ ($p= 0.944$) and ASRS (IA) ($p= 0.117$) did not predict hit rate at baseline, see Tab. C.5. Similarly, the questionnaires did not predict baseline CoV (CFQ: $p= 0.14$, ASRS: $p= 0.664$), see Tab. C.6.

4.2.3 *Task Demand and Eye Dynamics*

Blink Rate and Duration. I explored the acquired eye data, to investigate how differences in task demand and performance were reflected in blink and pupil dynamics. Participants' mean blink rate per block was 98.31 ($SD=63.46$), mean blink duration was 183ms ($SD=109$).

When predicting blink rate, the model (conditional $R^2= 0.93$) revealed main effects of motivation ($p= 0.043$) and block ($p= 0.01$), see Tab. C.7. As seen in Fig. C.3, blink rate was significantly higher when motivation was rated lower $\beta=-6.09$ (95%CI= [-11.98, -0.19]).

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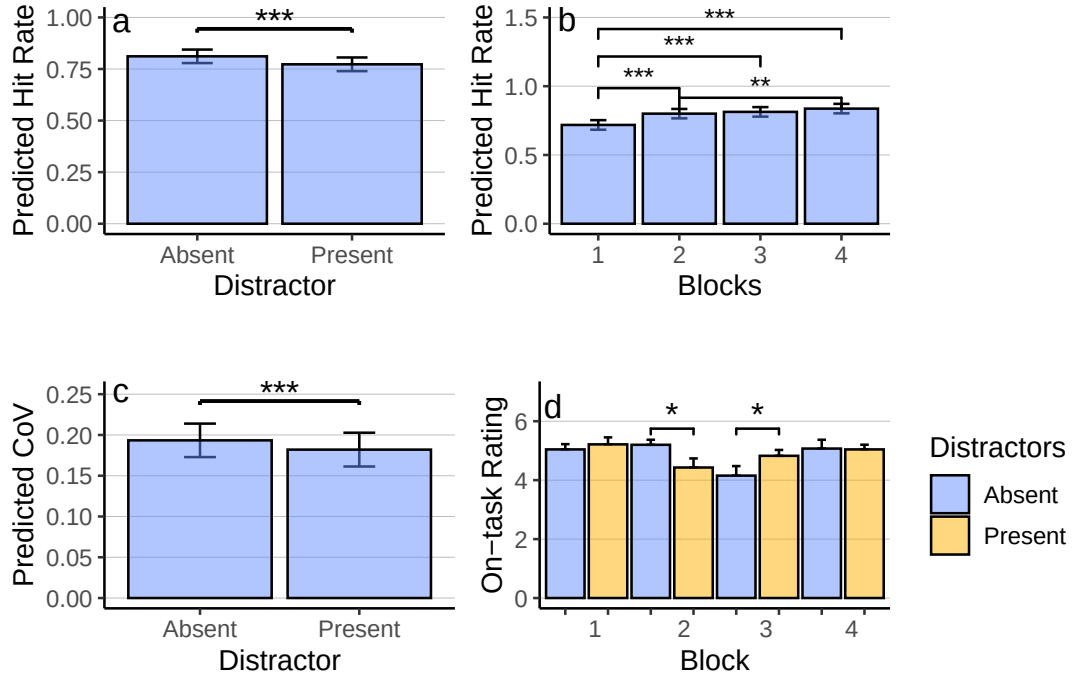


Figure 4.3: Behavioural results of task parameter effects on attention measures. a. Distractor condition significantly predicted hit rate in the task ($p < .001$). The figure shows a higher predicted hit rate when distractors were absent ($M = 0.81$) compared to when they were present ($M = 0.77$). b. Blocks significantly predicted hit rate in the task ($p < .001$). The figure shows a higher predicted hit rate in blocks 2 ($M = 0.80$), 3 ($M = 0.81$), and 4 ($M = 0.84$) compared to block 1 ($M = 0.72$), and a higher hit rate in block 4 compared to block 2. c. Distractor condition significantly predicted CoV in the task ($p = .019$). The figure shows a higher predicted CoV when distractors were absent compared to when they were present. d. When predicted on-task ratings, there was an interaction between distractor condition and block ($p = .031$), pairwise comparisons between distractors were compared within blocks indicating significant differences in block 2 and 3. Error bars represent the standard error of the mean estimates. Significance marked by ***: $p < .001$, **: $p < .01$, *: $p < .05$.

The number of eye blinks increased significantly from blocks 1 ($M = 91.8$, 95%CI = [68.93, 114.66]), to block 4 ($M = 106.93$, 95%CI = [84.88, 128.98]), $p = 0.016$). The difference between block 2 ($M = 92.75$, 95%CI = [70.02, 115.48]) and block 4 was also significant ($p = 0.019$), see Fig. 4.4a.

Task parameters, motivation or sleepiness were not predictive of the duration of eye blinks, see Tab. C.8.

Pre-Trial Pupil Size. As predicted, the model (adjusted $R^2 = 0.12$) revealed

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main effects of distractor ($p = 0.011$), and block ($p = <.001$) on pre-trial pupil size, see Tab. C.9. As seen in Fig. 4.4b, pupil size was predicted significantly smaller in non-distractor blocks with $M = -0.08$ (95%CI = $[-0.15, 0]$) than in distractor blocks ($M = 0.06$, 95%CI = $[-0.01, 0.14]$).

Predicted pre-trial pupil size was significantly smaller in blocks 2 ($M = -0.08$, 95%CI = $[-0.19, 0.02]$, $p = <.001$), 3 ($M = -0.05$, 95%CI = $[-0.16, 0.06]$, $p = 0.005$), and 4 ($M = -0.11$, 95%CI = $[-0.21, 0]$, $p = <.001$) compared to block 1 ($M = 0.22$, 95%CI = $[0.11, 0.32]$), see Fig. 4.4c.

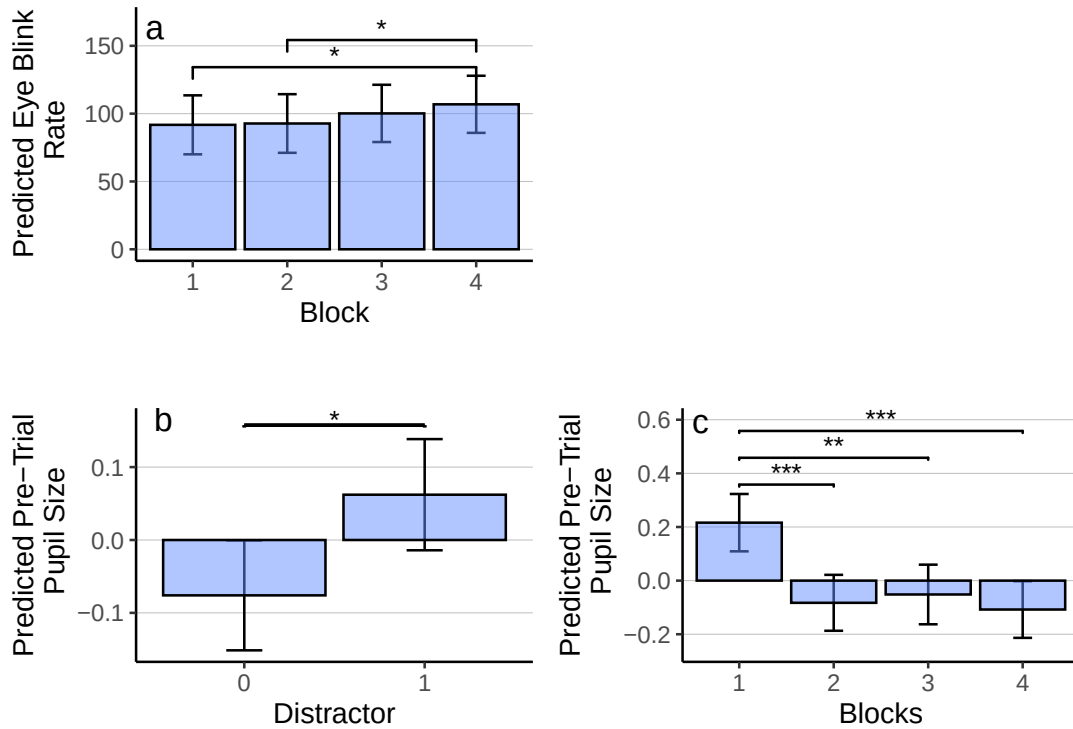


Figure 4.4: Task parameter effects on eye dynamics. a. Blocks significantly predicted blink rate per block ($p < .010$). The figure shows more predicted blinks in block 4 ($M = 106.93$) compared to block 1 ($M = 91.80$) and block 2 ($M = 92.75$). b. Distractor condition significantly predicted pre-trial pupil size (standardised; $p = .011$). The figure shows a smaller predicted pre-trial pupil size when distractors were absent ($M = -0.08$) compared to when they were present ($M = 0.06$). c. Blocks significantly predicted pre-trial pupil size (standardised; $p < .001$). The figure shows a smaller predicted pupil size in blocks 2 ($M = -0.8$), 3 ($M = -0.05$), and 4 ($M = -0.11$) compared to block 1 ($M = 0.22$). Error bars represent the standard error of the mean estimates. Significance marked by ***: $p < .001$, **: $p < .01$, *: $p < .05$.

4.2.4 *Behavioural Markers of Eye Dynamics*

Questionnaires and Eye Dynamics. CFQ was predictive of blink duration (Tab. C.10, with longer eye blinks predicting more reported cognitive failures ($\beta=3.18$, 95%CI= [0.07, 6.29], $p= 0.046$), see Fig. 4.5b. CFQ and ASRS (IA) scores were not predicted by blink rate (Tab. C.11), or pupil size, see Tab. C.12.

Performance Markers. Blink rate or blink duration did not significantly predict hit rate during the task, but there was a main effect of pre-trial pupil size ($p= 0.012$), see Tab. C.13. As depicted in Fig. 4.5a, a better hit rate was associated with smaller pupil size ($\beta= -0.04$, 95%CI= [-0.08, -0.01]).

In contrast, both blink rate and duration explained changes in CoV, see Tab. C.14. Less eye blinks were recorded when CoV was high ($\beta= < - .01$, 95%CI= [$< - .01$, $< - .01$], $p = 0.02$), see Fig. 4.5c. The duration of eye blinks was predicted to increase with higher CoV ($\beta= < - .01$, 95%CI= [$< - .01$, $< - .01$], 95%CI= [10^{-5} , 10^{-4}], $p = 0.02$), but the scatter plot shows very little data of longer eye blinks resulting in a less accurate prediction, see Fig. 4.5d.

Task Focus. While eye blinks, blink duration, and pupil size were no significant predictors of task focus ratings (see Tab. C.15), there was a significant effect of both blink rate ($p= 0.001$), see Fig. 4.6a, and blink duration ($p= 0.044$) on MW, see Fig. 4.6b and Tab. C.16. Blink rate decreased when MW was reported less ($\beta=-0.04$ (95%CI= [-0.07, -0.02])). Additionally, as MW increased, blinks were predicted to last longer ($\beta=0.01$ (95%CI= [0, 0.03])). However, there was little data for longer blink duration resulting in a large confidence interval.

Motivation predicted both task focus ($\beta=0.36$, 95%CI= [0.1, 0.62], $p= 0.008$), and MW ($\beta=-1.48$, 95%CI= [-2.7, -0.27], $p= 0.006$, indicating that higher motivation levels increased task focus and reduced MW. Less MW was also significantly predicted by lower sleepiness ratings ($\beta=1.39$, 95%CI= [0.17, 2.61], $p= 0.008$)

Thought Categories. To examine whether pre-trial pupil size could predict subjective thought categories, a Bayesian multinomial mixed effect model was run with MW as the reference category, see Tab. C.17. To replicate the findings from

4. Eye-Dynamics Capture Sustained Attention and Mind-Wandering

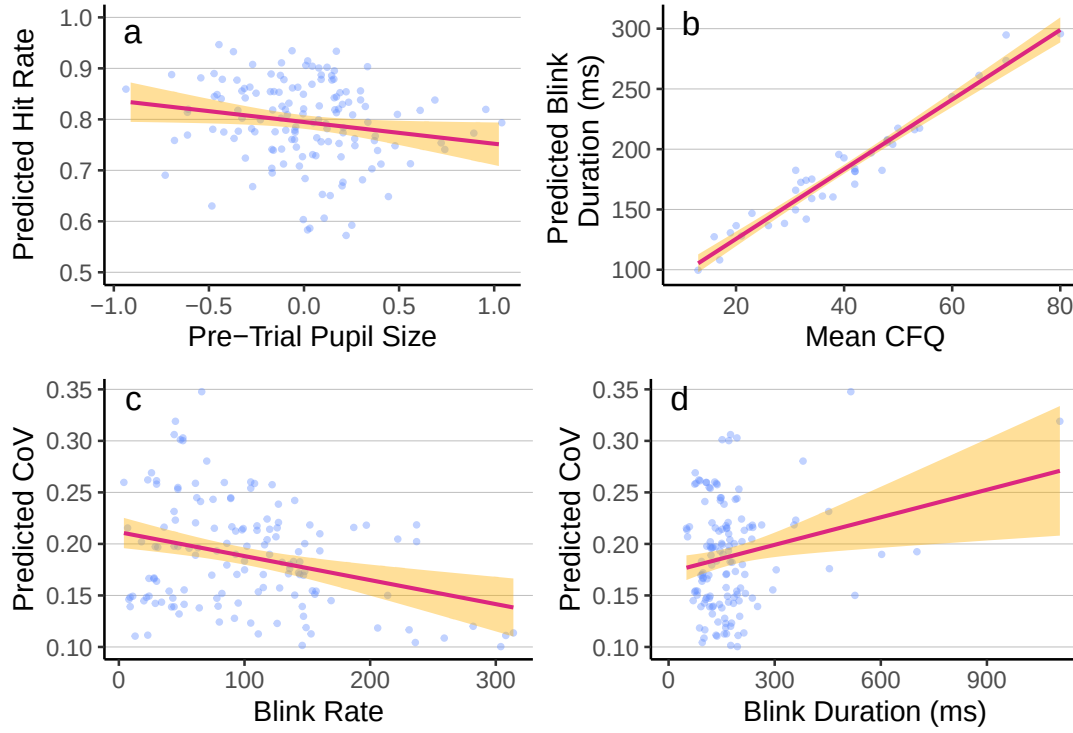


Figure 4.5: Associations between behavioural attention marker and eye dynamics. a. Hit rate predicted pre-trial pupil size (standardised; $p = .012$). Better hit rate was associated with smaller pre-trial pupil size. b. CoV was significantly predicted by blink rate per block ($p = .020$). Higher CoV during the task was associated with less eye blinks. c. Longer eye blinks also predicted a higher CoV ($p = .020$). The shaded areas represent the 95% confidence interval of the estimates. Predicted on-task ratings are displayed in blue.

Unsworth & Robison (2016), the model was in addition run comparing to the overall baseline pre-trial pupil size. When referencing pre-trial pupil size during MW, ($M = -0.08$), the model revealed an effect of pupil size for on-task thoughts ($\beta = 1.92$, 95%CI = [0.04, 3.97]) with a mean of $M = 0.02$ and task-relevant thoughts ($\beta = 1.52$, 95%CI = [0.09, 3.12]) with a mean of $M = 0.03$, see Fig. 4.6c(#).

Compared to the overall mean pre-trial pupil size as reference, the model revealed an effect of pupil size for MW ($\beta = 1.99$, 95%CI = [0.02, 4.09]) with a mean of $M = 0.02$, see Fig. 4.6c(+).

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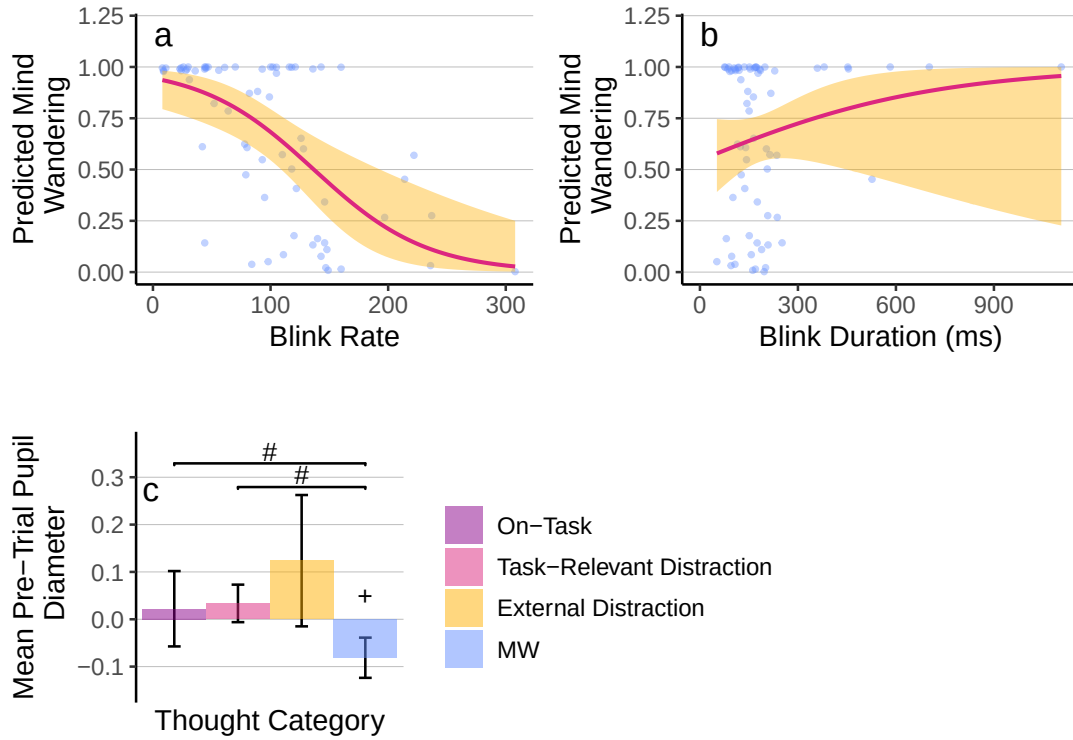


Figure 4.6: MW ratings and thought categories were predicted by eye dynamics. a. MW rating (0 = totally focused on the current task, 1 = zoning out/MW) was predicted by blink rate ($p = .001$). More reported MW compared to task-focused thoughts was associated with a smaller amount of eye blinks during the task block. b. Furthermore, more reported MW predicted longer blink duration (ms) than during on-task thoughts ($p = .044$). c. When predicting all 4 rated thought categories by pre-trial pupil size, the credible interval for MW reports showed a smaller pupil size compared to the overall average pre-trial pupil size (+). With the reference category MW, on-task and task-relevant thoughts were distinguished by pupil size via credible interval (#). The shaded areas represent the 95% confidence interval of the estimates. Predicted MW values are displayed in blue. Error bars represent the standard error of the mean estimates. Significance equivalence ($p < .05$) marked by # and +: 95% credible interval excluding zero.

4.3 Discussion

Overall, the behavioural results in the current lab-based study replicated those from the previous chapter. Mean hit rate and CoV were comparable to Study 2 from Chapter 3. As expected, both hit rate and CoV were higher in non-distractor blocks, suggesting worse accuracy but less response variability compared to distractor blocks. Hit rate improved with blocks.

Blink rate and pre-trial pupil size were predicted by task demand with increased

4. Eye-Dynamics Capture Sustained Attention and Mind-Wandering

blink rate in the last task block, and pupil size was smaller in non-distractor blocks and decreased with time compared to block 1.

A smaller pre-trial pupil size indicated better accuracy in the task. Moreover, the number of eye blinks was lower when CoV was high and when participants reported to be MW compared to being focused on the task. In contrast, longer eye blinks were associated with higher CFQ scores, greater CoV, and more MW. Lastly, pupil size was used to predict the 4 thought categories with both MW and the overall average pre-trial pupil size as reference (Unsworth & Robison, 2016). Compared to rated MW, pupil size was predicted higher for on-task ratings and task-relevant thoughts, and pupil size during MW was also smaller compared to the overall average pupil baseline. Pupils were smallest when participants reported MW.

4.3.1 Sustained Attention Effort Linked to Cognitive Control

The behavioural results confirmed the findings from the previous chapter, namely that distractors reduced accuracy but improved response variability when the ACT is performed for longer periods of time. This is in support of control and arousal accounts of attention which speculate that increased attentional demands worsen accuracy, but a more optimal level of arousal can be maintained when the task is demanding (Aston-Jones & Cohen, 2005; Demeter et al., 2011; Pinggal et al., 2022; Thomson et al., 2015). Replicating the results from Chapter 3, performance improved over the 4 task blocks indicating that the ACT benefits from practice, compared with other traditional, more monotonous vigilance tasks (Martínez-Pérez et al., 2021).

4.3.2 Pupil Correlates of Task Demand and Performance in the ACT

As expected, pupil size decreased with blocks and replicated the strong difference in the first 2 blocks found in Unsworth & Robison (2016). Pupil measurements were also sensitive to the difference in distractor conditions, confirming a larger pupil

4. Eye-Dynamics Capture Sustained Attention and Mind-Wandering

when distractors were present (Pan et al., 2022). This was consistent with hit rate being lower in distractor blocks and a larger pupil size predicting decreased accuracy in this sample, as was also reported by Unsworth & Robison (2016), suggesting that a larger pupil size represented worse performance coherent with increased task demands. Interestingly, although CoV indicated more variability when distractors were absent which is consistent with Magliacano et al. (2020), pupil size did not significantly predict this difference. Instead, eye blinks were less frequent but longer when responses were more variable. One possible explanation could be that when task demand was low and responses became more variable, attentional focus might have shifted from more externally directed attention towards internally directed attention which is associated with fewer fixations and longer eye blinks (Benedek et al., 2017). This would suggest that CoV, although behaviourally predicting task demands in line with differences in arousal, was a less useful indicator of LC-related changes than hit rate in this study. However, CoV could potentially be a marker for attention disengagement related to internal thoughts.

4.3.3 MW Marked by Decreased Pupil Dilation

Consistent with Martínez-Pérez et al. (2023), MW did not differ between low and high effort task conditions. However, in line with Stawarczyk et al. (2020), sleepiness ratings were associated with MW and decreased task focus. Moreover, in the current chapter, the effects of eye blinks, blink duration remained significant. Furthermore, pupil size during MW was smaller compared to the overall baseline and compared to when task focus was maintained, even when sleepiness was accounted for. In addition, I did not find a significant influence of sleepiness on pupil size, number of blinks, or blink duration when performance was not included in the model.

Pupil size was significantly smaller during MW than for on-task ratings, and visually replicated the patterns reported in Unsworth & Robison (2016). However, due to the low number of reported external distractions, the difference was not statistically confirmed. Since the study was performed in a shielded booth in a quiet

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lab area, it is expected that only few participants would have experienced distractions. Future studies might investigate inter-individual differences in the tendency to focus thought internally or externally when disengaging from attention tasks.

The current results support the finding that lapses in task performance rely on a different mechanism than MW (Jin et al., 2020; Martínez-Pérez et al., 2023), since performance differences due to task difficulty were not mirrored for MW ratings. This stands in contrast to the Resource-Control Account (Thomson et al., 2015), which predicts that any additional attentional resources that are not required and devoted to task performance are redirected towards MW. Given that more resources are free in the task condition requiring less control (i.e. no distractor), more resources should be occupied by internally directed attention. Instead, my data would imply that MW-related processes are performed in parallel.

Although pupil size successfully distinguished MW from task-focused thoughts, the same could not be confirmed for the more general self-rating of task focus. One explanation could be that off-task thoughts arise from suboptimally low and high arousal levels, indicated by either smaller than task-focused pupil size (MW) or larger pupil size (distractions) compared to focused thoughts (Unsworth & Robison, 2016). This highlights the importance of distinguishing between different off-task states in sustained attention arousal and cognitive control studies.

Contrary to my hypothesis, less eye blinks predicted increased MW compared to focused thoughts. Although the opposite has been found in some studies, Grandchamp et al. (2014) only included 2 subjects in their sample and in (D. J. Frank et al., 2015), participants performed a reading task. Differences in eye fixations required in the ACT might have caused the different results. It is plausible that instead of MW due to low arousal, in the ACT, MW occurred as a compensation for increased cognitive load which is associated with more frequent eye blinks (Magliacano et al., 2020). However, eye blinks increased with blocks, which would indicate a decrease in MW towards the end of the task. In Stawarczyk et al. (2020), more eye blinks were entirely explained by increased drowsiness. this was less likely the case here as sleepiness was controlled for.

4.3.4 Strengths and Limitations

This study showed the advantage of testing different behavioural markers of sustained attention in combination with MW and pupil proxies of the underlying mechanisms of sustained attention maintenance in a low and high demand version of the same sustained attention task. Controlling for motivation and sleepiness enabled me to explore how performance and MW related to pupillometry markers. Although a similar design, Martínez-Pérez et al. (2023) manipulated task demands in a SART-like task by changing the target frequency, which has been criticised to shift the speed-accuracy trade-off in responses (Wilson et al., 2016). As a target becomes less likely to appear, participants respond quicker and make more mistakes. Therefore, in the current study, I kept the target frequency the same in the low- and high-demand condition and difficulty was introduced solely by visual distractors, with all other parameters stable. It is however possible that due to the increased visual load, searches became longer and responses were made with less certainty and variability compared to the low-demand condition, or were made prematurely with participants running out of time to respond. Responses could be made up to 1000 after stimulus onset, but differently to Martínez-Pérez et al. (2023) and Wilson et al. (2016), in the ACT participants have to respond in each trial, therefore withholding a response would always count as a mistake.

Tonic pupil dilation has previously been shown sensitive to changes in luminance, with larger pupil dilation with dim stimulus backgrounds, and a dim background also increased the difference in tonic pupil dilation between low and high working memory load (Peysakhovich et al., 2017). A similar effect could have affected the pupil difference between distractor and non-distractor condition in the current study where larger pupils in the distractor condition was a result of the darker stimuli enhanced by the grey screen colouring. However, the differences in pupil size reported here were also consistent with changes in performance irrespective of the task condition.

4.3.5 Conclusion

In summary, the current chapter explored performance and task demand effects on pupil markers. In line with Chapter 3, task demand decreased accuracy but improved stable response times. In line with the LC mechanisms of arousal underlying task maintenance, pupil size was predictive of accuracy and marked changes in task demand in the ACT, as well as distinguishing between different attentional states, especially MW. The study confirmed that sustained attention performance was affected by attentional control demands in the same task, but MW was unaffected.

Large pupil dilation marked states of greater arousal via increased task demand, length of task, and worse accuracy, which could indicate distracted behaviour. Eye blinks became less frequent with increased CoV and MW, and with later task blocks, which could indicate a shift towards internally directed attention. A longer duration of eye blinks was predictive of higher rates of MW, CoV, and associated with more cognitive failures.

5

Sustained Attention Improvement from tRNS predicted by Performance Markers

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5. Sustained Attention Improvement from tRNS predicted by Performance Markers

Abstract

Sustained attention is an important skill that supports goal-directed behaviour and learning. Failures in sustained attention can be identified by poor task performance and co-occur with changes in fronto-parietal attention networks which are activated by cognitive control and arousal adjusted to the task demands. One method to compensate for suboptimal cortical engagement is transcranial random noise stimulation (tRNS) which has an excitatory effect on the cortex below. Prior studies show a benefit of tRNS on perception and attention, especially for participants with lower baseline ability. The current chapter aimed to investigate the effect of tRNS on sustained attention tasks of different complexity ranging from monotonous to distracting. In addition, baseline performance, mind-wandering (MW), pupil size, theta/beta ratio (TBR), and aperiodic exponent (AE), were explored to predict which participants would profit the most from the intervention compared to sham stimulation. Thirty-nine participants were included in the double-blind, within-subject experiment and completed three versions of an airplane control task (ACT) with active (1 mA) or sham tRNS over the right fronto-parietal cortex. During the task, pupil-dilation was measured and prompts recorded self-reported thought content such as mind-wandering (MW). Resting-state TBR was calculated before and after baseline and tRNS task blocks. The results revealed an overall benefit on all ACT conditions for those participants with lower baseline accuracy. In addition, all participants showed improved accuracy in the monotonous vigilance task during active tRNS compared to sham. Greater response variability was associated with higher arousal in the monotonous task but with lower arousal in the two search conditions, indicating a link between performance and arousal level depending on the complexity of the task. Pupil size and TBR did not predict tRNS outcome. The study suggests that tRNS could be a valuable intervention tool for individuals with difficulties to focus in boring, as well as in difficult tasks. Predicting the success of this intervention based on baseline characteristics, such as performance, could improve successful intervention in educational settings.

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The ability to focus on one chosen task is important for learning and education outcomes (Erickson et al., 2015; K. Godwin & Fisher, 2014). When task focus is maintained on one task for a long time, performance can become more error prone and inconsistent, and studies have shown associated changes in frontal and parietal attention networks (Esterman et al., 2013; Fortenbaugh et al., 2018; Kondo et al., 2023).

5.0.1 Benefits of Transcranial Random Noise Stimulation on Sustained Attention

The excitatory effect that tRNS has on the underlying cortical structures (Laczó et al., 2014), is believed to boost subthreshold activity in neuronal networks engaged in the task (Fertonani & Miniussi, 2017; Paulus, 2011; Van Der Groen & Wenderoth, 2016). Several theories have attempted to explain the underlying mechanism of tRNS. One theory states that opening of ion channels facilitates neuronal communication and causes changes in excitation and inhibition (Antal & Herrmann, 2016; Van Der Groen & Wenderoth, 2016). Another theory explains that electrical noise added to subthreshold activity has a boosting effect on the signal, similar to how visual noise can improve detection of a noisy image (Antal & Herrmann, 2016; Van Bueren et al., 2023; Van Der Groen & Wenderoth, 2016). Previous research has identified performance benefits when tRNS was applied via right frontal and parietal electrodes when participants performed a monotonous sustained monitoring task (Harty & Cohen Kadosh, 2019). In particular, participants with poorer attention at baseline profited the most when receiving 1 mA but not at sham or 2 mA tRNS. In the attention network task (ANT), left frontal tRNS improved response speed for executive control of incongruent stimuli, alerting or readiness to respond to stimuli, and orienting or shifting focus (Lema et al., 2021). In addition, Tyler et al. (2018) found an improvement in temporal attention during bilateral parietal tRNS. Apart from sustained attention, tRNS has been reported to improve solving demanding maths problems (Popescu et al., 2016; Van Bueren et al., 2023) and visual detection accuracy (Van Der Groen & Wenderoth, 2016).

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Although no studies of tRNS and mind-wandering (MW) have been published, Martínez-Pérez et al. (2023) showed elevated MW reported during excitatory transcranial direct current stimulation.

These results suggest that tRNS could be a valuable tool to improve sustained attention in monotonous tasks, as well as in tasks requiring more executive control due to the task demands or individuals baseline ability. However, no study to date directly tested the effects of tRNS on less and more complex versions of the same sustained attention task and self-reported MW.

5.0.2 Physiological Markers of Sustained Attention

As discussed in previous chapters, sustained attention relies on top down control and optimal levels of arousal adapting to the task demands which is controlled via tonic and phasic noradrenergic activity (Aston-Jones & Cohen, 2005; Esterman & Rothlein, 2019).

In line with behavioural effects, tRNS has been reported to reduce the resting theta/beta ratio (TBR), a cortical marker of sustained attention and top-down control (Angelidis et al., 2016; Harty & Cohen Kadosh, 2019). As evident from the results of Harty & Cohen Kadosh (2019) and Chapter 2, a higher pre-stimulation TBR was associated with poorer continuous monitoring task (CMT) performance and predicted stimulation success next to behavioural markers of sustained attention.

The TBR extracts periodic activity from resting EEG in slower theta bands and faster beta bands to calculate the ratio between slow and fast oscillations (Angelidis et al., 2016; Clarke et al., 2019). TBR over frontal and central midline regions has been known to relate to attention skills, especially in children with attention difficulties (Herrera-Morales et al., 2023; S. M. Snyder & Hall, 2006). However, since TBR is traditionally calculated based on the relative power in theta and beta frequencies, it has been noted that a great proportion of the TBR measure can be confounded by the overall power slope of the full EEG spectrum (Donoghue et al., 2020). This slope, also known as aperiodic exponent (AE) or 1/f activity, has

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itself been identified to mark information processing via the excitation/inhibition (E/I) balance and is raised in patients with attention deficit hyperactivity disorder (ADHD) indicating a low E/I ratio (Dakwar-Kawar et al., 2024; M. M. Robertson et al., 2019). The AE also related to performance in healthy participants (Ostlund et al., 2021) and was successful in predicting those participants with high AE to improve more in a learning task during tRNS (Van Bueren et al., 2023).

Not much is known about the impact of tRNS on pupil markers of arousal. Pupil dilation increases with higher arousal levels induced by the locus coeruleus (LC) via noradrenergic projections innervating frontal and parietal cortices (Alnæs et al., 2014). Since tRNS has an excitatory effect on the cortex, it is possible that it can compensate for suboptimal network engagement (Harty & Cohen Kadosh, 2019; Van Der Groen & Wenderoth, 2016) but it is unclear whether the pupil marker would adapt under those circumstances. Indeed, tRNS over the cerebellum did not cause significant changes in pupil dilation (Kawakami et al., 2024). However, no motor learning benefits during tRNS were observed behaviourally which might explain these results.

5.0.3 The Current Chapter

The current chapter aimed to examine sustained attention improvements in visually monotonous and distracting tasks during right fronto-parietal tRNS, and to identify participants who profit the most based on baseline performance and physiological markers of attention performance.

Introduction of a Monotonous Vigilance Condition

To align the Airplane Control Task (ACT) from previous chapters (3-4) more closely with the monotonous detection task without search component used in Harty & Cohen Kadosh (2019), an additional vigilance condition was added to the previous two search conditions. In the vigilance tasks, participants had to detect rare bird trials within frequent airplane trials, all trials were congruent. Participants performed this extended ACT with 10-minute blocks of three complexity

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levels (vigilance, simple search, distractor search) on two consecutive days. In a counterbalanced fashion, on one of the days, the participants received 1 mA tRNS during the task blocks and on the other they received a sham protocol with 30 s ramp up and 30 s ramp down of the current at the start of the task. Stimulation parameters were replicated from Harty & Cohen Kadosh (2019), targeting the right dorsolateral prefrontal cortex (dlPFC) and the inferior parietal lobule (IPL) which are key regions in sustained alertness and attentional control in uncued paradigms (Fan et al., 2005; Singh-Curry & Husain, 2009) and resulted in a performance improvement before (Harty & Cohen Kadosh, 2019).

TBR was measured at rest before and after the baseline and tRNS intervention task blocks to assess baseline and changes induced by tRNS. Pupil size was measured during the resting state and during the task. As before, participants filled out questionnaires and were prompted to report MW and thought content, sleepiness and motivation levels during the task.

Accuracy and response variability were performance scores of interest, next to the prompted ratings of thought content (i.e. MW, on-task, distracted, etc). TBR was compared between the traditional calculation based on the relative theta and beta power, see Harty & Cohen Kadosh (2019), and the extraction of periodic power after removal of the AE (Donoghue et al., 2020). In addition, the AE was also used as a predictor for the E/I balance. Pre-trial and resting-state pupil sizes were extracted from task and resting periods of the session.

Research Questions

The current chapter aimed to answer whether tRNS had an enhancing effect on sustained attention, specifically changes in performance, MW, and physiological attention markers. It was of special interest whether tRNS could improve performance in a monotonous and simple task, and in more difficult, distracting, and arousing tasks. In addition, I examined whether all participants profited from the stimulation or whether a subsample could be identified using baseline markers of sustained attention.

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Since sustained attention benefits have been observed in previous studies, tRNS, compared to sham stimulation, was expected to improve sustained attention performance in the ACT, along with a reduction in MW, TBR, AE, and pupil size. Baseline attention markers (performance or physiological) were expected to distinguish between participants that profited from tRNS and those that did not, specifically indicating that poor baseline ability would lead to greater improvements during real tRNS.

Furthermore, no association between baseline pupil size and TBR was expected, which is in line with the difference between the markers of arousal and cognitive control independently underlying sustained attention.

5.1 Methods

Methods of Study 5 were preregistered ([10.17605/OSF.IO/2A6S8](https://osf.io/2A6S8)) on OSF, however some of the analyses were adapted. Since CoV was not affected by tRNS as expected, it was excluded as covariate from other models. To provide a more concise results section, on-task analyses were focused on the thought categories including task focus, distractions, and MW. Lastly, for some analyses, the data did not fulfil assumptions or proved unfeasible as initially intended and were adapted or excluded.

5.1.1 *Participants*

A sample of healthy, young adults was recruited via posters in Oxford University buildings, student and public recruitment schemes hosted by the University, local social media groups, and word-of-mouth.

The eligible age was 18-35, and participants were required to have normal or corrected-to-normal vision (contact lenses or glasses), be right-handed, and fluent English speakers. Only healthy, non-pregnant individuals, specifically without diagnosed neurological or psychiatric conditions, history of migraines or fainting,

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previous head trauma, neurosurgical procedures, hearing problems, metallic implants, or drug treatments could take part. Participants were not eligible if they consumed alcohol or drugs (regularly, or more than 3 units during the 24h prior to the study), caffeine (more than 1 cup of coffee/ tea in the hour before the study), or if they reported less than 6 hours of sleep in the previous night.

Forty-five participants attended at least one session of the study. After the second session, their time was reimbursed with £10/ hour paid via bank transfer, or corresponding study credits. Ethical approval was granted via the Medical Sciences Interdivisional Research Ethics Committee (R82513/RE002).

5.1.2 Apparatus and Materials

The experiment took place in the same study space as in Chapter 4. The computerised task was displayed on a computer monitor in a sound-proof experimental booth with the researcher present. Participants were seated at a table with their chin stabilised approximately 50 cm away from the display (28.5 degrees horizontally, 24.6 degrees vertically). The room was lit by a ceiling light. The task was presented on Windows 7 in Matlab (Version R2019a) using the Psychophysics Toolbox 3 ([Brainard, 1997](#)) and custom scripts.

Stimuli. The previous version of the ACT was reused (see Chapter 3 and 4) but an additional vigilance condition was added to the existing distractor and non-distractor search conditions. The vigilance task was designed with a similar motoric and visual load as the non-distractor search (4 stimuli on the radar) but in each trial, participants saw only congruent stimuli and had to respond whether all stimuli were airplanes or birds. Thought probes for task focus, motivation, and sleepiness, the MW probe, and CFQ and ASRS (IA) questionnaires, are described in previous chapters (Chapter 3 and 4).

Eye-tracking. The same desktop-mounted Eyelink 1000-Plus (SR Research, Ontario, Canada) with chin-rest collected monocular eye dynamics data at a sampling rate of 500Hz from the dominant eye. A 9-point calibration was run using

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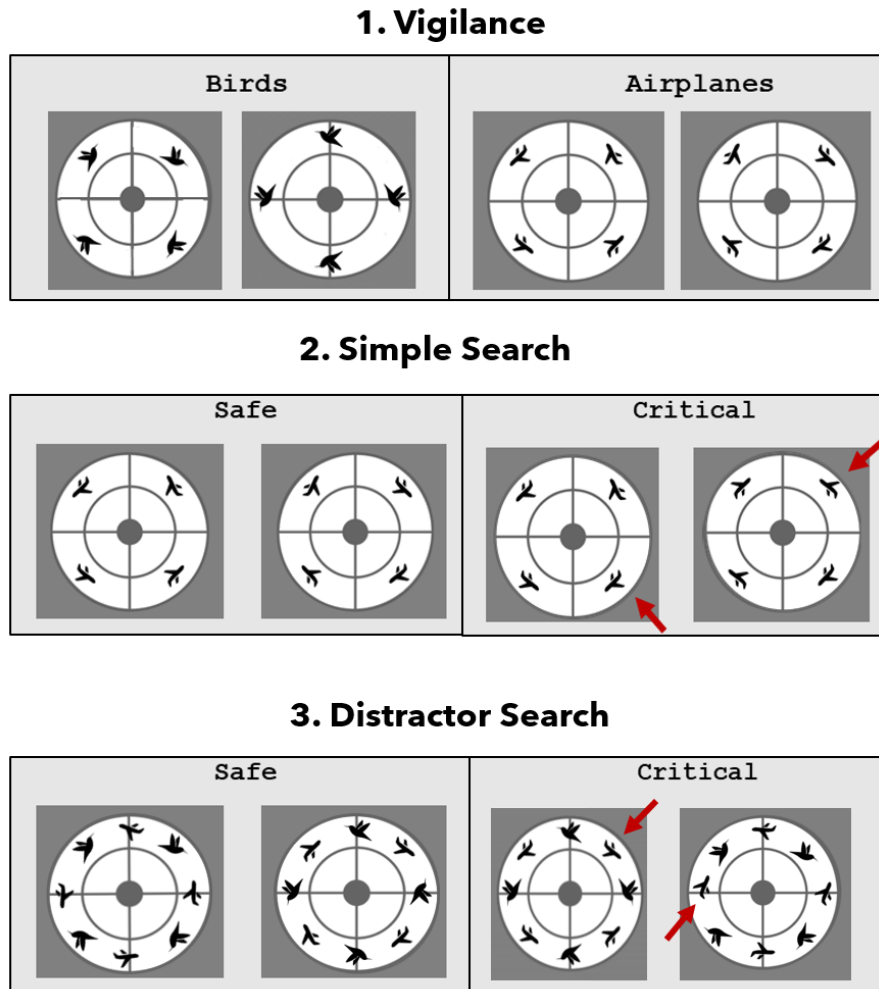


Figure 5.1: ACT Stimuli. The same simple and distractor search conditions from previous chapters were used in this chapter. For the search task, a block contained congruent (89%) trials (safe) and incongruent trials (11%), indicated by red arrows, which were distinguished by pressing the respective button. Task blocks were either without or with distractor items. In addition, a monotonous vigilance condition was added, which displayed either 4 airplanes, or 4 bird distractors. Via button press, participants were asked to identify whether they saw airplanes or birds. All responses were made with the dominant index finger on adjacent buttons of a response box (left, right). The blockorder between vigilance, simple search, and distractor search conditions was randomised between participants.

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customised coordinates (20% horizontal, 35% vertical) to cover the stimulus display area of the screen.

EEG Acquisition. EEG was recorded from 32 scalp locations (international 10-20 system: Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, 01, 0z, 02) according to the international 10-20 system via the StarStim32® and NIC2 software (Version 2.1.3.4). Data samples were acquired at 500 Hz via Bluetooth lab streaming layer (LSL) connection. Circular 12mm Ag/AgCl sintered electrodes (NG Pistim, Neuroelectronics®) served as EEG and as tRNS electrodes throughout the whole session. Mastoid electrodes served as common mode sense (CMS) reference and driven right leg (DRL) feedback, which together cancel out common-mode noise in the body. Impedance was kept at 0-10 k Ω . The resting state EEG recording was run in Matlab using the ‘MatNIC2’ Toolkit (Version 10). Participants initiated the EEG recording which triggered the display of a white fixation cross (font ‘Arial’, size 70) on a black background by button press.

tRNS. Per session, a total of 30 minutes (3x 10-minute blocks) of 1 mA (peak-to-peak) high-frequency tRNS was applied using the same StarStim32® device as for the EEG. A short resistance test was performed before intervention to ensure that the connection was adequate. Stimulation was slowly introduced via a 30 s ramp up at the start and a 30 s ramp down to 0 mA at the end of each block. Sham stimulation consisted only of 30 s ramp up and 30 s ramp down at the start of the blocks, without further tRNS. Double-blinding of the stimulation condition was ensured via renaming of the stimulation protocols by an independent researcher and automatic randomisation and protocol selection in the experimental script. All portions of the screen that could indicate whether the protocol was sham or real tRNS were obscured during the full study course.

5.1.3 Procedure

All participants performed the same set of tasks and questionnaires on two consecutive days around the same time of day, see Fig. 5.2. Participants received the study

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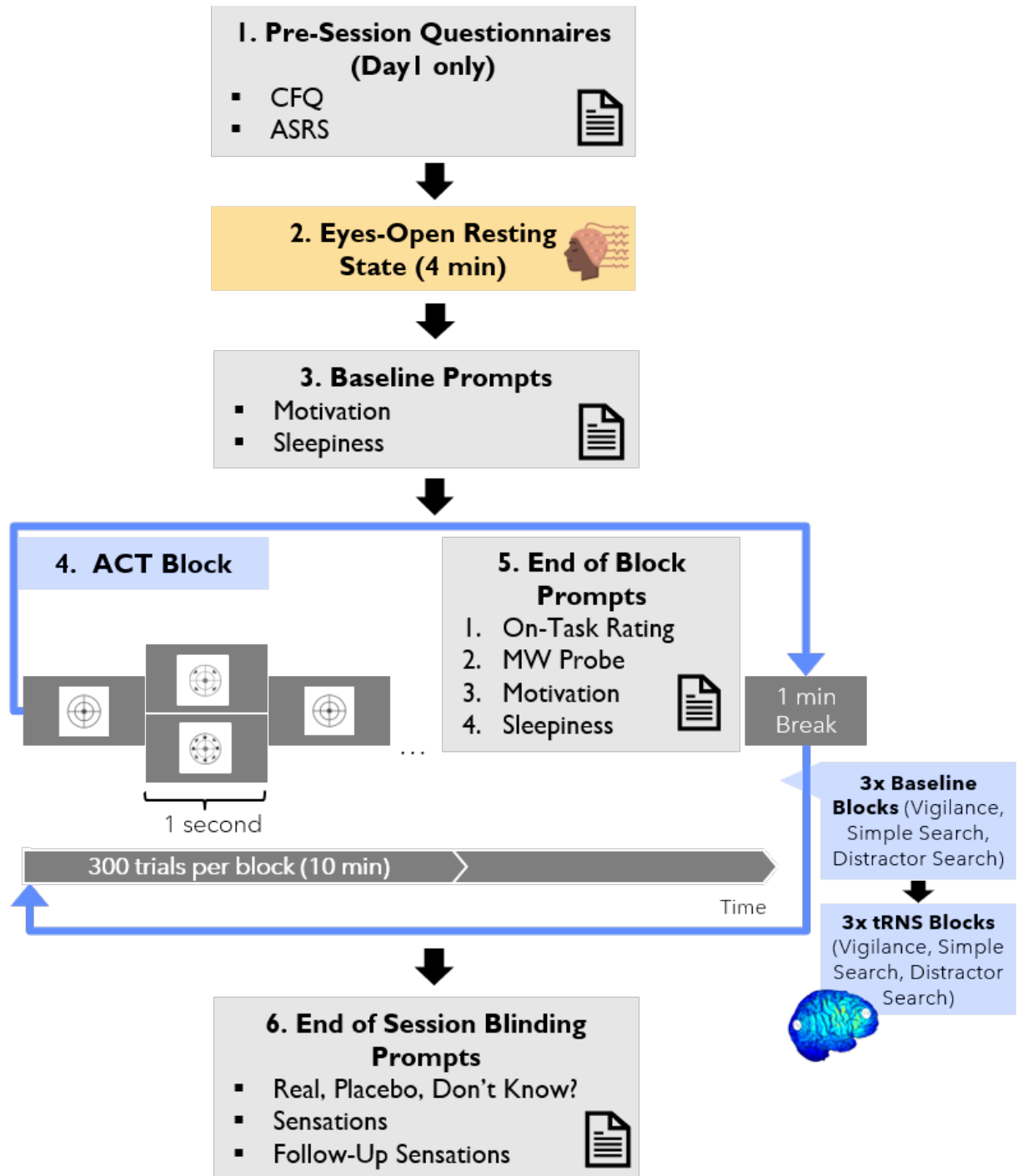


Figure 5.2: Procedure. On day 1, participants first completed the CFQ and ASRS questionnaires (1.). In both sessions, after fitting the headgear, a 4-min baseline EEG eyes-open resting state was recorded (2.) Then, participants rated their motivation and sleepiness before the ACT blocks began. There were 6 10-min (300 stimuli) ACT blocks in total, 3 baseline blocks without tRNS, and 3 with active tRNS with a 1 min break between each block (grey screen, no tRNS). The block order between vigilance, simple search, and distractor search conditions was randomised between participants. After each task block, participants rated on-task behaviour, categorised their thoughts in the MW probe, and rated their motivation and sleepiness in the previous block. At the end of the 3 tRNS blocks, participants also answered questions to assess blinding and sensations perceived during the tRNS blocks.

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information after signing up and at least 48 hours before the session. On arrival, the study was summarised and participants could ask any remaining questions, before giving consent to participate. Only on day 1, pre-questionnaires including personal information, CFQ, and ASRS were presented. This was followed by the headgear setup for EEG recording and tRNS. The experimenter measured the head circumference and the dominant eye was determined. Next, two mastoid electrodes (Sticktrodes, Covidien) were fitted behind the right ear as reference and feedback electrode. The EEG cap was fitted with the Cz location at the intersection of theinion-nasion and the ear-to-ear distance. All 32 electrode locations were cleaned with abrasive skin gel and surgical spirit, before conductive gel was inserted. The electrode caps and cables were subsequently attached. In the experimental booth, the Starstim headset was attached via Velcro in the back of the EEG cap and all cables were connected. Then, the eye-tracker was adjusted and calibrated for the first of three EEG resting state recordings. Participants were instructed to keep their chin on the chin-rest, to focus on the fixation cross at the centre of the screen, to relax their face and upper body, and to try not to control their thoughts. They were shown the ongoing EEG recording and were encouraged to try out the effects of clenching their teeth as an example. After 4 minutes, participants could rest their eyes briefly and then received instructions for the ACT.

They completed practice trials for the MW probes (practice items reported in Chapter 3) and the ACT. First, the vigilance condition was practiced slowly (6 seconds/trial) with feedback on screen (10 trials total, 4 bird stimuli) and at normal speed with verbal feedback if necessary (2 seconds/ trial, 45 trials total, 5 bird trials). Then, participants completed 10 trials (4 critical) each for the simple search and the distractor search at slow pace followed by 45 trials (5 critical) each at normal task speed (1000 ms fixation, 1000 ms stimulus).

Before the task started, participants reported their motivation and sleepiness at baseline and then completed 2 sets of 3 blocks (3 baseline, 3 tRNS) with 150 trials (300 stimuli) each of the ACT. Each block lasted approximately 10 minutes. Participants all completed all three conditions (vigilance, simple search, distractor

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search) and the block order was randomised between participants, but remained the same for one participant in the baseline and tRNS blocks in both sessions. Immediately after each ACT block, thought content and MW probes, motivation, and sleepiness were rated and reported. Between blocks, a timed 1-minute break allowed participants to drink, rest their eyes and neck while remaining seated. Responses were recorded using right and left index fingers on a response box with two buttons labelled ‘R’ and ‘L’. The association between left and right buttons and critical and safe trials was randomised between participants.

After the 3 stimulation blocks were complete, participants were asked whether they believed the stimulation was real, placebo, or whether they did not know. Then, on a scale of 1 (no pain) to 9 (worst pain imaginable), they rated any perceived scalp sensations (itching, pain, burning, warmth/heat, fatigue/decreased alertness, flashing lights other than the stimulus). If a sensation was rated higher than 1, a follow up question inquired about how much the sensation affected their general state (1, not at all - 5 very much), and for how long the sensations were felt (1 to 9+ minutes).

5.1.4 Data Analysis

All analyses were performed in R (Version 4.3.0) or Matlab (Version 2023b) using custom scripts. Outliers, exclusion criteria, and calculation of performance (hit rate, CoV, CFQ, ASRS) were the same as in the previous chapters, as was the method for all linear models. In addition to the procedure of random slopes followed in previous chapters, the variable for task block was entered in all mixed effect models as a random slope but did not contribute significant explanatory power to any model to justify its inclusion. Motivation, sleepiness, and task-focus (On-task rating) were analysed as ordinal variables. Multicollinearity was kept below the conservative threshold of $GVIF < 2.23$ where possible but since in models with categorical predictors, multicollinearity can occur more severely, moderate multicollinearity (equivalent to $Vif < 10$) was accepted with values of

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$G\text{VIF} < 3.16$ (Minkow & Fuerst, 2024). Multiple comparisons were corrected using the Holm procedure.

Sample-Size Calculation. Using data from Chapter 4, the mixedpower package in R (Kumle et al., 2021) was used to determine a minimum sample size of $N=50$ to detect an effect of behaviour between the different task versions with at least 80% power. In addition, based on Harty & Cohen Kadosh (2019)'s medium-large effect sizes for repeated-measures, within-subject differences in tRNS for CoV and TBR, G*Power estimated a minimum sample of 30 participants to detect medium-sized effects with 80% power. Therefore, a minimum sample size of $N=50$ was aimed for, with the possibility to collect 10 additional participants before the closing date of the study to account for excluded data. However, when the maximum time period for data collection was reached, only 45 participants had been collected and no further subjects could be added.

Eye blinks. Number of eye blinks and blink duration were recorded by the EyeLink On-line Parser. An extra 100 ms of data around detected eye-blinks was removed. Mean eye blinks was based on all eye blinks during the entire task block, mean trial eye blinks took only blinks during the stimulus display into account (200 ms-1000 ms after stimulus onset), and mean pre-trial blinks were calculated from blinks during the fixation display (200 ms-1000 ms after fixation onset). Blink duration for all included eye blinks were extracted as recorded by the Eye-Link.

Pupil size. Mean pupil size was calculated including any pupil size data not marked as eye blinks in the aforementioned procedure. Pupil sizes were also averaged over the whole block, the trial period (200 ms-1000 ms after stimulus onset), and the pretrial period (200 ms-1000 ms after fixation onset). Then pupil sizes within all 4 baseline blocks were Z-scored per participant.

EEG preprocessing. For the analyses, data from the central midline electrode (Cz) was selected to provide TBR measurements as it previously shown results with high sensitivity and specificity (Harty & Cohen Kadosh, 2019; Monastra et al., 1999). The parietal electrode directly between the two tRNS electrodes (C4) was selected for the AE since it lay at the centre of the bidirectional current between

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F4 and P4 as has been done before (Van Bueren et al., 2023), the results were consistent with the AE at F4 and P4 corresponding to the two major nodes of the fronto-parietal attention network.

The raw EEG data was preprocessed using the EEGLAB toolbox (Delorme & Makeig, 2004) in Matlab. Closely following the protocol from Harty & Cohen Kadosh (2019), the data was low-pass filtered (40 Hz) to remove electrical interference and higher frequency artifacts and epoched into segments of two seconds. Noisy epochs (>100 microV) were rejected. The data was Fast Fourier Transformed (FFT) with data that was missing 50% or more epochs being excluded.

TBR. For the traditionally calculated TBR, absolute theta (4-7.5 Hz) and beta power (14-30 Hz) were divided by the absolute power of the full spectrum (1.5-30 Hz). The resulting relative theta power was divided by the relative beta power and log transformed.

Periodic TBR and Aperiodic Signal. Additional preprocessing steps were performed to prepare the data for the parameterisation. Channels were re-referenced to average, baseline removed and a high-pass filter (0.5 Hz) was applied. Then an ICA was run to remove artefacts. I specifically excluded prominent eye blinks, muscle activity, and heart artifacts based on visual inspection of the topographical maps, time course and frequency distribution. The Fourier transformed data was then processed into aperiodic and periodic components using the *fooof* - *fitting oscillations \& one over f* package (Donoghue et al., 2020) in Spyder (Version 6.0.3) with Python (Version 3.12.4). The slope of the EEG power spectrum was extracted from the power spectrum between 1.5 and 40 Hz using the following parameters: `peak_with_limits = [1.0, 8.0]`, `max_n_peaks = 5`, `aperiodic_mode = 'fixed'`. Subsequently, the AE was fitted and oscillatory power from the existing peaks in theta and beta bands was extracted. To calculate the periodic TBR, the power in the extracted peaks from the theta range was divided by the periodic beta power and log-transformed.

5.2 Results

5.2.1 Sample

Out of 45 data sets, two participants were excluded for insufficient task responses in the first session, a further two did not complete two sessions due to equipment malfunction, one other participant missed the second session, and one last participant discontinued after the baseline part of the session (task practice and baseline, and EEG resting state) due to feeling unwell. 3 blocks of 2 participants were excluded because 60% or more of the responses were missing. A further 8.66% of blocks were identified as outliers in performance (hit rate and CoV) and removed from the analyses. Specifically, 3 baseline CoV values were outliers (2 participants), and 7 baseline hit rates (4 participants), in addition during tRNS 4 CoV outcomes (3 participants, 1 sham) and 6 hit rates during tRNS (3 participants, 3 sham) were excluded as outliers. The final sample included 39 participants (age 18-32, $M=22.03$, $SD=4.03$, 32 female).

5.2.2 Effects of tRNS on Behaviour and Physiology

CoV. CoV was predicted to reduce from active (but not sham) tRNS. Moreover, participants with high baseline CoV were predicted to profit from the intervention the most. As shown in Tab. D.1, the only significant effects when predicting CoV (conditional $R^2=0.75$) were main effects in task condition ($p<.001$), baseline CoV ($\beta=0.02$, $p<.001$, 95%CI= [0.02, 0.03]), and sleepiness ($\beta=0.01$, $p=0.02$, 95%CI= [0, 0.02]). CoV differed significantly in all three task conditions, with the highest CoV in the vigilance task ($M=0.27$, 95%CI= [0.26, 0.29]), followed by the simple search ($M=0.25$, 95%CI= [0.24, 0.27]), and the distractor search ($M=0.23$, 95%CI= [0.21, 0.25]), see Fig. 5.3a.

Hit Rate. Apart from main effects of baseline hit rate ($p<.001$), task condition ($p<.001$), and sleepiness ($\beta=-0.02$, $p<.001$, 95%CI= [-0.02, -0.01]), tRNS interacted with baseline hit rate and also with task, see Tab. D.2 (conditional $R^2=0.71$).

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The interaction between tRNS and task ($p=0.023$) indicated only in the vigilance task, hit rate was higher for 1mA tRNS ($M=0.98$, 95%CI= [0.96, 1]) compared to sham stimulation ($M=0.94$, 95%CI= [0.92, 0.97]), see Fig. 5.3b.

The interaction between tRNS and baseline hit rate ($p=0.047$) showed that for participants with lower baseline hit rate, performance was better during 1 mA tRNS ($\beta=0.03$ (95%CI= [0, 0.05]) compared to sham stimulation ($\beta=0.06$ (95%CI= [0.03, 0.08])). This is indicated by the significant difference between the slopes, which marked a larger difference between low and high performers, with lower performance for participants with low baseline hit rate, see Fig. 5.3c.

MW. A three-way interaction between tRNS, task, and baseline MW responses showed signs of overfitting the data, therefore, I planned to fit two models to estimate whether tRNS interacted with task and baseline MW individually. However, there was an imbalance of the rating conditions, with only 23 votes for task-focused thoughts, compared with 103 ratings of MW. Instead, I performed a linear analysis on the mean MW ratings across all blocks to estimate the effect of tRNS on MW. Again, the assumptions for the model were not fulfilled and data transformation did not improve the data. Therefore, the binary MW variable was not further investigated in this sample.

Pupil Size. Since block was a significant predictor of pupil size in Chapter 4, it was entered in this model as a covariate (adjusted $R^2=0.56$). There was no significant effect of tRNS on pre-trial pupil size, but main effects of task ($p=0.011$), baseline pupil size ($p<.001$) with a trend of $\beta=0.21$ (95%CI= [0.17, 0.26]), and block ($p=0.004$) were significant, see Tab. D.3.

Pupil size during the vigilance task ($M=-0.01$, 95%CI= [-0.1, 0.07]) and simple search ($M=0.01$, 95%CI= [-0.05, 0.07]) were smaller than during the distractor search condition ($M=0.13$, 95%CI= [0.06, 0.2]), see Fig. 5.4a.

Pupils were also largest during the first block ($M=0.12$, 95%CI= [0.06, 0.19]) compared to block 2 ($M=-0.01$, 95%CI= [-0.07, 0.05]) and 3 ($M=0.01$, 95%CI= [-0.05, 0.07]), see Fig. 5.4b.

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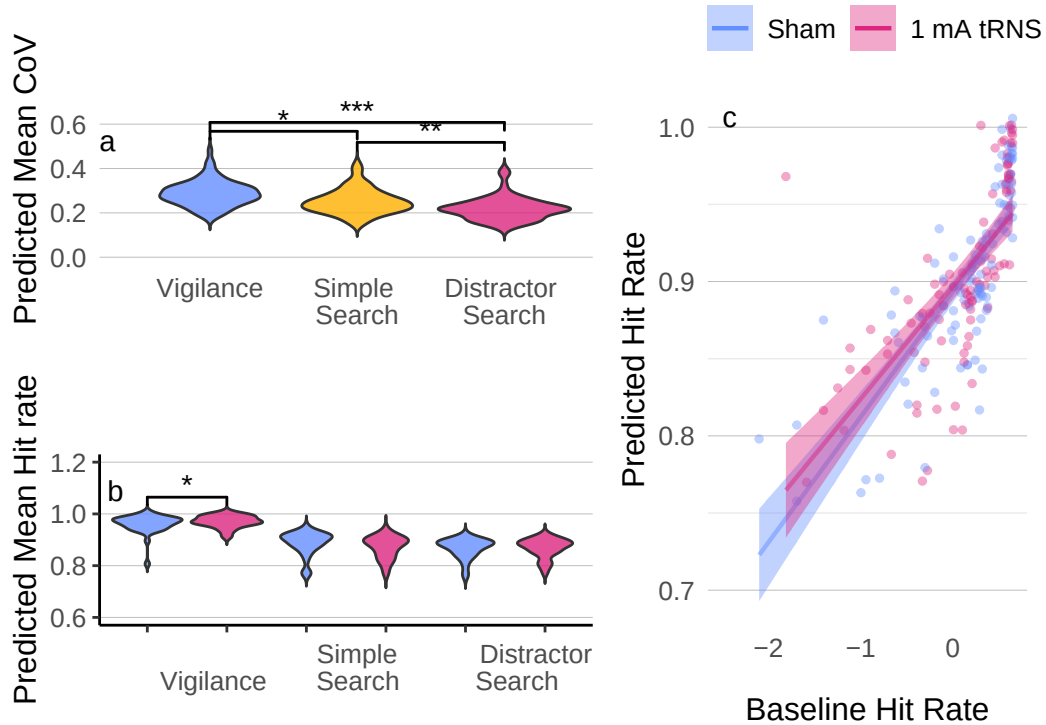


Figure 5.3: Behavioural results of tRNS and task parameter effects on attention performance. a. Task condition significantly predicted CoV in the task ($p < .001$). The figure shows that CoV was higher in the Vigilance condition ($M = 0.27$) than in the simple search ($M = 0.25$), and lowest in the distractor search condition ($M = 0.23$). b. The task significantly predicted hit rate in interaction with tRNS condition ($p = .023$). Only, in the vigilance task, responses were more accurate during real tRNS ($M = 0.98$) compared to sham ($M = 0.94$). c. Baseline hit rate also interacted with tRNS ($p = .047$) across all three task conditions. The figure shows a higher predicted hit rate when baseline was low during real tRNS compared to the sham tRNS condition. Error bars represent the standard error of the mean estimates. Significance marked by ***: $p < .001$, **: $p < .01$, *: $p < .05$. The shaded area represents the 95% confidence interval of the estimates.

Theta/Beta Ratio. Since TBR was only recorded before and after three task blocks, an interaction with task condition could not be estimated, instead I ran models to predict traditional TBR (as in Harty & Cohen Kadosh (2019)), the TBR calculated only on periodic activity, and the aperiodic exponent of the EEG power spectrum by stimulation, including an interaction with the baseline hit rate effect that was significant earlier.

The traditional TBR was only predicted by the baseline TBR ($p = < .001$) with

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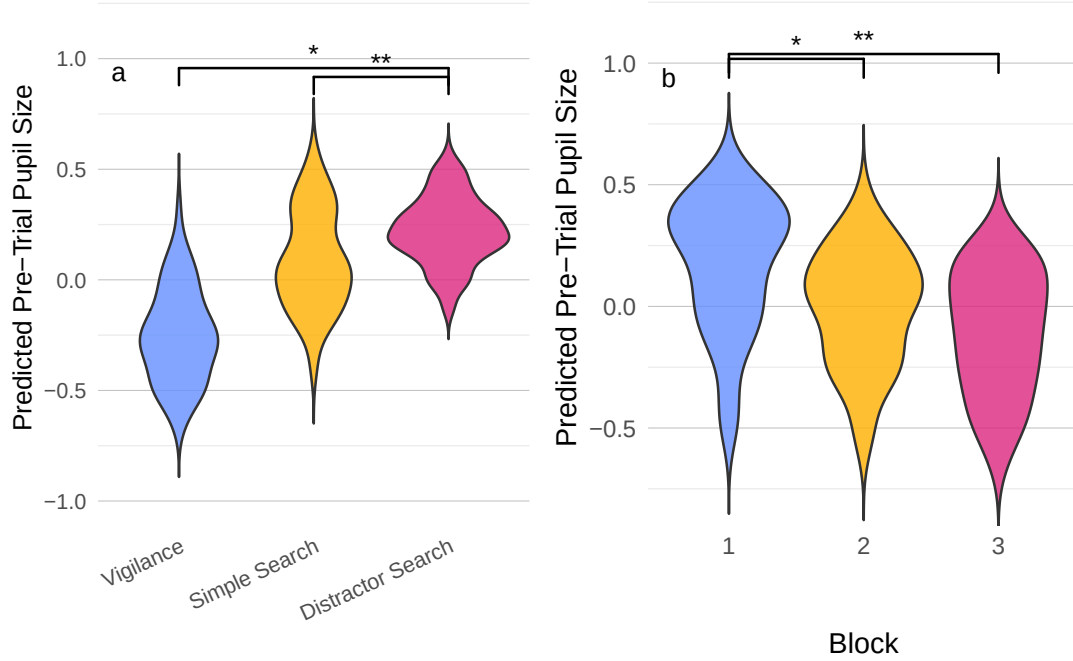


Figure 5.4: tRNS effects on pre-trial pupil size during the ACT. a. Task condition significantly predicted pre-trial pupil size (Z-scored) in the ACT ($p = .011$). The figure shows a higher predicted pupil size during the distractor search ($M = 0.13$) compared to simple search ($M = 0.01$) and vigilance ($M = -0.01$). b. Blocks significantly predicted pupil size ($p < .001$). The figure shows a higher predicted pupil size in block 1 ($M = 0.12$) compared to block 2 ($M = -0.01$) and 3 ($M = 0.01$). Error bars represent the standard error of the mean estimates. Significance marked by ***: $p < .001$, **: $p < .01$, *: $p < .05$.

trending effects of baseline hit rate ($p = 0.074$) and the interaction between baseline hit rate and baseline TBR ($p = 0.066$), see Tab. D.4 (conditional $R^2 = 0.53$).

Periodic TBR was only predicted by its baseline (conditional $R^2 = 0.87$), and AE had no significant predictors (adjusted $R^2 = 0.55$), see D.5 and D.6 for details.

5.2.3 Resting-State and Behavioural Results

Baseline Response Variability Predicted by Pupil Size. As shown in Tab. D.7, there were both main effects of pre-trial pupil size ($p = 0.004$) and task condition ($p < .001$) and an interaction between the two predictors ($p < .001$). The interaction revealed that the slope of baseline pre-trial pupil size differed between all three task conditions, in the vigilance condition, a positive trend ($\beta =$

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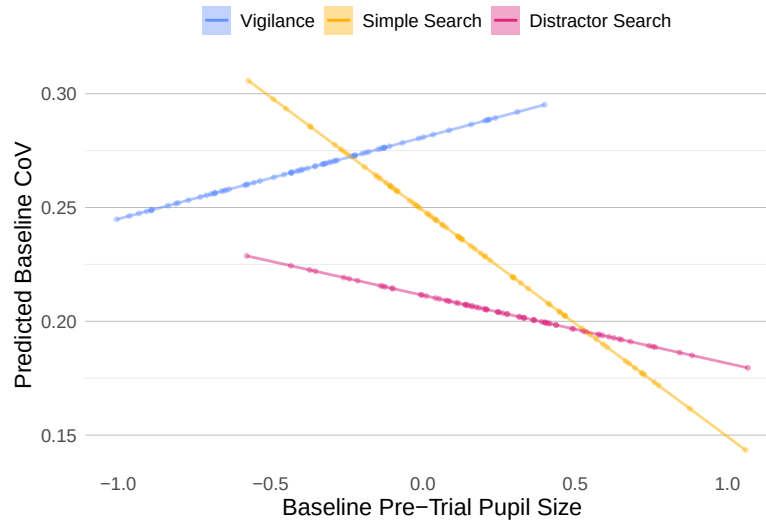


Figure 5.5: Baseline pre-trial pupil size predicted CoV in baseline task blocks ($p < .001$). In the vigilance task, larger pupils were associated with larger response variability. In both simple search and distractor search the trend was negative. The shaded area represents the 95% confidence interval of the estimates.

-0.04, 95%CI= [-0.06, -0.03]) predicted larger pupil size with larger CoV at baseline, but during the simple search ($\beta = 0.02$ (95%CI= [0, 0.03])) and distractor search ($\beta = -0.01$ (95%CI= [-0.03, 0])) the trends were negative, indicating smaller pupil size predicted larger response variability, see Fig. 5.5.

The same analysis could not be repeated for hit rate since it still violated the assumption of normal residuals after transformation attempts and fitting the model in a generalised linear model with different link functions.

Relation Between Physiology Measures and Behaviour. To explore how TBR and aperiodic measures related to resting state pupil size and baseline performance, I performed a spearman correlation, see Tab. 5.1. Except for a significant correlation between the AE and the traditionally calculated TBR ($r = 0.72$, $p < .001$), no EEG measure correlated with one another or with baseline resting pupil size. As traditional TBR is calculated by the total power at beta and theta frequencies, the AE is included in the measure and a correlation is expected. Mean baseline CoV and MW were correlated ($r = 0.36$, $p < .05$).

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Table 5.1: Correlating Resting-State and Baseline Behaviour

Variable	Traditional TBR	Periodic TBR	AE	Pupil Size	CoV	HR	MW
Traditional TBR	1.00						
Periodic TBR	-0.53	1.00					
AE	0.74***	-0.49	1.00				
Pupil Size	0.00	0.35	0.05	1.00			
CoV	-0.14	-0.05	0.03	-0.20	1.00		
HR	-0.19	0.05	-0.22	-0.21	-0.06	1.00	
MW	-0.06	-0.25	0.04	-0.08	0.36*	-0.02	1.00

Notes. Spearman correlation coefficients between all EEG baseline resting-state measures resting pupil size, and mean baseline behavioural scores from the ACT. Significance is marked as ***: $p < .001$, *: $p < .05$

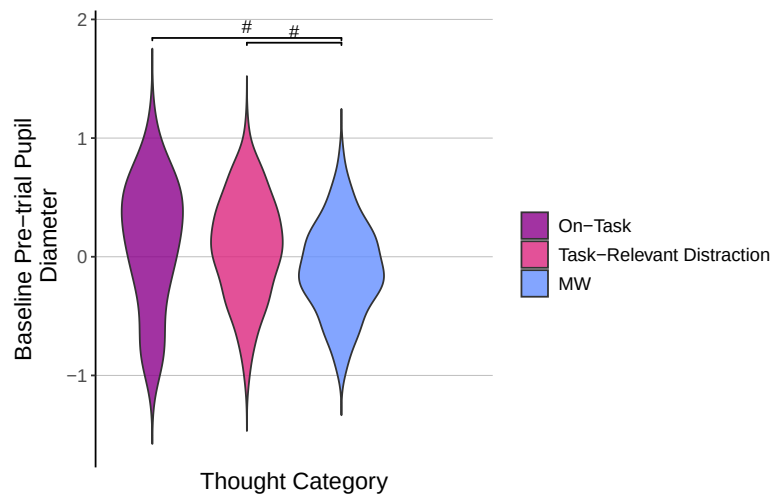


Figure 5.6: MW thought categories were predicted by eye dynamics. When predicting task-focused thoughts, task-relevant distractions, and MW by pre-trial pupil size, the credible interval for on-task and task-relevant thoughts showed a larger pupil size compared to the reference category MW (#). Error bars represent the standard error of the mean estimates. Significance equivalence ($p < .05$) marked by #: 95% credible interval excluding zero.

Baseline Pupil Size and MW. Only 5 out of 228 thought categories were rated as externally distracted, therefore I replicated the MW category results from chapter 4, with only the categories on-task, task-relevant distractions, and MW

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ratings. As expected, baseline pre-trial pupil size predicted subjective thought categories, see Tab. D.8. With pre-trial pupil size during MW as reference, ($M = -0.1$), the model revealed an effect of pupil size for on-task thoughts ($\beta = 1.31$, 95%CI = [0.33, 2.32]) with a mean of $M = 0.12$ and task-relevant thoughts ($\beta = 1.14$, 95%CI = [0.38, 1.93]) with a mean of $M = 0.08$, see Fig. 5.6(#).

5.2.4 Blinding

To ensure that tRNS effects were not due to a placebo effect, the effectiveness of the sham stimulation was assessed after each session by a questionnaire. Participants rated whether the brain stimulation was perceived as real, placebo, or whether they did not know. After the active tRNS session, 89.74% of participants rated the session as real tRNS. After the sham tRNS session 76.32% of participants rated the session as real. A McNemar test for within subject ratings was performed to assess whether participants accurately distinguished real and sham stimulation sessions. 28 participants rated both sessions as real stimulation, 1 participant rated both session as sham. 1 participants rated the real tRNS session as placebo and the sham session as real. Only 2 accurately identified the real tRNS session and the sham session. statistically, there was no indications for a placebo effect ($X^2 = 0$, $p = 1$).

5.3 Discussion

The results of this chapter indicated that 1 mA tRNS over the fronto-parietal areas induced performance improvements in the ACT. Firstly, participants improved in accuracy when performing the monotonous vigilance condition. Secondly, a general improvement in all three task versions was seen for those participants that had the lowest hit rate during baseline. Importantly these effects were not due to blinding since a large majority of participants perceived both real and sham stimulation as genuine. Different to Chapter 2, CoV was not affected by tRNS in this study.

CoV increased with increased task complexity. Similarly, pre-trial pupil size was affected by task condition, with increased pupil size in the distractor search

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compared to the two easier ACT tasks, indicating a similar pupil size between the vigilance and simple search tasks. Furthermore, pupils were reduced in later blocks compared to the first block, which aligns with Chapter 4. An additional analysis revealed that at baseline in the vigilance condition, pretrial pupil size and CoV were positively associated, indicating that a greater pupil lead to more variable responses. Moreover, in the two search tasks, the opposite was true, namely a negative association predicting more stable performance when pupils were dilated.

Furthermore, I attempted to compare the outcomes between the TBR calculated in a traditional way based on the absolute power in the theta and beta frequencies, and the TBR calculated based only on periodic activity. In addition, I also aimed to examine whether the slope of the full power spectrum, also called AE or $1/f$, was a marker of sustained attention. There were no significant effects except for the respective baseline measures, indicating that the EEG spectrum did not change with tRNS, nor relate to behavioural performance and baseline pupil size in this experiment.

MW scores were imbalanced during the intervention part of the session, revealing that only a small proportion of the blocks was reported as task-focused. However, the baseline data confirmed a smaller pupil size when participants mind wandered during the task compared to when they were focused or distracted by task-relevant thoughts.

5.3.1 Behavioural Improvements during tRNS

Random noise has previously been suggested to benefit sustained attention performance. My results align with those found by Harty & Cohen Kadosh (2019), despite the difference between the CMT and ACT tasks from both studies. Overall, tRNS improved performance only during the monotonous vigilance condition which most closely resembles the CMT in terms of task demand. The current study followed the tRNS protocol closely and replicated the device and electrodes used, montage and current intensity. The tRNS was applied across three different tasks lasting 10 minutes each, whereas Harty & Cohen Kadosh (2019)'s stimulation

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lasted 20 minutes in total and was applied during four 5-minute blocks. My results indicated that participants became more accurate during the intervention but response variability was unaffected. In contrast, Harty & Cohen Kadosh (2019) found improved response variability but did not report better accuracy. One reason might be that in the ACT vigilance condition, more emphasis is placed on pressing the correct button in response to seeing a stimulus that is predictable in time. In contrast, the CMT is focused on detecting a change in the presented stimulus as early as possible in a long response interval of 1600 ms and respond as fast as possible. The latter might have allowed participants to respond accurately most of the time with the salience of the stimulus steadily increasing during the response interval, but differences in sustained attention could be measured by the speed at which participants noticed the stimulus change and the consistency at which they performed the task. In comparison, the ACT requires a decision about which button to press, and, although the instructions asked to make fast and accurate responses before the stimuli disappear, participants might have prioritised speed by submitting a response within the shorter 1000 ms response interval, which could have led to more mistakes when attention was diverting from the task. Indeed, another tRNS study (Lema et al., 2021) found performance improvements on all three conditions of the ANT, consisting of alerting (sustaining a state of readiness similar to sustained vigilance), orienting (spatial attention such as detection a novel stimulus), and executive (conflict resolution associated with a goal), see Petersen & Posner (2012). Importantly, when participants were asked to focus on speed, left frontal tRNS increased accuracy, but when focused on both fast and accurate responses, participants showed a decrease in RT during the executive task only (Lema et al., 2021). The difference in electrode montage might suggest that the studies are difficult to compare. However, since the ANT is a cued paradigm, left frontal brain regions might be more involved in supporting task performance, whereas in the CMT and ACT, right fronto-parietal and bilateral regions are implied to sustain attention in monotonous and non-cued tasks (Fan et al., 2005). For example, bilateral tRNS over the parietal cortex improved

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attentional selection (N. Shalev et al., 2018), detection sensitivity to temporal differences in stimulus display (Tyler et al., 2018) and orientation discrimination along with increased functional connectivity in the dorsal and ventral attention networks (Contò et al., 2021).

In contrast to the finding of improved accuracy in a simple monotonous task, Moret et al. (2021) found improved RT's but no change in the speed-accuracy trade-off in a simple Go/No-go task in a simple reaction time task with and without training when 1.5 mA left frontal tRNS was applied. However, bilateral frontal tRNS improved performance on a simple monitoring task (B. Frank et al., 2018). Interestingly, performance on the primary waste water treatment simulation task in the study did not improve after a single session, but when performing the same tasks 2 weeks later without stimulation, participants in the tRNS group performed better at the more difficult simulation task. Moreover, the improvement depended on participants' general mental ability, indicating a greater benefit of the tRNS for participants with lower mental scores.

This is in line with my results, predicting an overall benefit on all ACT conditions for participants that performed worse at baseline and with Harty & Cohen Kadosh (2019)'s finding of greater improvements for participants with lower TBR indicating lower baseline attention. Importantly, the effect was significant across the different versions of the ACT suggesting that tRNS can be beneficial for complex tasks as well as monotonous environments. Similar effects have been proposed in the field of arithmetic skill (Pasqualotto, 2016; Snowball et al., 2013). This could have important implications for learning and education and is in line with literature on tRNS and mathematical problems (Snowball et al., 2013; Van Bueren et al., 2023).

Together with Chapter 2, the difference between CoV and hit rate predicting the stimulation success might indicate that the differences between sustained attention requirements specify which predictor is most valuable in the context of the task. In both chapters, behavioural scores were the most predictive of tRNS gains.

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Although one might argue that participants with low baseline have more room for improvement, in my study participants with more room to improve performed better during active tRNS in a within-subject design, which indicated that the same participants with low baseline did not improve to the same degree during sham stimulation. In addition, the performance improvement was significant across the three task difficulties, showing that performance improved both with less and more room to improve in those individuals. Similarly, placebo effects can account for behavioural effects in brain stimulation studies (Fassi et al., 2023), which is unlikely in the current study as the blinding procedure was found to be effective.

The study results indicated that participants that have more difficulties with sustained attention tasks profited more from tRNS but at the same time, tRNS improved performance during an easy task for all participants and there were no benefits when the task was difficult. These two results stand in contrast with each other, one in line with previous studies improving monotonous and simple task performance via tRNS (B. Frank et al., 2018) and the other with improvements when performance is more difficult, within or between participants, (Harty & Cohen Kadosh, 2019; Van Bueren et al., 2023). Yet, previous studies found improvement in both monotonous and executive tasks (Lema et al., 2021; Moret et al., 2021). It is also possible that some studies found an overall effect but did not test for an interaction with baseline. The literature seems to support performance benefits during frontoparietal tRNS in a monotonous task and it is possible that a different head montage could have supported the control component of the search tasks similar to (Lema et al., 2021; Van Bueren et al., 2023). This is supported by a lesion-study which showed more involvement of the middle frontal gyrus and superior parietal lobe which are both superior to the tRNS electrodes chosen in this study and could have lead to suboptimal tRNS (Cojan et al., 2021). Since the final sample was smaller than planned, it is also possible that the study was under-powered to detect a 3-way interaction between tRNS, task, and baseline.

Overall, the outcome of this experiment imply that tRNS could be a valuable tool to improving sustained attention but it is important to target the intervention

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to those who experience difficulties. The improvement was predicted by baseline accuracy but not by other behavioural or physiological predictors. Future studies should investigate the benefits of sustained attention intervention in a learning context.

5.3.2 Effects of Pupil Dilation in Sustained Attention

Pupil dynamics have been linked to cognitive arousal processes associated with the LC which support sustained vigilance (Alnæs et al., 2014). Pupillometry has also been used as a marker for increased task demands (Alnæs et al., 2014; Pan et al., 2022; Zénon et al., 2014). This was supported by my results, indicating a greater pupil size in more demanding conditions. Specifically, I found greater pupil dilation during the distractor condition which could indicate that performing this task for 10 min elicited greater arousal in participants than when they had to detect targets or perform a simple search. This is in line with previous findings (Alnæs et al., 2014; Pan et al., 2022; Zénon et al., 2014). One alternative explanation could be that a larger pupil was triggered by the darker screen because more black stimuli were displayed during this condition. Pupils are known to constrict in brighter conditions (Guillon et al., 2016). Since the vigilance and simple search task have identical screen luminance, whereas the distractor search, by displaying double the amount of stimuli has a lower luminance could explain why pupils constricted more during the brighter stimuli blocks. However, pupils were measured only during the pre-trial fixation screen which was the same between all three tasks.

Furthermore, pupil size explained changes in CoV and this association was different between the vigilance condition and the two search tasks. In particular, responses were more stable when pupil sizes were small when the task was monotonous, indicating a performance benefit when arousal was low. In contrast, when performing the search tasks, higher levels of arousal were associated with better performance. Importantly, the latter effect was the same with and without distractors, which contradicts an influence of luminance and indicate that the difference arose from changes in task demands.

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These results contradict previous findings stating that difficult tasks require less arousal than simple tasks (Teigen, 1994), but is in line with Chapter 4 and Pan et al. (2022). Since the relationship between arousal and performance is described as an inverted U-shape (Teigen, 1994), it is possible that in the monotonous task, too high levels of arousal lead to distractibility and hence more variable responses. Furthermore, in difficult tasks, when arousal was lower than required for the given search requirements, unstable responses might have been consistent with the other end of the inverted U-shape, leading to hypoarousal and inconsistent button presses. Although it is counter-intuitive to the prediction of required arousal for simple and difficult tasks, it might be possible if the baseline arousal induced by the search tasks was higher than in the vigilance task leading to overall higher pupil sizes than during the vigilance task. Future studies might want to investigate the interaction between induced and required arousal in visual tasks.

Additionally, baseline pupil size predicted MW ratings, revealing smaller pupils when participants reported having internal task-unrelated thoughts compared to when they were focused, indicating that MW was associated with low arousal. This finding is in line with Chapter 4 and Unsworth & Robison (2016). Overall, this indicates that diverting thoughts during the ACT did not depend on the demands of the performed task and occurs in all task conditions when arousal is low (Thomson et al., 2015).

Furthermore, small pupils and low arousal have been associated with MW, and large pupils with high arousal and distractibility (Unsworth & Robison, 2016). Although the data did not allow me to test this directly, in the search tasks, participants were more focused when their pupils were large. Together with the larger pupil size for task-focus thoughts, it is possible that MW occurred due to hypoarousal when performance was less stable. This is consistent with Martínez-Pérez et al. (2021)'s finding that unintentional MW was greater in tasks that required high-effort. In the vigilance task, however, less stable performance could have been due to distractibility and hyperarousal, with MW occurring during periods of more stable task performance. It would be interesting to explore further

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whether more variable response times are related to distractibility rather than MW during monotonous ACT.

The current results suggest that tRNS may not affect pupil dilation. No previous studies known to me at this time have assessed the effects of pre-frontal tRNS on pupil dilation during a sustained attention task. However, Kawakami et al. (2024) applied 1mA tRNS over the cerebellum while participants performed a visuomotor learning task with no significant effects on performance or pupil size compared to sham. One reason why pupil size did not change with tRNS, might be that the fronto-parietal excitability compensated for sub-optimal control and arousal relevant to the task and improved behaviour rather than boosting the underlying top-down and bottom-up processes activating the sustained attention network.

In conclusion, pupil size was found to mark arousal states across different tasks and in line with performance outcomes and attentional states but more research is needed to disentangle the states of arousal during low and high effort tasks in relation to MW and task performance.

5.3.3 Strengths and Limitations

This study was the first to test the effects of tRNS on behavioural and physiological predictors in a sustained attention task with different levels of complexity while controlling for the effects of motivation and sleepiness. All tasks and interventions were within-subject and an effective double-blind protocol ensured that the outcomes are not due to placebo.

In addition, the EEG measurements included two different versions of the TBR and the overall slope of the aperiodic power. In contrast to Harty & Cohen Kadosh (2019), the current results did not indicate involvement of these markers of cognitive control. Previous studies have criticised the validity of TBR as a cognitive marker (Saad et al., 2018). A limitation of the current study was that resting-state EEG was only measured before and after the baseline and tRNS intervention but not in between different tasks. Therefore, one explanation could be that the different task versions had opposing effects on the EEG markers, which was the case in Perone et

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al. (2021) and as a result would be cancelled out. Future research should investigate changes in EEG markers between high and low effort sustained attention tasks.

Previous literature suggests that flattened aperiodic slopes have been found to be associated with slower and worse performance across domains (Euler et al., 2024), individuals with reduced cognitive control (Pi et al., 2024), and greater arithmetic gains when applied over the bilateral prefrontal cortices (Sheffield et al., 2020; Van Bueren et al., 2023). The current results did not suggest an association between baseline AE and performance on the ACT.

Assessment of MW was limited to the baseline period in the current task. As before in Chapter 4, very few blocks were rated as external distractions which can be attributed to the quiet environment in the study room. Furthermore, during the second session on each day (with either sham or real tRNS), very few blocks were rated as task-focused which made it impossible to estimate the effects of tRNS. Future studies might consider more controlled experiments to induce external distractions and MW in order to achieve a more homogeneous sample.

5.3.4 Conclusion

The current study showed that active tRNS had an effect on monotonous vigilance performance in a sample of young healthy adults. In addition, participants with low performance at baseline improved in monotonous and higher complexity sustained attention tasks. Future studies should examine whether the current findings could be extended to target for medical intervention across a variety of settings with implications for learning in educational settings. Secondly, the differences between monotonous and difficult task demands indicated the modulation of arousal and task performance, leaving interesting questions about attentional states and MW to be explored by future research.

6

General Discussion

In this thesis, I aimed to investigate behavioural and physiological sustained attention markers during low and high demand visual tasks, which could have prognostic benefits in brain stimulation interventions in neurotypical, young adults, specifically transcranial random noise stimulation (tRNS). To that end, I assessed data on behavioural performance in sustained attention paradigms, self-reported mind wandering (MW), pupil dynamics, electroencephalography (EEG) spectral markers, and tRNS intervention. I analysed data from one previously published study in our lab ([Harty & Cohen Kadosh, 2019](#)) and collected data across two online, and two lab-based studies.

6.1 Summary of the Experiments

All studies recruited young adults (18-35 years old) without any psychiatric or neurological conditions. In Chapter 2, I examined whether behavioural and EEG markers at baseline could predict tRNS-related performance improvements during a continuous monitoring task (CMT), see O’Connell et al. ([2012](#)). Then, I compared which marker could best explain the data. In Chapter 3, I adapted a simple airplane control task (ACT; see Nelson et al. ([2014](#))) to test visual search with low and high load. This was achieved by adding visual distractors while keeping motor responses

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and timing stable. In two consecutive online studies, I explored the relationship between performance and attentional state measures to investigate the difference between sustained attention tasks with lower and higher complexity and longer and shorter duration.

In Chapter 4, I replicated the online findings in a lab-based study and examined pupil dynamics as markers of arousal and cognitive control. Lastly, in Chapter 5, I added a vigilance condition to the ACT, which enabled me to test the differences between monotonous vigilance, simple search, and distractor search. In a double-blind, within-subject, sham-controlled study, I investigated the benefits of tRNS on sustained attention markers including performance scores, attentional state ratings, pupil dynamics, and EEG resting-state measures.

The thesis focused on a number of sustained attention outcomes. Task performance was evaluated with regards to hit rate and response variability (Coefficient of Variation; CoV). Prompts assessing attentional states such as MW, distraction, or task focus appeared between task blocks. Everyday-life attentional and cognitive failures were reported via questionnaires. The Cognitive Failures Questionnaire (CFQ) focused on attention and memory lapses in daily life, and the Adult ADHD Self-Report Scale (ASRS) assessed attention difficulties in coherent with Attention-Deficit/Hyperactivity Disorder (ADHD) symptoms ([Broadbent et al., 1982](#); [Kessler et al., 2005](#)). Pupil size was recorded during resting-state recordings and during task performance, analysing the pre-trial fixation periods, which reflect the baseline arousal state. EEG was recorded from resting-states, and I analysed the theta/beta ratio (TBR) and aperiodic exponent, i.e. the slope of the EEG frequency spectrum. The tRNS was applied online during attention tasks for either 20 or 30 minutes over fronto-parietal sites (F4 and P4 of the international 10-20 system) with a current strength of 1 mA peak-to-peak.

6.2 Summary of the Findings

On the behavioural level, I found an effect of task complexity which affected accuracy and CoV in the opposite way, indicating that more complex visual search decreased accuracy but facilitated more consistent response times. This effect was found for task blocks that were at least 90 seconds long and was true for online and lab-based studies in Chapter 3, 4, and 5.

Across studies from Chapter 4 and 5, pre-trial pupil size decreased in later blocks and increased with heightened task demands. In Chapter 4, greater pre-trial pupil size predicted lower accuracy on the ACT, indicating increased arousal was disadvantageous to perform well. CoV in Chapter 5 was predicted to be lower by smaller pre-trial pupil size in the vigilance task, but by larger pupils in the two search tasks. This would suggest that less arousal was indicative of better vigilance performance whereas search tasks required higher arousal for better performance. Chapter 4 and 5 found that a smaller pupil size was predicted in blocks where participants reported to be MW compared to blocks when they were focused on the task.

tRNS improved task performance but there was no indication that it induced changes in MW, pupil or EEG markers. In both Chapters 2 and 5, tRNS improved performance in a monotonous sustained attention task and in both studies, there was a tRNS-related advantage for participants who performed worse at baseline which was predicted by the respective behavioural score (CoV, HR). In Chapter 2, response variability decreased, and in Chapter 5, hit rate was improved compared to sham. Whereas CFQ was a significant predictor for the improvement in CoV in Chapter 2, there was no association of questionnaire outcomes with performance on the ACT. In addition, Harty & Cohen Kadosh (2019) found that TBR predicted tRNS success in the sample from Chapter 2.

The findings concluded that:

- 1) A single session of tRNS improved sustained attention performance in neurotypical, young adults and this improvement was moderated by baseline

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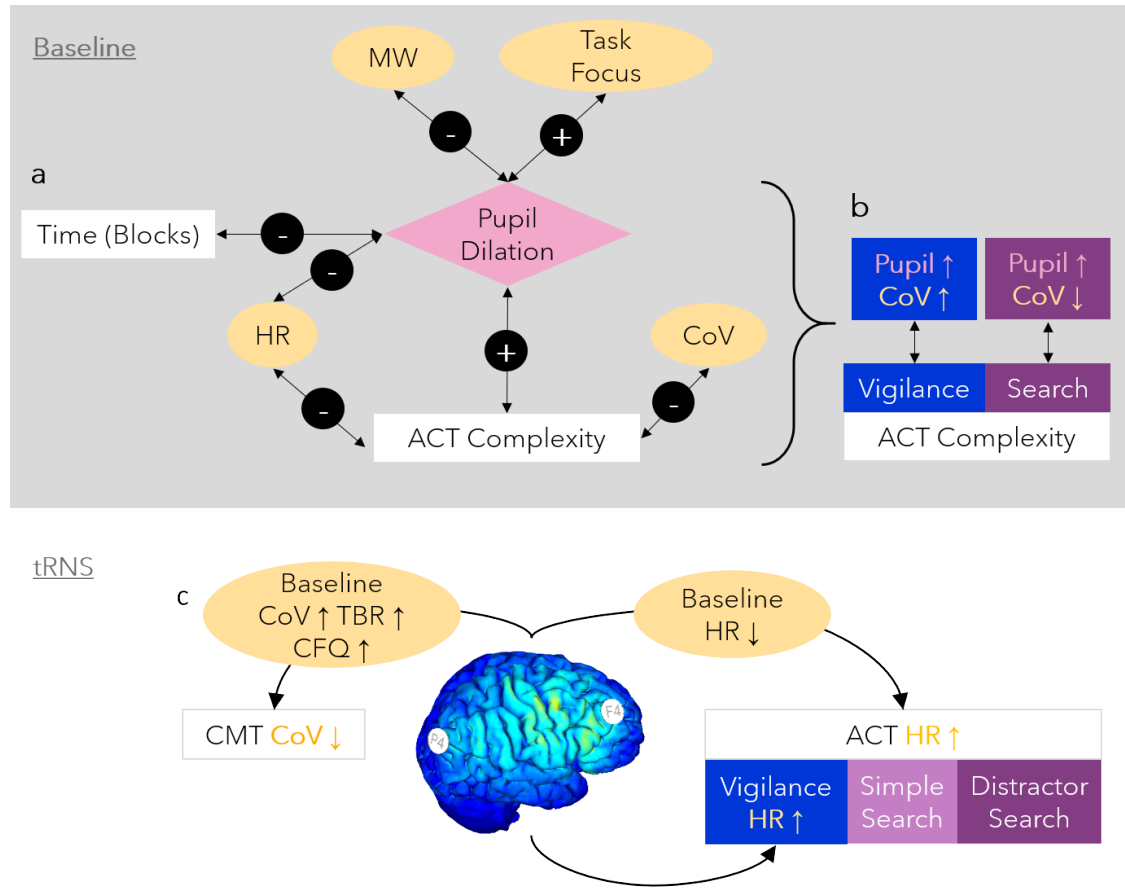


Figure 6.1: Summary of the findings. The results for all experimental chapters are summarised, separated into baseline findings (grey) and findings during tRNS (white). a. Baseline association between ACT complexity, pupil dilation, and sustained attention measures. Pupil size was smaller during reported states of MW, and larger during task focus. Pupil size decreased in later ACT blocks. Pupils dilated with increased task complexity and with reduced hit rates. ACT complexity also reduced hit rate and CoV. b. There was an interaction between pupil sizes, CoV and ACT complexity. During the vigilance condition, larger pupil size was associated with more response variability, whereas in the search conditions (with distractors absent and present) larger pupil size was associated with less response variability. c. tRNS improved performance in the CMT and ACT. A reduced CoV during active tRNS compared to sham stimulation was predicted by higher baseline CoV, TBR, and CFQ. In the ACT, lower baseline hit rate predicted improved hit rate during the ACT across all three conditions. In addition, tRNS improved hit rates in the vigilance condition for all participants.

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ability and task complexity. These effects could not be explained by placebo effects.

- 2) CoV and hit rate measure sustained attention outcome but represent different aspects of sustained attention depending on the task parameters and complexity.
- 3) Pupil dilation reflected changes in task demand and cognitive arousal and predicted CoV, but was not significantly affected by tRNS.
- 4) Although TBR was a significant predictor of tRNS improvement in the sample from Chapter 2 (Harty & Cohen Kadosh, 2019), none of the EEG measures assessed in Chapter 5 were significantly associated with other sustained attention markers and TBR did not significantly change after tRNS.

6.3 tRNS Benefits on Sustained Attention

With regards to my aims, I confirmed that tRNS can improve attention outcomes in sustained visual tasks. Chapter 5 was the first study to replicate sustained attention benefits in participants with poor baseline performance, and the first study to examine tRNS effects in context of both monotonous and complex sustained attention requirements. In line with Harty & Cohen Kadosh (2019), tRNS over the right fronto-parietal region improved performance during a new monotonous vigilance task. This benefit was present for a sample of young, neurotypical adults as has been the case with overall attention-related tRNS improvements from previous studies (Berger et al., 2021; Contò et al., 2021; Moret et al., 2021; N. Shalev et al., 2018; Tyler et al., 2018). What is more, in both Chapter 2 and 5, the notion that participants with poor baseline improve more during active tRNS (Harty & Cohen Kadosh, 2019) was replicated. This benefit could be predicted via baseline performance in the two respective tasks. High baseline CoV was the best predictor for improved CoV on the CMT, and low baseline hit rate predicted improved hit rate in the ACT. CFQ and TBR were predictive of improvements on the CMT

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in Chapter 2, but could not be replicated in the ACT. In the field of sustained attention, not much is known about how baseline ability impacts the effects of tRNS. However, my results are in line with previous studies (B. Frank et al., 2018; Van Bueren et al., 2023).

The enhancement of a suboptimal or weak signal via an optimal level of noise (visual or tRNS), also known as the phenomenon of stochastic resonance, follows an inverted U-shape function (Van Der Groen & Wenderoth, 2016). In Van Der Groen & Wenderoth (2016), detection accuracy of a weak visual stimulus was improved via visual and random noise (tRNS). Moreover, the amount of noise needed to maximise performance was in the medium range and very low and very high noise were not as effective. Although only one current intensity was used in the studies presented in this thesis (1 mA), stochastic resonance can explain the prognostic role of baseline. In my case, the suboptimal or weak signal in the right fronto-parietal attention network might be the source for low baseline performance in some participants, whereas others might have close to optimal network activity that do not benefit from added noise. One explanation why participants with low baseline can experience an improvement, might be that the increased cortical excitability (Brancucci et al., 2023) compensates for lower top-down and bottom-up engagement.

Overall, my findings are consistent with the tRNS literature and contribute novel insights into the performance improvements and limitations of this methodology. Firstly, sustained attention accuracy performance was improved in young, neurotypical adults when the task was monotonous and simple. Furthermore, task performance was identified as a useful baseline marker for sustained attention, predicting improved accuracy and response variability across tasks with different complexity.

6.4 Sustained Attention, MW, and Physiological Markers of Performance

Decreased performance can be identified by a decrease in accuracy as more errors are made (J. F. Mackworth, 1964; Makeig & Inlow, 1993). Response variability is another measure quantifying performance, especially in sustained attention tasks by estimating the fluctuation between focused, or stable responses and unfocused, or variable responses (Esterman et al., 2013; Fortenbaugh et al., 2018; Yamashita et al., 2021). Therefore, in sustained attention tasks, higher hit rates and smaller CoV scores indicate better performance. These two measures can be associated with one another in the same task (Esterman et al., 2013; Fortenbaugh et al., 2015). In the ACT, both performance markers, i.e. hit rate and CoV were affected by changes in task complexity, although in the opposite direction. While distractors facilitated more coherent response times, hence a smaller CoV, hit rate was reduced, indicating an interplay between cognitive control and arousal (O’Connell et al., 2008). Distractors are known to increase cognitive control demands of a task (Alnæs et al., 2014; Demeter et al., 2011; Martínez-Pérez et al., 2023), which might have led to lower accuracy on the distractor condition of the ACT. CoV, on the other hand improved, which is consistent with the finding of higher arousal in more complex tasks (Matthews & Davies, 2001). In support of this hypothesis, I found increased pupil dilation for the more complex ACT condition, which is a marker for increased locus coeruleus (LC) arousal (Alnæs et al., 2014; Pan et al., 2022; Zénon et al., 2014). In line with previous research, pupil size decreased after the first block of the ACT and were associated with better hit rate (Unsworth & Robison, 2016).

Moreover, pupil size predicted changes in CoV, revealing that higher levels of arousal as indicated by larger pupil size, were associated with more response variability in the vigilance condition, but with smaller variability in the two search conditions. Although it is generally accepted that more arousal is required for optimal performance in monotonous tasks than in more demanding tasks (Teigen, 1994), it has also been found that more demanding tasks induce higher levels of

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arousal (Aston-Jones & Cohen, 2005; Thomson et al., 2015). In addition, the relationship between arousal and performance is often described by an inverted U-shape function, indicating optimal performance at moderate arousal levels (Teigen, 1994; Yerkes & Dodson, 1908). While the current study could not directly test a difference between induced and required arousal, higher arousal might have been induced when distractors were present, as reflected by the larger pupil size compared to vigilance and simple search. Furthermore, it can be hypothesised that when arousal was suboptimally high during the vigilance task, responses became more inconsistent due to distractibility. However, in the search task, a higher arousal level indicated by greater pupil dilation, co-occurred with more stable responses, which could mean that the required arousal for optimal performance in this task was high. If arousal was lower than optimal, this could lead to higher CoV due to hypoarousal. For example, a high CoV in context of sustained attention has been found related to both a distracted cognitive state and hypoarousal in individuals with ADHD (Adams et al., 2011).

A clearer picture of the interplay between induced and required arousal might be investigated by keeping required arousal stable compared to when required arousal is different between task conditions, while measuring arousal via pupil size.

In this example, similar to the ACT, two tasks with low and high demand might be used. Overall pupil size difference between a low and high-demand condition are measured along with the difference in performance. Since performance differences marked increases in task demand in the ACT, if the same performance levels are achieved in both conditions, the required arousal would be comparable. This could be achieved using a staircase procedure and adjust, for example, the response time window. The difference in the measured arousal could then be compared as induced arousal without the influence of required arousal.

The presented studies did not indicate a significant association between task performance and MW, and different from performance, MW was not significantly predicted by task parameters, such as condition and blocks, or tRNS. This mirrors previous findings where MW was not significantly affected by task performance

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(Walker & Trick, 2018). Yet, other results indicate that task demand and MW covary but arise from different brain states (Jin et al., 2020). While visuospatial processing in parietal temporal and occipital areas underlies low task demand, MW was classified by processes of thought generation, semantic processing, and memory retrieval. The right medial frontal gyrus, known to support inhibitory control, selective attention, and visual perception was associated with both processes, potentially indicating sensory decoupling during both low task demand and MW (Jin et al., 2020).

Although the relationship between performance and MW was not painted clearly based on my results, MW and pupil markers indicated that the relation between pupil size and MW was not coherent with performance, i.e. pupil dilation indicated reduced accuracy and reduced MW. Pupil size was larger when participants were focused on the task, compared to MW. Furthermore, less but longer blinks predicted more MW. These results are in line with previous findings. Pupil size has been predictive of MW during breath-counting and vigilance, with larger pupils during task focus (Grandchamp et al., 2014; Unsworth & Robison, 2016). A link of MW with longer blink duration has been proposed during reading (Huette et al., 2016), and with fewer and longer blinks in cognitive tasks (Benedek et al., 2017). The current findings extend this insight for low- and high demand search tasks.

6.5 Limitations and Challenges

The current series of experiments was subject to limitations and challenges. While Chapter 4 provided some interesting insights into the relationship between pupil markers and MW, MW was assessed via thought probes after each task block. In order to prolong periods of required task focus, these probes were minimal, especially in Chapter 5 (3 at baseline and 3 during tRNS) which resulted in unbalanced ratings and difficulties analysing this data. Future studies should emphasise MW and incorporate probes more often during the task in order to gather more data. Moreover, one rating option was to indicate external distractions

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from sights and sounds. Since the studies were carried out in a soundproof booth, very few participants reported this type of distraction leading to difficulties of replicating the results from Unsworth & Robison (2016) in Chapters 4 and 5. One solution could be to design a primary attention task which encourages MW directly, e.g. by instructing to mind wander specifically (Safati et al., 2024), by prompting participants with personal thoughts (McVay & Kane, 2013), or inducing a negative mood (Smallwood & O'Connor, 2011). Furthermore, to induce external distractions, a secondary stimulus (same or different modality) could be introduced, or a task-unrelated feature in the relevant stimuli could be manipulated to facilitate distracted states. In this way, more balanced thought probes could be gathered to investigate the effects of tRNS on performance.

One limitation in the ACT, was that the typical performance decrement was not present across task blocks, instead, performance improved over time indicating that search performance showed learning effects. A decrement in performance is an essential part of sustained attention as described by J. F. Mackworth (1964) and has since been adopted in numerous studies (e.g. Martínez-Pérez et al., 2023; Ralph et al., 2015; Thomson et al., 2015). My studies were instead focused around block-based accuracy and response variability scores to relate to physiological measures and record improvement compared to previous blocks. However, the original study using a version of the simple search condition of the ACT noted a vigilance decrement over the course of 40 minutes (Nelson et al., 2014). Different to my study, participants did not have the opportunity to rest between each task block which might have caused the absence of a vigilance decrement.

A further, well-known complication of sustained attention and vigilance tasks is the component of fast responses, frequency of responses, and the requirement to change or withhold responses when targets are detected. Especially Go/No-Go paradigms with frequent Go trials have been scrutinised for the impact of response inhibition in these execute tasks (Stevenson et al., 2011). Although the processes are not identical (Tiego et al., 2018), for goal directed attention, the impact of cognitive control is important (Diamond, 2013) and has been discussed in this thesis

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as an underlying cognitive mechanism for sustained attention. Both attentional control and inhibitory control are reliant on prefrontal control areas (Stevenson et al., 2011; Tiego et al., 2018). Right dlPFC excitatory transcranial direct stimulation has been shown to improve stop signal performance (Friebs et al., 2021), and along with attentional difficulties, reduced inhibitory control is one symptom of ADHD (Shen et al., 2011). Moreover, theta activity and pupil correlates of response inhibition have been identified, which closely mirror markers of sustained attention, and the authors argue that a link between the LC noradrenergic is possible (Dippel et al., 2017). As discussed in the previous section, pupil markers have been found to mark arousal and cognitive control related processes that are required during the maintenance of attention on a task over time. These findings underline the close relationship between inhibitory control and sustained attention, which was beyond the scope of my thesis. However, the current chapters featured different attention tasks with differing task demands. Both, in the CMT and ACT, tRNS could improve performance. Importantly, the CMT relies on infrequent target detection, similar to what is also referred to as traditionally formatted tasks, and is accepted to place less response inhibition demands (Stevenson et al., 2011). The ACT, in contrast, is formatted similar to the SART paradigms with frequent congruent trials and infrequent target detection trials and associated with higher response inhibition demands (Stevenson et al., 2011). With regards to tRNS, I found results in both monotonous vigilance conditions assessed in both formats, as well as in more demanding search tasks, which could indicate that differing control requirements cannot explain the effects fully. Since inhibitory control could still be a confounding factor in the current research, further studies could shed light its contribution in both paradigms. Due to the frontal impact of response inhibition, future studies may investigate the individual impact of frontal compared to parietal tRNS during the CMT and the ACT, or introduce an additional ACT condition in traditionally formatted style.

6.6 Conclusion and Future Directions

The results of the presented thesis indicate that pupil dynamics have close association with sustained attention through a link with MW, task performance, and task demand in line with theories of arousal and cognitive control. Furthermore, sustained attention, during monotonous and difficult tasks, is susceptible to the positive effects of tRNS. Importantly, the results indicate that while neurotypical young adults profited from the intervention, individual baseline differences are valuable prognostic aids to determine the benefit from tRNS. This result is especially meaningful in the context of improving sustained attention in educational settings and in patient groups that show impairments in sustained attention. Few studies have already investigated the effects of tRNS with training and over several days, indicating long-term benefits and changes in plasticity (Berger et al., 2021; B. Frank et al., 2018; Popescu et al., 2016; Snowball et al., 2013; Van Der Groen et al., 2022). Similar results could be extended to sustained attention, not only investigating whether there are long-term benefits but importantly, which predictors for these changes can be identified. Furthermore, the behavioural predictors that I identified in Chapters 2 and 5, could be applied in more advanced research targeting personalised benefits from tRNS. One recent study found optimised parameters for transcranial alternative current stimulation targeted to improve arithmetic problem-solving using machine learning (Van Bueren et al., 2021). Indeed, preliminary findings from a study that I co-authored (Cohen Kadosh et al., n.d., submitted for review) suggested that across three sessions, personalisation of tRNS based on baseline performance using Bayesian Optimisation, yielded greater sustained attention performance improvements than generic current intensity or sham tRNS. By harnessing the powers of closed-loop intervention systems which update parameters and course of the intervention, tRNS benefits could be maximised. Use-cases might be, but are not limited to patient treatment, training and learning environments, professions that rely on machine monitoring, or driving accident prevention.

Appendices



Chapter 2 Appendix

A.1 Replicated Analysis

Table A.1: Baseline TBR Predicting CoV during tRNS

model term	estimate	SE	df	t	p
Intercept	0.46	0.00	201	103.10	<.001
1 mA tRNS	-0.02	0.01	201	-3.65	<.001
2 mA tRNS	-0.01	0.01	201	-1.18	0.238
Baseline TBR	0.01	0.01	201	0.65	0.515
Baseline CoV	0.69	0.04	201	15.59	<.001
1 mA tRNS x Baseline TBR	-0.04	0.01	201	-2.90	0.004
2 mA tRNS x Baseline TBR	-0.01	0.02	201	-0.65	0.517

Notes. The Table shows the fixed effects for the mixed model $\text{CoVs} \sim \text{tRNS} * \text{TBRpre} + \text{baseline CoV} + (1 | \text{subject})$ predicting coefficient of variation during tRNS by baseline TBR for all main effects and interactions.

A.2 Changes in CoV during tRNS

Table A.2: Baseline CoV Predicting CoV during tRNS

model term	estimate	SE	df	t	p
Intercept	0.46	0.00	195	102.66	<.001
1 mA tRNS	-0.02	0.01	195	-3.65	<.001
2 mA tRNS	-0.01	0.01	195	-1.22	0.223
Baseline CoV	0.91	0.08	195	11.54	<.001
1 mA tRNS x Baseline CoV	-0.43	0.11	195	-4.09	<.001
2 mA tRNS x Baseline CoV	-0.26	0.10	195	-2.54	0.012

The Table shows the fixed effects for the mixed model $\text{CoVs} \sim \text{tRNS} * \text{Covbl} + (1 | \text{subject})$ predicting coefficient of variation during tRNS by baseline CoV for all main effects and interactions.

Table A.3: CFQ Predicting CoV during tRNS

model term	estimate	SE	df	t	p
Intercept	0.46	0.00	201	103.71	<.001
1 mA tRNS	-0.02	0.01	132	-3.69	<.001
2 mA tRNS	-0.01	0.01	132	-1.16	0.248
CFQ	0.00	0.00	201	2.00	0.046
Baseline CoV	0.66	0.04	104	15.39	<.001
1 mA tRNS x CFQ	0.00	0.00	132	-3.53	<.001
2 mA tRNS x CFQ	0.00	0.00	132	-0.29	0.775

The Table shows the fixed effects for the mixed model $\text{CoVs} \sim \text{tRNS} * \text{CFQ} + \text{Covbl} + (1 | \text{subject})$ predicting coefficient of variation during tRNS by CFQ for all main effects and interactions.

A.3 Discriminability as Outcome Predictor

Table A.4: Baseline A' not a Predictor of CoV during tRNS

model term	estimate	SE	df	t	p
Intercept	0.46	0.00	188	96.49	<.001

Table A.4: Baseline A' not a Predictor of CoV during tRNS

model term	estimate	SE	df	t	p
1 mA tRNS	-0.02	0.01	188	-3.35	<.001
2 mA tRNS	-0.01	0.01	188	-1.18	0.238
Baseline A'	0.41	0.54	188	0.76	0.446
Baseline CoV	0.65	0.04	188	14.46	<.001
1 mA tRNS x Baseline A'	-0.84	0.77	188	-1.09	0.275
2 mA tRNS x Baseline A'	0.10	0.85	188	0.11	0.909

The Table shows the fixed effects for the mixed model CoVs ~ tRNS * A' + CoVbl + (1| subject) predicting coefficient of variation during tRNS by baseline A' for all main effects and interactions.

Table A.5: Baseline A' not predicting A' during tRNS

Fixed.Effects	estimate	SE	df	t	p
Intercept	0.99	0.00	192	870.27	<.001
1 mA tRNS	0.00	0.00	129	-0.48	0.633
2 mA tRNS	0.00	0.00	130	-1.85	0.067
Baseline A'	0.26	0.13	193	2.02	0.045
1 mA tRNS x Baseline A'	-0.13	0.18	194	-0.72	0.473
2 mA tRNS x Baseline A'	-0.23	0.20	181	-1.18	0.242

The Table shows the fixed effects for the mixed model (A's ~ tRNS * A'bl + Covbl + (1| subject) predicting coefficient of variation during tRNS by baseline A' for each predictor.

A.4 Changes in Post-Stimulation TBR during tRNS

Table A.6: Baseline TBR Predicting TBR after tRNS.

model term	estimate	SE	df	t	p
Intercept	1.63	0.04	201	37.41	<.001
1 mA tRNS	-0.23	0.06	133	-3.72	<.001

Table A.6: Baseline TBR Predicting TBR after tRNS.

model term	estimate	SE	df	t	p
2 mA tRNS	-0.03	0.06	133	-0.47	0.638
Baseline TBR	0.73	0.11	201	6.76	<.001
1 mA tRNS x Baseline TBR	-0.72	0.14	147	-5.11	<.001
2 mA tRNS x Baseline TBR	-0.03	0.15	145	-0.20	0.84

Notes. The Table shows the fixed effects for the mixed model $TBR_{post} \sim tRNS * TBR_{pre} + (1 | \text{subject})$ predicting TBR during tRNS by baseline TBR for all main effects and interactions.

Table A.7: Baseline CoV no Predictor of TBR after tRNS

model term	estimate	SE	df	t	p
Intercept	1.62	0.05	201	34.77	<.001
1 mA tRNS	-0.22	0.07	201	-3.28	0.001
2 mA tRNS	-0.03	0.07	201	-0.49	0.628
Baseline CoV	1.35	0.85	201	1.60	0.112
Baseline TBR	0.41	0.07	201	5.96	<.001
1 mA tRNS x Baseline CoV	-1.87	1.11	201	-1.69	0.092
2 mA tRNS x Baseline CoV	-0.82	1.08	201	-0.76	0.446

Notes. The Table shows the fixed effects for the mixed model $TBR_{post} \sim tRNS * CoV_{bl} + TBR_{pre} + (1 | \text{subject})$ predicting TBR during tRNS by baseline CoV for all main effects and interactions.

Table A.8: CFQ not a predictor of TBR after tRNS

model term	estimate	SE	df	t	p
Intercept	1.62	0.05	201	34.49	<.001
1 mA tRNS	-0.21	0.07	201	-3.22	0.001
2 mA tRNS	-0.03	0.07	201	-0.46	0.647
CFQ	0.00	0.00	201	0.37	0.709
Baseline TBR	0.44	0.07	201	6.49	<.001

Table A.8: CFQ not a predictor of TBR after tRNS

model term	estimate	SE	df	t	p
1 mA tRNS x Baseline CoV	0.00	0.00	201	-0.79	0.429
2 mA tRNS x Baseline CoV	0.00	0.00	201	-0.35	0.724

Notes. The Table shows the fixed effects for the mixed model $TBR_{post} \sim tRNS * CFQ + TBR_{pre} + (1 | subject)$ predicting TBR during tRNS by CFQ score for all main effects and interactions.

Table A.9: Baseline Discriminability (A') not a Predictor of TBR after tRNS

model term	estimate	SE	df	t	p
Intercept	1.62	0.05	195	35.39	<.001
1 mA tRNS	-0.24	0.06	195	-3.71	<.001
2 mA tRNS	-0.03	0.07	195	-0.46	0.647
A'	8.43	5.22	195	1.62	0.108
Baseline TBR	0.47	0.06	195	7.43	<.001
1 mA tRNS x Baseline CoV	-3.82	7.46	195	-0.51	0.609
2 mA tRNS x Baseline CoV	-4.32	8.17	195	-0.53	0.597

Notes. The Table shows the fixed effects for the mixed model $TBR_{post} \sim tRNS * A' + TBR_{pre} + (1 | subject)$ predicting TBR during tRNS by A' for all main effects and interactions.

B

Chapter 3 Appendix

B.1 Study 1

B.1.1 MW Practice

Participants performed 10 practice items to learn how to categorise their thoughts during later thought probes.

Table B.1: Thought Probe Practice Items

Example thought to be categorised	Correct answer choice	Thought Category
I was thinking about the people I can hear talking outside	3: I am distracted by information present in the room (sights and sounds)	Task-unrelated and stimulus-dependent
I was thinking about a conversation I had yesterday	4: I am zoning out/ my mind is wandering	Task-unrelated and stimulus-independent
I was wondering whether my last response was correct	2: I am thinking about my performance on the task or how long it is taking	Task-related and stimulus-independent
I was thinking about which airplanes were on a safe path	1: I am totally focused on the current task	Task-related and stimulus-dependent
I was thinking that the airplanes on the screen look like birds	4: I am zoning out/ my mind is wandering	Task-unrelated and stimulus-independent

Table B.1: Thought Probe Practice Items

Example thought to be categorised	Correct answer choice	Thought Category
I was thinking that the airplanes on the screen are moving too fast	2: I am thinking about my performance on the task or how long it is taking	Task-related and stimulus-independent
I was thinking about which button to press	1: I am totally focused on the current task	Task-related and stimulus-dependent
I was thinking about feeling a little cold at the moment	3: I am distracted by information present in the room (sights and sounds)	Task-unrelated and stimulus-dependent
I was thinking about what food to add to my shopping list	4: I am zoning out/ my mind is wandering	Task-unrelated and stimulus-independent
I don't remember what I was thinking	5: Other	Other

At the beginning of the online session, participants received instructions to categorise their thoughts according to 5 categories (Unsworth & McMillan, 2014; Stawarczyk et al., 2011). Ten example thoughts were given for the participant to categorise during the practice session.

B.1.2 Response Variable Distributions

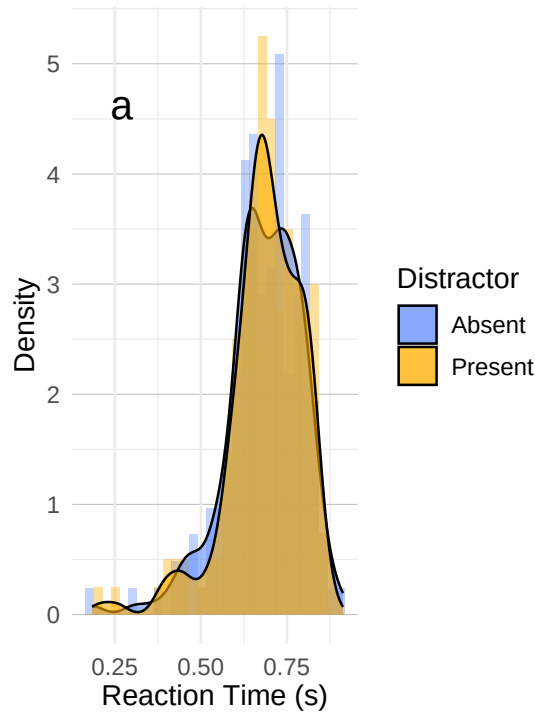
B.1.3 Preregistered Analyses

Table B.2: Task Focus Predicted by Motivation

model term	Chi-square	df	p
CoV	2.68	1	0.101
Distractor	<.01	1	0.982
Block Duration	<.01	1	0.988
Motivation	19.29	1	<.001
Sleepiness	2.56	1	0.11
CoV x Distractor	0.03	1	0.852

The Table shows the likelihood ratio for the linear model on-task rating ~ CoV * distractor + motivation + sleepiness predicting subjective task focus in the ACT by performance.

Response Time Distributions



Hit Rate Distributions

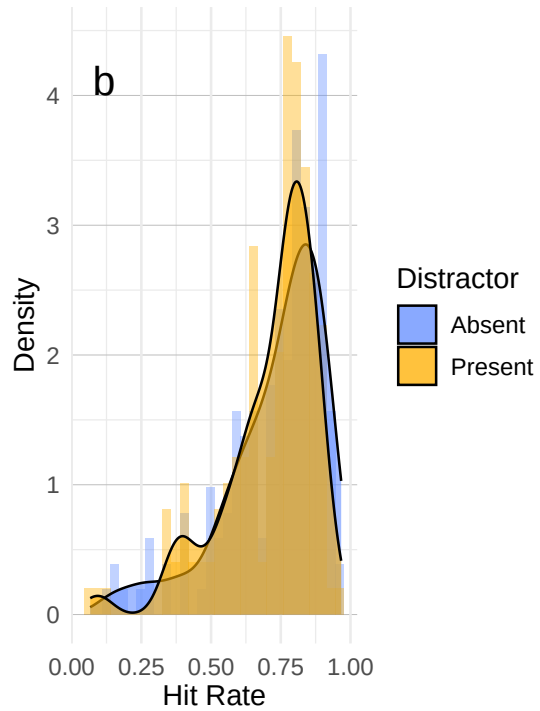


Figure B.1: Density plots for response time (a) and hit rate distributions by task condition (simple search without distractor and distractor search). a. Response times in the simple search condition were distributed with a wider range than during the distractor search. Both distributions showed a negative skew (simple search: -1.06, distractor search: -1.32) and a leptokurtic shape (simple search: 5.34, distractor search: 6.15). b. Hit rate distributions had a similar shape with the distractor condition shifted towards the left, indicating lower overall scores. Both distributions showed similar skewness (simple search: -1.31, distractor search: -1.41) and kurtosis (simple search: 4.45, distractor search: 5.1).

Table B.3: MW Predicted by Motivation and Sleepiness

model term	Chi-square	df	p
CoV	0.32	1	0.57
Distractor	0.01	1	0.914
Block Duration	1.38	1	0.24
Motivation	51.84	1	<.001
Sleepiness	14.47	1	<.001

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The Table shows the joint test for the generalised linear model (MW probe ~ CoV + distractor + block Duration + motivation + sleepiness + (1| subject) predicting MW ratings in the ACT by performance.

Table B.4: CoV Predicted by Sleepiness

model term	df1	df2	F	p
CFQ	1	39	0.17	0.678
Motivation (mean)	1	39	0.13	0.725
Sleepiness (mean)	1	39	18.39	0.000

The Table shows the joint test for the linear model (CoV ~ CFQ + motivation + sleepiness) predicting response variability in the ACT by CFQ.

Table B.5: Response Variability Predicted by Sleepiness

model term	df1	df2	F	p
ASRS (IA)	1	39	0.68	0.416
Motivation (mean)	1	39	0.13	0.720
Sleepiness (mean)	1	39	19.30	0.000

The Table shows the joint test for the linear model (CoV ~ ASRS + motivation + sleepiness) predicting CoV in the ACT by ASRS.

Table B.6: MW Predicted by MW Intention

model term	df1	df2	F	p
CFQ	1	35	3.60	0.066
MW Intention	1	35	4.03	0.052
Motivation (mean)	1	35	3.27	0.079
Sleepiness (mean)	1	35	0.10	0.754
CFQ x MW Intention	1	35	0.01	0.940

The Table shows the joint test for the linear model (mean MW Probe ~ CFQ * MW intention + motivation + sleepiness) predicting mean MW by CFQ and MW intention.

Table B.7: MW Predicted by MW Intention

model term	df1	df2	F	p
ASRS (IA)	1	35	1.64	0.208
MW Intention	1	35	5.46	0.025
Motivation (mean)	1	35	2.88	0.098
Sleepiness (mean)	1	35	0.08	0.784
ASRS (IA) x MW Intention	1	35	0.10	0.748

The Table shows the joint test for the linear model (mean MW Probe ~ ASRS (IA) * MW intention + motivation + sleepiness) predicting mean MW by ASRS and MW intention.

B.1.4 Exploratory Analyses

Table B.8: No Significant Effects on Hit Rate

model term	df1	df2	F	p
Distractor	1	243.33	3.75	0.054
Block Duration	1	243.85	1.85	0.175
Block	7	243.89	1.31	0.246
Motivation	1	278.01	0.56	0.454
Sleepiness	1	262.76	3.31	0.070
Block Duration x Distractor	1	243.84	0.95	0.330
Distractor x Block	7	247.43	0.47	0.854
Block Duration x Block	7	248.54	0.71	0.660
Block Duration x Distractor x Block	7	247.35	0.64	0.725

The Table shows the joint test for the mixed model hit rate ~ distractor * block duration * blocks + motivation + sleepiness + (1|subject) predicting response variability.

Table B.9: CoV Predicted by Distractor

model term	df1	df2	F	p
Distractor	1	43.92	21.03	<.001
Block Duration	1	189.94	1.7	0.193
Block	7	120.23	1.83	0.087
Motivation	1	232.99	0.84	0.361
Sleepiness	1	250.37	<.01	0.952
Block Duration x Distractor	1	192.27	3.17	0.077
Distractor x Block	7	50.01	0.58	0.773
Block Duration x Block	7	208.46	0.88	0.519
Block Duration x Distractor x Block	7	208.43	1.03	0.413

The Table shows the joint test for the mixed model CoV ~ distractor * block duration * blocks + motivation + sleepiness + (1 + distractor| subject) predicting response variability.

B.2 Study 2

B.2.1 Response Variable Distributions

Table B.10: Hit Rate Predicted by Task Parameters

model term	df1	df2	F	p
Distractor	1	51.94	11.41	0.001
Block Duration	1	244.99	3.60	0.059
Block	7	118.36	4.93	<.001
Motivation	1	284.38	0.13	0.719
Sleepiness	1	218.37	2.07	0.152
Distractor * Block Duration	1	248.52	0.59	0.442
Distractor * Block	7	64.03	1.81	0.1
Block Duration * Block	7	269.80	3.03	0.004
Distractor * Block Duration * Block	7	270.39	0.74	0.642

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Table B.10: Hit Rate Predicted by Task Parameters

model term	df1	df2	F	p
The Table shows the joint test for the mixed model hit rate ~ distractor * block duration * block + motivation + sleepiness + (1 + distractor subject) predicting hit rate in the ACT by task conditions.				

Table B.11: CoV Predicted by Distractor

model term	df1	df2	F	p
Distractor	1	43.92	21.03	<.001
Block Duration	1	189.94	1.7	0.193
Block	7	120.23	1.83	0.087
Motivation	1	232.99	0.84	0.361
Sleepiness	1	250.37	<.01	0.952
Block Duration x Distractor	1	192.27	3.17	0.077
Distractor x Block	7	50.01	0.58	0.773
Block Duration x Block	7	208.46	0.88	0.519
Block Duration x Distractor x Block	7	208.43	1.03	0.413

The Table shows the joint test for the mixed model CoV ~ distractor * block duration * blocks + motivation + sleepiness + (1 + distractor| subject) predicting response variability.

Table B.12: On-task Rating Predicted by Motivation

model term	df1	df2	F	Chi-Square	p
Distractor	1	Inf	0.06	0.06	0.801
Block Duration	1	Inf	0.02	0.02	0.9
Block	7	Inf	0.08	0.53	0.999
CoV	1	Inf	0.66	0.66	0.418
Motivation	1	Inf	29.60	29.60	<.001
Sleepiness	1	Inf	0.60	0.60	0.438

Table B.12: On-task Rating Predicted by Motivation

model term	df1	df2	F	Chi-Square	p
Block Duration x Distractor	1	Inf	0.10	0.10	0.758
Distractor x Block	7	Inf	0.07	0.47	1
Block Duration x Block	7	Inf	0.05	0.36	1
Block Duration x Distractor x Block	7	Inf	0.03	0.19	1

The Table shows the joint test for the generalised linear model on-task rating
 $\sim$ distractor * block duration * blocks + CoV + motivation + sleepiness + (1 +
distractor| subject) predicting self-rated task focus.

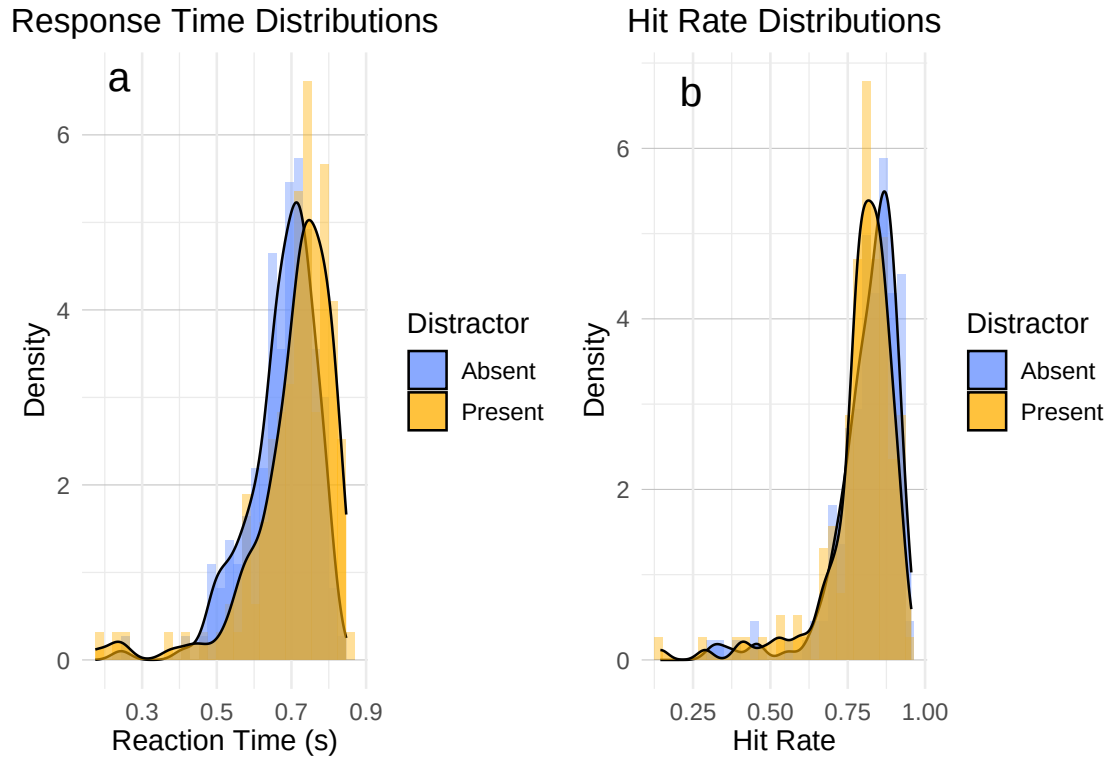
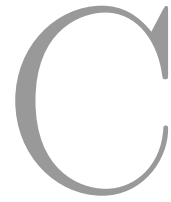


Figure B.2: Density plots for response time (a) and hit rate distributions by task condition (simple search without distractor and distractor search). a. Response times in the simple search condition were shifted to the left compared to the distractor search, indicating that a shorter amount of time was required to find targets when distractors were absent. Responses in the distractor condition were more negatively skewed (-2.19) and showed stronger leptokurtosis (9.47) indicating a steeper cut-off of the right tail and more values nearer the mean than in the simple search (skew= -1.25, kurtosis= 5.76). b. Hit rate distributions in the distractor condition was shifted towards the left, indicating lower overall scores compared to the simple search condition. Skewness (simple search: -2.27, distractor search: -2.54) and kurtosis (simple search: 9.99, distractor search: 11.82) values were similar in both conditions.



Chapter 4 Appendix

C.1 Behavioural Effects

Table C.1: Distractor and Block Predicted Hit Rate

model term	df1	df2	F	p
Distractor	1	103.97	26.95	<.001
Block	3	103.39	43.70	<.001
Motivation	1	129.04	0.06	0.803
Sleepiness	1	127.75	0.86	0.357
Distractor * Block	3	41.46	2.25	0.096

The Table shows the joint test for the mixed model $HR \sim \text{distractor} * \text{block} + \text{motivation} + \text{sleepiness} + (1 | \text{subject})$ predicting hit rate by task parameters.

Table C.2: Distractor Predicted CoV

model term	df1	df2	F	p
Block	3	101.01	2.23	0.089
Distractor	1	101.02	5.67	0.019
Motivation	1	125.50	0.64	0.424
Sleepiness	1	126.38	0.76	0.386

Table C.2: Distractor Predicted CoV

model term	df1	df2	F	p
Distractor * Block	3	41.15	0.71	0.552

The Table shows the joint test for the mixed model CoV ~ distractor * block + motivation + sleepiness + (1 | subject) predicting response variability by task parameters.

Table C.3: Task Focus Predicted by Task, Motivation, and Sleepiness

model term	df1	df2	F	p
Block	3	105.04	1.85	0.143
Distractor	1	107.20	0.41	0.522
Motivation	1	112.46	8.87	0.004
Sleepiness	1	117.05	5.86	0.017
Distractor * Block	3	58.53	3.15	0.031

The Table shows the joint test for the mixed model On-task Rating ~ block * distractor + motivation + sleepiness + (1 | subject) predicting self-reported task focus by task parameters.

Table C.4: MW Predicted by Sleepiness

model term	Chi-square	df	p
Block	0.29	3	0.961
Distractor	0.01	1	0.937
Motivation	1.92	1	0.166
Sleepiness	5.18	1	0.023
Distractor * Block	1.99	3	0.574

The Table shows the Chi-square test for the generalised linear model MW ~ block * distractor + motivation + sleepiness predicting whether participants rated themselves to be focused on the task or MW (excluding external distractions, and task-related distractions, or other thought categories).

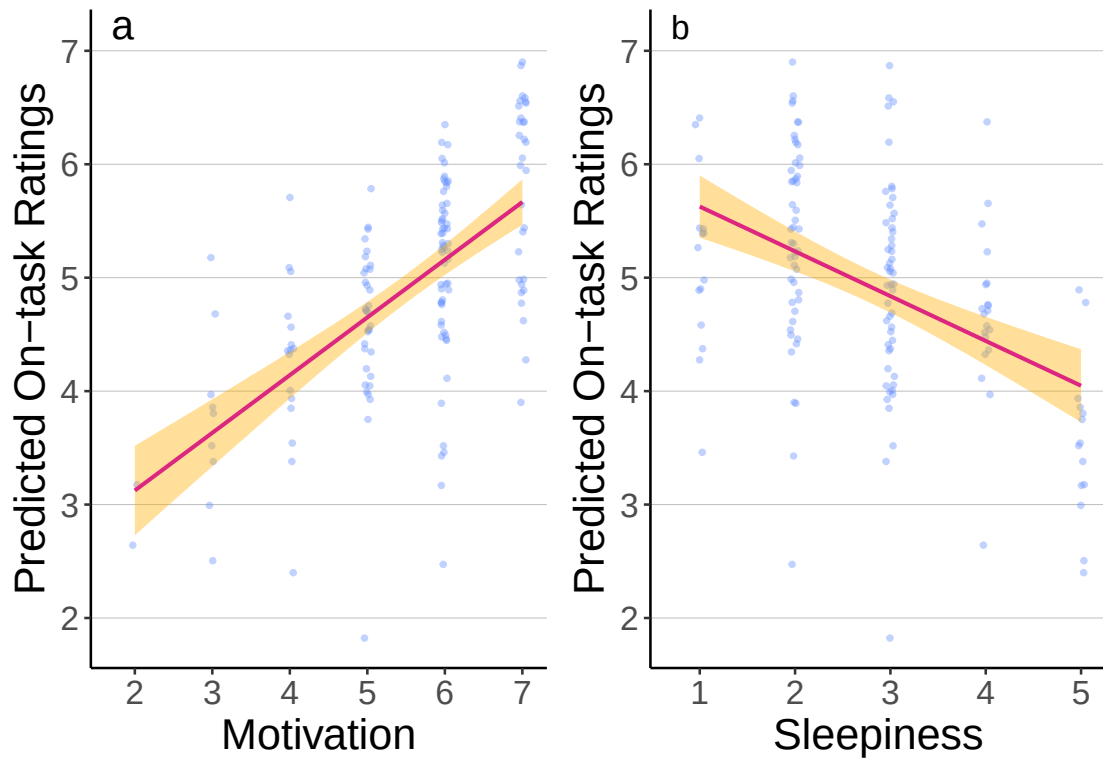


Figure C.1: Task-focus ratings (1 = completely off-task, 7= completely on-task) were predicted by a) motivation (1 = not motivated, 7 = completely motivated), $p = .004$, and b) sleepiness (1 = feeling active/vital/alert, 7 = sleepy/woozy/fighting sleep), $p = .017$. a. Higher motivation during the previous task block predicted more task focus. b. In contrary, greater sleepiness predicted less task focus. The shaded areas represent the 95% confidence interval of the estimates. Predicted on-task ratings are displayed in blue.

Table C.5: No Significant Effects for Questionnaires and Accuracy

model term	df1	df2	F	p
CFQ	1	34	0.00	0.944
ASRS (IA)	1	34	2.59	0.117
Motivation	1	34	1.11	0.300
Sleepiness	1	34	0.05	0.829

The Table shows the joint test for the linear model ($HR \sim CFQ + ASRS (IA) + motivation + sleepiness$) predicting HR by questionnaires.

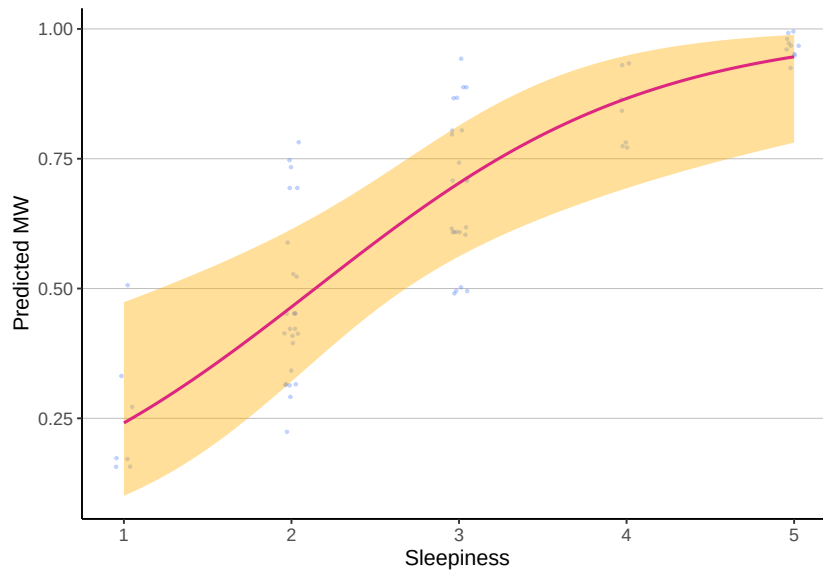


Figure C.2: Predicted mind wandering ratings for the significant main effect of sleepiness ($p = .017$). Higher rated sleepiness (1 = feeling active/vital/alert, 7 = sleepy/woozy/fighting sleep) predicted more mind wandering. The shaded areas represent the 95% confidence interval of the estimates. Predicted mind wandering ratings are displayed in blue.

Table C.6: No Significant Effects for Questionnaires and CoV

model term	df1	df2	F	p
CFQ	1	34	2.29	0.140
ASRS (IA)	1	34	0.19	0.664
Motivation	1	34	0.27	0.604
Sleepiness	1	34	0.28	0.598

The Table shows the joint test for the linear model $\text{CoV} \sim \text{CFQ} + \text{ASRS (IA)} + \text{motivation} + \text{sleepiness}$ predicting CoV by questionnaires.

C.2 Eye Dynamics

Table C.7: Blink Rate Predicted by Block

model term	df1	df2	F	p
Block	3	79.73	4.01	0.010
Distractor	1	40.62	0.14	0.706

Table C.7: Blink Rate Predicted by Block

model term	df1	df2	F	p
Motivation	1	128.85	4.18	0.043
Sleepiness	1	124.42	3.81	0.053
Distractor * Block	3	42.42	0.36	0.779

The Table shows the joint test for the mixed model blink rate ~
distractor * block + motivation + sleepiness + (1+ distractor |
subject) predicting blink rate by task parameters

Table C.8: No Effects on Blink Duration

model term	df1	df2	F	p
Block	3	117.56	1.02	0.386
Distractor	1	119.62	0.71	0.401
Motivation	1	144.68	0.67	0.415
Sleepiness	1	148.10	2.23	0.138
Distractor * Block	3	61.21	0.76	0.520

The Table shows the joint test for the mixed model blink duration ~
distractor * block + motivation + sleepiness + (1+ distractor |
subject) predicting blink duration (ms).

Table C.9: Task Parameters Predicted Pre-Trial Pupil Size

model term	df1	df2	F	p
Block	3	138	7.76	<.001
Distractor	1	138	6.71	0.011
Motivation	1	138	0.03	0.874
Sleepiness	1	138	0.06	0.802
Distractor * Block	3	138	1.05	0.372

The Table shows the joint test for the linear model pre-trial pupil ~
distractor * block + motivation + sleepiness predicting blink rate by
task parameters.

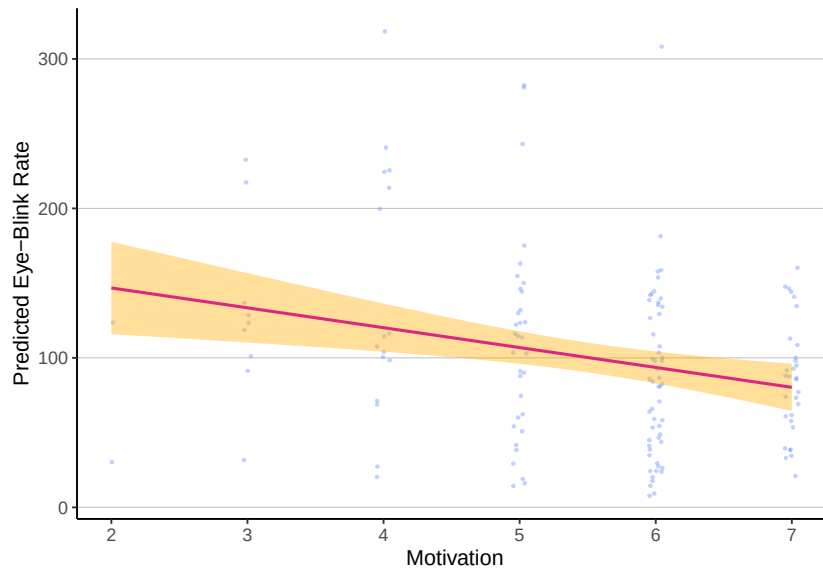


Figure C.3: Predicted eye blink rate for the significant main effect of motivation (1 = not motivated, 7 = completely motivated), $p = .043$. More eye blinks were predicted by lower motivation scores. The shaded areas represent the 95% confidence interval of the estimates. Predicted mind wandering ratings are displayed in blue.

Table C.10: CFQ Predicted Blink Duration

model term	df1	df2	F	p
CFQ	1	34	4.31	0.046
ASRS (IA)	1	34	0.13	0.722
Motivation	1	34	0.13	0.721
Sleepiness	1	34	0.38	0.544

The Table shows the joint test for the linear model blink duration ~ CFQ + ASRS (IA) + motivation + sleepiness predicting blink duration by questionnaire scores.

Table C.11: No Significant Blink Predictors from Questionnaire Scores

model term	df1	df2	F	p
CFQ	1	33	1.05	0.314
ASRS (IA)	1	33	0.67	0.420
Motivation	1	33	2.94	0.096
Sleepiness	1	33	0.90	0.349

Table C.11: No Significant Blink Predictors from Questionnaire Scores

model term	df1	df2	F	p
The Table shows the joint test for the linear model blink rate ~ CFQ + ASRS (IA) + motivation + sleepiness predicting blink rate by questionnaire scores.				

Table C.12: Pupil Size Not Significantly Predicted by Questionnaires

model term	df1	df2	F	p
CFQ	1	34	0.28	0.597
ASRS (IA)	1	34	0.66	0.420
Motivation	1	34	0.02	0.883
Sleepiness	1	34	0.10	0.752
The Table shows the joint test for the linear model pre-trial pupil size ~ CFQ + ASRS (IA) + motivation + sleepiness predicting pupil size by questionnaire scores				

Table C.13: Hit Rate Predicted by Pre-Trial Pupil Size

model term	df1	df2	F	p
Blink Rate	1	90.14	0.00	0.949
Blink Duration	1	138.88	0.40	0.529
Pre-Trial Pupil Size	1	109.55	6.57	0.012
Motivation	1	147.23	1.16	0.283
Sleepiness	1	147.24	1.18	0.278
The Table shows the joint test for the mixed model hit rate ~ blink rate + blink duration (ms) + pre-trial pupil size + motivation + sleepiness + (1 subject) predicting hit rate.				

Table C.14: Blink Rate and Duration predict CoV

model term	df1	df2	F	p
Blink Rate	1	101.33	5.61	0.020
Blink Duration	1	115.97	5.58	0.020

Table C.14: Blink Rate and Duration predict CoV

model term	df1	df2	F	p
Pre-Trial Pupil Size	1	98.97	0.80	0.374
Motivation	1	126.96	1.44	0.233
Sleepiness	1	129.26	0.52	0.470

The Table shows the joint test for the mixed model CoV ~ blink rate + blink duration (ms) + pre-trial pupil size + motivation + sleepiness + (1 | subject) predicting response variability.

Table C.15: Motivation predicts On-Task Rating

model term	df1	df2	F	p
Blink Rate	1	53.37	0.06	0.806
Blink Duration	1	133.01	0.03	0.871
Pre-Trial Pupil Size	1	104.57	0.34	0.562
Motivation	1	112.42	7.36	0.008
Sleepiness	1	114.56	3.78	0.054

The Table shows the joint test for the mixed model on-task rating ~ blink rate + blink duration (ms) + pre-trial pupil size + motivation + sleepiness + (1 | subject) predicting response variability.

Table C.16: Blink Rate and Duration, Motivation, and Sleepiness Predict MW

model term	Chi-square	df	p
EBR	29.59	1	<.001
BDUR	4.63	1	0.031
Pre-Trial Pupil Size	1.91	1	0.167
Motivation	7.52	1	0.006
Sleepiness	7.05	1	0.008

The Table shows the Chi-square test for the linear model CoV ~ blink rate + blink duration (ms) + pre-trial pupil size + motivation + sleepiness predicting MW ratings.

Table C.17: Pupil Size for MW was Distinct from On-Task and Task-Relevant Thoughts

model term	estimate	lower 95% CrI	upper 95% CrI
Pre-trial Pupil Size (On-Task)	1.92	0.04	3.97
Motivation (On-Task)	0.82	-0.07	1.86
Sleepiness (On-Task)	-1.01	-1.99	-0.08
Pre-trial Pupil Size (Task-Relevant)	1.52	0.09	3.12
Motivation (Task-Relevant)	0.17	-0.30	0.66
Sleepiness (Task-Relevant)	-0.39	-0.91	0.10
Pre-trial Pupil Size (External Distraction)	2.35	-0.67	5.44
Motivation (External Distraction)	0.80	-0.27	2.17
Sleepiness (External Distraction)	0.00	-1.11	1.10

The table displays coefficients from the Bayesian multinomial mixed effect model MW category ~ pre-trial pupil size + motivation + sleepiness + (1 | subject) with reference category MW. The model term describes the tested variable (pupil size, motivation, sleepiness) in combination with the thought category (on-task, task-relevant, external distraction). The 95% CrI's are calculated based on posterior distributions. CrI's not containing zero are regarded as significant equivalent ($p < .05$). CrI= Credible Interval.

D

Chapter 5 Appendix

D.1 tRNS Results

Table D.1: CoV was Predicted by Task Condition

model term	df1	df2	F	p
tRNS	1	108.18	0.13	0.721
Task Condition	2	41.73	11.09	<.001
Baseline CoV	1	169.80	28.62	<.001
Motivation	1	188.68	1.80	0.181
Sleepiness	1	186.27	5.51	0.02
Head Circumference	1	131.38	0.05	0.83
tRNS * Task Condition	2	107.05	0.43	0.653
tRNS * Baseline CoV	1	133.67	0.14	0.711
Task Condition * Baseline CoV	2	58.73	2.14	0.126
tRNS * Task Condition * Baseline CoV	2	123.46	0.88	0.419

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The Table shows the joint test for the mixed model CoV ~ tRNS condition * task condition * baseline CoV + motivation + sleepiness + head circumference + (1+ task condition|ID) predicting response variability by the interaction between tRNS, task parameters and baseline performance. CoV= Coefficient of Variation, tRNS= transcranial random noise stimulation, ID= subject.

Table D.2: HR Improved during 1 mA tRNS

model term	df1	df2	F	p
tRNS	1	134.36	0.87	0.353
Baseline HR	1	26.87	20.84	<.001
Task Condition	2	118.36	41.32	<.001
Motivation	1	86.40	1.14	0.288
Sleepiness	1	115.32	17.73	<.001
Head Circumference	1	161.80	0.18	0.671
tRNS * Baseline HR	1	93.14	4.07	0.047
tRNS * Task Condition	2	101.19	3.91	0.023
Task Condition * Baseline HR	2	93.14	2.07	0.132
tRNS * Task Condition * Baseline HR	2	71.10	2.17	0.122

The Table shows the joint test for the mixed model HR ~ tRNS condition * task condition * baseline HR + motivation + sleepiness + head circumference + (1+ task condition|ID) predicting accuracy by the interaction between tRNS, task parameters and baseline performance. HR= hit rate, tRNS= transcranial random noise stimulation, ID= subject.

Table D.3: Pupil Size Affected by Task and Block

model term	df1	df2	F	p
tRNS	1	207	0.07	0.796
Task Condition	2	207	4.61	0.011
Baseline Pupil	1	207	83.92	<.001
Block	2	207	5.57	0.004

Table D.3: Pupil Size Affected by Task and Block

model term	df1	df2	F	p
Motivation	1	207	0.21	0.644
Sleepiness	1	207	1.10	0.295
Head Circumference	1	207	0.18	0.674
tRNS * Task Condition	2	207	1.95	0.145
tRNS * Baseline Pupil	1	207	0.02	0.881
Task Condition * Baseline Pupil	2	207	1.47	0.233
tRNS * Task Condition * Baseline Pupil	2	207	0.66	0.517

The Table shows the joint test for the linear model pre-trial pupil size ~ tRNS condition * task condition * baseline pre-trial pupil + block + motivation + sleepiness + head circumference predicting pupil size by the interaction between tRNS, task parameters and baseline pupil size. tRNS= transcranial random noise stimulation

Table D.4: TBR Predicted by Baseline

model term	df1	df2	F	p
tRNS	1	36.08	0.18	0.674
Baseline TBR	1	62.15	30.77	<.001
Baseline HR	1	60.30	3.31	0.074
Head Circumference	1	65.87	0.00	0.957
tRNS * Baseline TBR	1	47.39	0.87	0.355
tRNS * Baseline HR	1	48.55	0.38	0.543
Baseline TBR * Baseline HR	1	65.69	3.49	0.066
tRNS * Baseline TBR * Baseline HR	1	64.50	0.07	0.786

The Table shows the joint test for the linear model TBR ~ tRNS condition * baseline TBR * baseline HR + head circumference predicting tRNS effects of traditional TBR. TBR= theta/beta ratio, tRNS= transcranial random noise stimulation, HR= hit rate.

Table D.5: Periodic TBR Effects

model term	df1	df2	F	p
tRNS	1	0.92	1.38	0.462
Baseline TBR (per)	1	0.91	0.41	0.645
Baseline HR	1	1.02	4.78	0.269
Head Circumference	1	1.00	0.59	0.582
tRNS * Baseline TBR (per)	1	0.96	0.58	0.59
tRNS * Baseline HR	1	0.95	2.80	0.352
Baseline TBR (per) * Baseline HR	1	0.82	4.01	0.335
tRNS * Baseline TBR (per) * Baseline HR	1	1.13	3.82	0.278

The Table shows the joint test for the linear model periodic TBR ~ tRNS condition * baseline TBR (per) * baseline HR + head circumference predicting tRNS effects of traditional TBR. TBR= theta/beta ratio, tRNS= transcranial random noise stimulation, HR= hit rate, per= periodic

Table D.6: Aperiodic Exponent Effects

model term	df1	df2	F	p
tRNS Condition	1	68	0.54	0.463
Baseline AE	1	68	73.93	<.001
Baseline HR	1	68	0.17	0.68
Head Circumference	1	68	0.16	0.685
tRNS * Baseline AE	1	68	0.00	0.983
tRNS * Baseline HR	1	68	0.07	0.796
Baseline AE * Baseline HR	1	68	0.01	0.903
tRNS * Baseline AE * Baseline HR	1	68	1.12	0.293

The Table shows the joint test for the linear model AE ~ tRNS condition * baseline AE * baseline HR + head circumference predicting tRNS effects of aperiodic exponent calculated from electrode location C4. tRNS= transcranial random noise stimulation, HR= hit rate, AE= aperiodic exponent.

D.2 Resting-State Results

Table D.7: Baseline Pupil Predicted CoV

model term	df1	df2	F	p
Baseline Pre-Trial Pupil Size	1	216	8.69	0.004
Task Condition	2	216	17.17	<.001
Baseline Pre-Trial Pupil Size * Task	2	216	14.34	<.001

The Table shows the joint test for the linear model baseline CoV ~ pre-trial pupil size * task condition predicting performance by pupil dilation. CoV= Coefficient of Variation.

Table D.8: Pupil Size for Mind-Wandering was Distinct from On-Task and Task-Relevant Thoughts

model term	estimate	lower 95% CrI	upper 95% CrI
Pre-trial Pupil Size (On-Task)	1.31	0.33	2.32
Pre-trial Pupil Size (Task-Relevant)	1.14	0.38	1.93

The table displays coefficients from the Bayesian multinomial mixed effect model MW category ~ pre-trial pupil size +(1 | ID) with reference category MW.

The model term describes the tested variable (pupil size, motivation) in combination with the thought category (on-task, task-relevant distractions).

The 95% CrI's are calculated based on posterior distributions. CrI's not containing zero are regarded as significant equivalent ($p < .05$). CrI= Credible Interval

References

- Adams, Z. W., Roberts, W. M., Milich, R., & Fillmore, M. T. (2011). Does Response Variability Predict Distractibility among Adults with Attention-Deficit/Hyperactivity Disorder? *Psychological Assessment*, 23(2), 427–436. <https://doi.org/10.1037/a0022112>
- Alnæs, D., Sneve, M. H., Espeseth, T., Endestad, T., Pavert, S. H. P. van de, & Laeng, B. (2014). Pupil size signals mental effort deployed during multiple object tracking and predicts brain activity in the dorsal attention network and the locus coeruleus. *Journal of Vision*, 14(4), 1. <https://doi.org/10.1167/14.4.1>
- Angelidis, A., Van Der Does, W., Schakel, L., & Putman, P. (2016). Frontal EEG theta/beta ratio as an electrophysiological marker for attentional control and its test-retest reliability. *Biological Psychology*, 121, 49–52. <https://doi.org/10.1016/j.biopsycho.2016.09.008>
- Antal, A., & Herrmann, C. S. (2016). Transcranial Alternating Current and Random Noise Stimulation: Possible Mechanisms. *Neural Plasticity*, 2016, 1–12. <https://doi.org/10.1155/2016/3616807>
- Arnett, A. B., Rutter, T. M., & Stein, M. A. (2022). Neural markers of methylphenidate response in children with attention deficit hyperactivity disorder. *Frontiers in Behavioral Neuroscience*, 16. <https://www.frontiersin.org/articles/10.3389/fnbeh.2022.887622>
- Aston-Jones, G., & Cohen, J. D. (2005). Adaptive gain and the role of the locus coeruleus–norepinephrine system in optimal performance. *Journal of Comparative Neurology*, 493(1), 99–110. <https://doi.org/10.1002/cne.20723>
- Aston-Jones, G., Rajkowski, J., & Cohen, J. (1999). Role of locus coeruleus in attention and behavioral flexibility. *Biological Psychiatry*, 46(9), 1309–1320. [https://doi.org/10.1016/S0006-3223\(99\)00140-7](https://doi.org/10.1016/S0006-3223(99)00140-7)
- Baird, B., Smallwood, J., & Schooler, J. W. (2011). Back to the future: Autobiographical planning and the functionality of mind-wandering. *Consciousness and Cognition*, 20(4), 1604–1611. <https://doi.org/10.1016/j.concog.2011.08.007>

"References"

- Ballard, J. C. (1996). Computerized assessment of sustained attention: A review of factors affecting vigilance performance. *Journal of Clinical and Experimental Neuropsychology*, 18(6), 843–863. <https://doi.org/10.1080/01688639608408307>
- Barnett, A. G., Van Der Pols, J. C., & Dobson, A. J. (2005). Regression to the mean: What it is and how to deal with it. *International Journal of Epidemiology*, 34(1), 215–220. <https://doi.org/10.1093/ije/dyh299>
- Battaglini, L., Casco, C., Fertoni, A., Miniussi, C., Di Ponzio, M., & Vicovaro, M. (2023). Noise in the brain: Transcranial random noise stimulation and perceptual noise act on a stochastic resonance-like mechanism. *European Journal of Neuroscience*, 57(12), 2097–2111. <https://doi.org/10.1111/ejn.15965>
- Bedi, A., Russell, P. N., & Helton, W. S. (2023). Go-stimuli probability influences response bias in the sustained attention to response task: a signal detection theory perspective. *Psychological Research*, 87(2), 509–518. <https://doi.org/10.1007/s00426-022-01679-7>
- Benedek, M., Stoiser, R., Walcher, S., & Körner, C. (2017). Eye behavior associated with internally versus externally directed cognition. *Frontiers in Psychology*, 8. <https://doi.org/10.3389/fpsyg.2017.01092>
- Berger, I., Dakwar-Kawar, O., Grossman, E. S., Nahum, M., & Cohen Kadosh, R. (2021). Scaffolding the attention-deficit/hyperactivity disorder brain using transcranial direct current and random noise stimulation: A randomized controlled trial. *Clinical Neurophysiology*, 132(3), 699–707. <https://doi.org/10.1016/j.clinph.2021.01.005>
- Borgaro, S., Pogge, D. L., DeLuca, V. A., Bilginer, L., Stokes, J., & Harvey, P. D. (2003). Convergence of Different Versions of the Continuous Performance Test: Clinical and Scientific Implications. *Journal of Clinical and Experimental Neuropsychology*, 25(2), 283–292. <https://doi.org/10.1076/jcen.25.2.283.13646>
- Boukrina, O., & Barrett, A. M. (2017). Disruption of the ascending arousal system and cortical attention networks in post-stroke delirium and spatial neglect. *Neuroscience & Biobehavioral Reviews*, 83, 1–10. <https://doi.org/10.1016/j.neubiorev.2017.09.024>
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10(4), 433–436. <https://doi.org/10.1163/156856897X00357>
- Brancucci, A., Rivolta, D., Nitsche, M. A., & Manippa, V. (2023). The effects of transcranial random noise stimulation on motor function: A comprehensive review of the literature. *Physiology & Behavior*, 261, 114073. <https://doi.org/10.1016/j.physbeh.2023.114073>

"References"

- [org/10.1016/j.physbeh.2023.114073](https://doi.org/10.1016/j.physbeh.2023.114073)
- Bridger, R. S., Johnsen, S. Å. K., & Brasher, K. (2013). Psychometric properties of the Cognitive Failures Questionnaire†. *Ergonomics*, 56(10), 1515–1524. <https://doi.org/10.1080/00140139.2013.821172>
- Broadbent, D. E. (1953). Noise, paced performance and vigilance tasks. *British Journal of Psychology*, 44(4), 295–303. <https://www.proquest.com/docview/1293465099/citation/2DF12C6D91124C0BPQ/1>
- Broadbent, D. E., Cooper, P. F., FitzGerald, P., & Parkes, K. R. (1982). The Cognitive Failures Questionnaire (CFQ) and its correlates. *British Journal of Clinical Psychology*, 21(1), 1–16. <https://doi.org/10.1111/j.2044-8260.1982.tb01421.x>
- Chandler, D. J., Gao, W.-J., & Waterhouse, B. D. (2014). Heterogeneous organization of the locus coeruleus projections to prefrontal and motor cortices. *PNAS*, 111(18), 6816–6821.
- Clarke, A. R., Barry, R. J., Karamacoska, D., & Johnstone, S. J. (2019). The EEG Theta/Beta Ratio: A marker of Arousal or Cognitive Processing Capacity? *Applied Psychophysiology and Biofeedback*, 44(2), 123–129. <https://doi.org/10.1007/s10484-018-09428-6>
- Clayton, M. S., Yeung, N., & Cohen Kadosh, R. (2015). The roles of cortical oscillations in sustained attention. *Trends in Cognitive Sciences*, 19(4), 188–195. <https://doi.org/10.1016/j.tics.2015.02.004>
- Clayton, M. S., Yeung, N., & Cohen Kadosh, R. (2019). Electrical stimulation of alpha oscillations stabilizes performance on visual attention tasks. *Journal of Experimental Psychology: General*, 148(2), 203–220. <https://doi.org/10.1037/xge0000502>
- Cohen Kadosh, R., Ciobotaru, D., Karstens, M. I., & Nguyen, V. (n.d.). Personalized Home-Based Neurostimulation via AI Optimization Augments Sustained Attention. *Submitted for Publication*.
- Cojan, Y., Saj, A., & Vuilleumier, P. (2021). Brain Substrates for Distinct Spatial Processing Components Contributing to Hemineglect in Humans. *Brain Sciences*, 11(12), 1584. <https://doi.org/10.3390/brainsci11121584>
- Contò, F., Edwards, G., Tyler, S., Parrott, D., Grossman, E., & Battelli, L. (2021). Attention network modulation via tRNS correlates with attention gain. *eLife*, 10, e63782. <https://doi.org/10.7554/eLife.63782>
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, 3(3), 201–215. <https://doi.org/10.1038/nrn755>

"References"

- Cosman, J. D., Lowe, K. A., Zinke, W., Woodman, G. F., & Schall, J. D. (2018). Prefrontal control of visual distraction. *Current Biology*, 28(3), 414–420.e3. <https://doi.org/10.1016/j.cub.2017.12.023>
- Coull, J. T. (1998). Neural correlates of attention and arousal: Insights from electrophysiology, functional neuroimaging and psychopharmacology. *Progress in Neurobiology*, 55(4), 343–361. [https://doi.org/10.1016/S0301-0082\(98\)00011-2](https://doi.org/10.1016/S0301-0082(98)00011-2)
- Dakwar-Kawar, O., Mentch-Lifshits, T., Hochman, S., Mairon, N., Cohen, R., Balasubramani, P., Mishra, J., Jordan, J., Cohen Kadosh, R., Berger, I., & Nahum, M. (2024). Aperiodic and periodic components of oscillatory brain activity in relation to cognition and symptoms in pediatric ADHD. *Cerebral Cortex*, 34(6), bhae236. <https://doi.org/10.1093/cercor/bhae236>
- deBettencourt, M. T., Norman, K. A., & Turk-Browne, N. B. (2018). Forgetting from lapses of sustained attention. *Psychonomic Bulletin & Review*, 25(2), 605–611. <https://doi.org/10.3758/s13423-017-1309-5>
- Del Bianco, T., Haartsen, R., Mason, L., Leno, V. C., Springer, C., Potter, M., Mackay, W., Smit, P., Plessis, C. D., Brink, L., Johnson, M. H., Murphy, D., Loth, E., Odendaal, H., & Jones, E. J. H. (2024). The importance of decomposing periodic and aperiodic EEG signals for assessment of brain function in a global context. *Developmental Psychobiology*, 66(4), e22484. <https://doi.org/10.1002/dev.22484>
- Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, 134(1), 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>
- Demeter, E., Hernandez-Garcia, L., Sarter, M., & Lustig, C. (2011). Challenges to attention: A continuous arterial spin labeling (ASL) study of the effects of distraction on sustained attention. *NeuroImage*, 54(2), 1518–1529. <https://doi.org/10.1016/j.neuroimage.2010.09.026>
- Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, 64(Volume 64, 2013), 135–168. <https://doi.org/10.1146/annurev-psych-113011-143750>
- Dinges, D. F., & Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments, & Computers*, 17(6), 652–655. <https://doi.org/10.3758/BF03200977>
- Doppel, G., Mückschel, M., Ziemssen, T., & Beste, C. (2017). Demands on re-

"References"

- sponse inhibition processes determine modulations of theta band activity in superior frontal areas and correlations with pupillometry – Implications for the norepinephrine system during inhibitory control. *NeuroImage*, 157, 575–585. <https://doi.org/10.1016/j.neuroimage.2017.06.037>
- Donald, F. M. (2008). The classification of vigilance tasks in the real world. *Ergonomics*, 51(11), 1643–1655. <https://doi.org/10.1080/00140130802327219>
- Dondé, C., Brevet-Aeby, C., Poulet, E., Mondino, M., & Brunelin, J. (2019). Potential impact of bifrontal transcranial random noise stimulation (tRNS) on the semantic stroop effect and its resting-state EEG correlates. *Neurophysiologie Clinique*, 49(3), 243–248. <https://doi.org/10.1016/j.neucli.2019.03.002>
- Donoghue, T., Haller, M., Peterson, E. J., Varma, P., Sebastian, P., Gao, R., Noto, T., Lara, A. H., Wallis, J. D., Knight, R. T., Shestyuk, A., & Voytek, B. (2020). Parameterizing neural power spectra into periodic and aperiodic components. *Nature Neuroscience*, 23(12), 1655–1665. <https://doi.org/10.1038/s41593-020-00744-x>
- Dosenbach, N. U. F., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in Cognitive Sciences*, 12(3), 99–105. <https://doi.org/10.1016/j.tics.2008.01.001>
- Dutra, T. G., Baltar, A., & Monte-Silva, K. K. (2016). Motor cortex excitability in attention-deficit hyperactivity disorder (ADHD): A systematic review and meta-analysis. *Research in Developmental Disabilities*, 56, 1–9. <https://doi.org/10.1016/j.ridd.2016.01.022>
- Egeland, J., Lund, O., Kowalik-Gran, I., Aarlien, A. K., & Söderlund, G. B. W. (2023). Effects of auditory white noise stimulation on sustained attention and response time variability. *Frontiers in Psychology*, 14. <https://doi.org/10.3389/fpsyg.2023.1301771>
- Erickson, L. C., Thiessen, E. D., Godwin, K. E., Dickerson, J. P., & Fisher, A. V. (2015). Endogenously and exogenously driven selective sustained attention: Contributions to learning in kindergarten children. *Journal of Experimental Child Psychology*, 138, 126–134. <https://doi.org/10.1016/j.jecp.2015.04.011>
- Esterman, M., Noonan, S. K., Rosenberg, M., & DeGutis, J. (2013). In the zone or zoning out? Tracking behavioral and neural fluctuations during sustained attention. *Cerebral Cortex*, 23(11), 2712–2723. <https://doi.org/10.1093/cercor/bhs261>
- Esterman, M., & Rothlein, D. (2019). Models of sustained attention. *Current*

"References"

- Opinion in Psychology*, 29, 174–180. <https://doi.org/10.1016/j.copsy.2019.03.005>
- Euler, M. J., Vehar, J. V., Guevara, J. E., Geiger, A. R., Deboeck, P. R., & Lohse, K. R. (2024). Associations between the resting EEG aperiodic slope and broad domains of cognitive ability. *Psychophysiology*, 61(6), e14543. <https://doi.org/10.1111/psyp.14543>
- Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, 26(2), 471–479. <https://doi.org/10.1016/j.neuroimage.2005.02.004>
- Fassi, L., Hochman, S., Daskalakis, Z. J., Blumberger, D. M., & Cohen Kadosh, R. (2023). *The Importance of Individual Beliefs in Assessing Treatment Efficacy: Insights from Neurostimulation Studies*. <https://doi.org/10.1101/2020.12.06.411850>
- Fertonani, A., Ferrari, C., & Miniussi, C. (2015). What do you feel if I apply transcranial electric stimulation? Safety, sensations and secondary induced effects. *Clinical Neurophysiology*, 126(11), 2181–2188. <https://doi.org/10.1016/j.clinph.2015.03.015>
- Fertonani, A., & Miniussi, C. (2017). Transcranial electrical stimulation: What we know and do not know about mechanisms. *The Neuroscientist*, 23(2), 109–123. <https://doi.org/10.1177/1073858416631966>
- Fertonani, A., Rosini, S., Cotelli, M., Rossini, P. M., & Miniussi, C. (2010). Naming facilitation induced by transcranial direct current stimulation. *Behavioural Brain Research*, 208(2), 311–318. <https://doi.org/10.1016/j.bbr.2009.10.030>
- Fiebelkorn, I. C., & Kastner, S. (2019). A rhythmic theory of attention. *Trends in Cognitive Sciences*, 23(2), 87–101. <https://doi.org/10.1016/j.tics.2018.11.009>
- Fiebelkorn, I. C., & Kastner, S. (2020). Functional Specialization in the Attention Network. *Annual Review of Psychology*, 71(Volume 71, 2020), 221–249. <https://doi.org/10.1146/annurev-psych-010418-103429>
- Finley, A. J., Angus, D. J., Reekum, C. M. van, Davidson, R. J., & Schaefer, S. M. (2022). Periodic and aperiodic contributions to theta-beta ratios across adulthood. *Psychophysiology*, 59(11), e14113. <https://doi.org/10.1111/psyp.14113>
- Flehmig, H., Steinborn, M., Langner, R., Scholz, A., & Karl, W. (2007). Assessing intraindividual variability in sustained attention: Reliability, relation to speed and accuracy, and practice effects. *Psychology Science*.

"References"

- Fortenbaugh, F. C., DeGutis, J., Germine, L., Wilmer, J. B., Grosso, M., Russo, K., & Esterman, M. (2015). Sustained Attention Across the Life Span in a Sample of 10,000: Dissociating Ability and Strategy. *Psychological Science*, 26(9), 1497–1510. <https://doi.org/10.1177/0956797615594896>
- Fortenbaugh, F. C., Rothlein, D., McGlinchey, R., DeGutis, J., & Esterman, M. (2018). Tracking behavioral and neural fluctuations during sustained attention: A robust replication and extension. *NeuroImage*, 171, 148–164. <https://doi.org/10.1016/j.neuroimage.2018.01.002>
- Fox, J., & Monette, G. (1992). Generalized collinearity diagnostics. *Journal of the American Statistical Association*, 87(417), 178–183. <https://doi.org/10.2307/2290467>
- Frank, B., Harty, S., Kluge, A., & Cohen Kadosh, R. (2018). Learning while multitasking: Short and long-term benefits of brain stimulation. *Ergonomics*, 61(11), 1454–1463. <https://doi.org/10.1080/00140139.2018.1563722>
- Frank, D. J., Nara, B., Zavagnin, M., Touron, D. R., & Kane, M. J. (2015). Validating older adults' reports of less mind-wandering: An examination of eye movements and dispositional influences. *Psychology and Aging*, 30(2), 266–278. <https://doi.org/10.1037/pag0000031>
- Friebs, M. A., Dechant, M., Vedress, S., Frings, C., & Mandryk, R. L. (2021). Shocking advantage! Improving digital game performance using non-invasive brain stimulation. *International Journal of Human-Computer Studies*, 148, 102582. <https://doi.org/10.1016/j.ijhcs.2020.102582>
- Gallen, C. L., Schaerlaeken, S., Younger, J. W., Anguera, J. A., & Gazzaley, A. (2023). Contribution of sustained attention abilities to real-world academic skills in children. *Scientific Reports*, 13(1), 2673. <https://doi.org/10.1038/s41598-023-29427-w>
- Gau, S.-F., Hwang-Gu, S.-L., Lin, Y. T., Hsu, C.-F., & Ni, H.-C. (2022). The Link between Mind-wandering and Performance in a Sustained Attention to Response Test in Adults with Attention-deficit/Hyperactivity Disorder Symptoms. *Taiwanese Journal of Psychiatry*, 36(2), 74. https://doi.org/10.4103/TPSY.TPSY_16_22
- Godwin, C. A., Smith, D. M., & Schumacher, E. H. (2023). Beyond mind wandering: Performance variability and neural activity during off-task thought and other attention lapses. *Consciousness and Cognition*, 108, 103459. <https://doi.org/10.1016/j.concog.2022.103459>
- Godwin, K., & Fisher, A. (2014). Selective Sustained Attention, the Visual Environment, and Learning in Kindergarten-age Children: Preliminary Results of an

"References"

- Individual Difference Study. *Proceedings of the Annual Meeting of the Cognitive Science Society*, 36(36). <https://escholarship.org/uc/item/8rm4v3jh>
- Grandchamp, R., Braboszcz, C., & Delorme, A. (2014). Oculometric variations during mind wandering. *Frontiers in Psychology*, 5. <https://doi.org/10.3389/fpsyg.2014.00031>
- Greene, C. M., Bellgrove, M. A., Gill, M., & Robertson, I. H. (2009). Noradrenergic genotype predicts lapses in sustained attention. *Neuropsychologia*, 47(2), 591–594. <https://doi.org/10.1016/j.neuropsychologia.2008.10.003>
- Guillon, M., Dumbleton, K., Theodoratos, P., Gobbe, M., Wooley, C. B., & Moody, K. (2016). The effects of age, refractive status, and luminance on pupil size. *Optometry and Vision Science*, 93(9), 1093. <https://doi.org/10.1097/OPX.0000000000000893>
- Gyurkovics, M., Clements, G. M., Low, K. A., Fabiani, M., & Gratton, G. (2022). Stimulus-Induced Changes in 1/f-like Background Activity in EEG. *Journal of Neuroscience*, 42(37), 7144–7151. <https://doi.org/10.1523/JNEUROSCI.0414-22.2022>
- Harty, S., & Cohen Kadosh, R. (2019). Suboptimal Engagement of High-Level Cortical Regions Predicts Random-Noise-Related Gains in Sustained Attention. *Psychological Science*, 30(9), 1318–1332. <https://doi.org/10.1177/0956797619856658>
- Hasenkamp, W., Wilson-Mendenhall, C. D., Duncan, E., & Barsalou, L. W. (2012). Mind wandering and attention during focused meditation: A fine-grained temporal analysis of fluctuating cognitive states. *NeuroImage*, 59(1), 750–760. <https://doi.org/10.1016/j.neuroimage.2011.07.008>
- Helfrich, R. F., Fiebelkorn, I. C., Szczepanski, S. M., Lin, J. J., Parvizi, J., Knight, R. T., & Kastner, S. (2018). Neural mechanisms of sustained attention are rhythmic. *Neuron*, 99(4), 854–865.e5. <https://doi.org/10.1016/j.neuron.2018.07.032>
- Helton, W. S., Head, J., & Russell, P. N. (2011). Relationship between a Self-Reported ADHD Questionnaire and Sustained Attention to Local and Global Target Features. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 55(1), 904–908. <https://doi.org/10.1177/1071181311551188>
- Helton, W. S., Lopez, N., & Tamminga, S. (2008). Performance on a Sustained Attention to Response Task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 52(18), 1214–1218. <https://doi.org/10.1177/154193120805201813>
- Herrera-Morales, W. V., Reyes-López, J. V., Tuz-Castellanos, K. N.-H., Ortigón-

"References"

- Abud, D., Ramírez-Lugo, L., Santiago-Rodríguez, E., & Núñez-Jaramillo, L. (2023). Variations in Theta/Beta Ratio and Cognitive Performance in Subpopulations of Subjects with ADHD Symptoms: Towards Neuropsychological Profiling for Patient Subgrouping. *Journal of Personalized Medicine*, 13(9), 1361. <https://doi.org/10.3390/jpm13091361>
- Herscovitch, J., & Broughton, R. (1981). Sensitivity of the Stanford Sleepiness Scale to the Effects of Cumulative Partial Sleep Deprivation and Recovery Oversleeping. *Sleep*, 4(1), 83–92. <https://doi.org/10.1093/sleep/4.1.83>
- Hoddes, E., Dement, W. C., & Zarcone, V. (1972). *Stanford sleepiness scale*. <https://doi.org/10.1037/t07116-000>
- Hou, R. H., Freeman, C., Langley, R. W., Szabadi, E., & Bradshaw, C. M. (2005). Does modafinil activate the locus coeruleus in man? Comparison of modafinil and clonidine on arousal and autonomic functions in human volunteers. *Psychopharmacology*, 181(3), 537–549. <https://doi.org/10.1007/s00213-005-0013-8>
- Huang, H., Li, R., & Zhang, J. (2023). A review of visual sustained attention: neural mechanisms and computational models. *PeerJ*, 11, e15351. <https://doi.org/10.7717/peerj.15351>
- Huette, S., Mathis, A., & Graesser, A. (2016). Blink durations reflect mind wandering during reading. *Cognitive Science*. <https://www.semanticscholar.org/paper/Blink-durations-reflect-mind-wandering-during-Huette-Mathis/fba2314dea3944723ddc0348dc41a6e823dd5410>
- Inukai, Y., Saito, K., Sasaki, R., Tsuiki, S., Miyaguchi, S., Kojima, S., Masaki, M., Otsuru, N., & Onishi, H. (2016). Comparison of Three Non-Invasive Transcranial Electrical Stimulation Methods for Increasing Cortical Excitability. *Frontiers in Human Neuroscience*, 10. <https://doi.org/10.3389/fnhum.2016.00668>
- Jin, C. Y., Borst, J. P., & Vugt, M. K. van. (2020). Distinguishing vigilance decrement and low task demands from mind-wandering: A machine learning analysis of EEG. *European Journal of Neuroscience*, 52(9), 4147–4164. <https://doi.org/10.1111/ejn.14863>
- Johnson, K. A., Kelly, S. P., Bellgrove, M. A., Barry, E., Cox, M., Gill, M., & Robertson, I. H. (2007). Response variability in attention deficit hyperactivity disorder: Evidence for neuropsychological heterogeneity. *Neuropsychologia*, 45(4), 630–638. <https://doi.org/10.1016/j.neuropsychologia.2006.03.034>
- Joshi, S., Li, Y., Kalwani, R. M., & Gold, J. I. (2016). Relationships between

"References"

- Pupil Diameter and Neuronal Activity in the Locus Coeruleus, Colliculi, and Cingulate Cortex. *Neuron*, 89(1), 221–234. <https://doi.org/10.1016/j.neuron.2015.11.028>
- Kane, M. J., Smeekens, B. A., Meier, M. E., Welhaf, M. S., & Phillips, N. E. (2021). Testing the construct validity of competing measurement approaches to probed mind-wandering reports. *Behavior Research Methods*, 53(6), 2372–2411. <https://doi.org/10.3758/s13428-021-01557-x>
- Karalunas, S. L., Ostlund, B. D., Alperin, B. R., Figuracion, M., Gustafsson, H. C., Deming, E. M., Foti, D., Antovich, D., Dude, J., Nigg, J., & Sullivan, E. (2022). Electroencephalogram aperiodic power spectral slope can be reliably measured and predicts ADHD risk in early development. *Developmental Psychobiology*, 64(3), e22228. <https://doi.org/10.1002/dev.22228>
- Kawakami, S., Inukai, Y., Ikarashi, H., Kamii, Y., Takahashi, H., Miyaguchi, S., Otsuru, N., & Onishi, H. (2024). No effects of cerebellar transcranial random noise stimulation on cerebellar brain inhibition, visuomotor learning, and pupil diameter. *Behavioural Brain Research*, 475, 115209. <https://doi.org/10.1016/j.bbr.2024.115209>
- Kessler, R. C., Adler, L., Ames, M., Demler, O., Faraone, S., Hiripi, E., Howes, M. J., Jin, R., Secnik, K., Spencer, T., Ustun, T. B., & Walters, E. E. (2005). The World Health Organization adult ADHD self-report scale (ASRS): a short screening scale for use in the general population. *Psychological Medicine*, 35(2), 245–256. <https://doi.org/10.1017/S0033291704002892>
- Kondo, H. M., Terashima, H., Kihara, K., Kochiyama, T., Shimada, Y., & Kawahara, J. I. (2023). Prefrontal GABA and glutamate–glutamine levels affect sustained attention. *Cerebral Cortex*, bhad294. <https://doi.org/10.1093/cercor/bhad294>
- Krause, B., & Cohen Kadosh, R. (2014). Not all brains are created equal: The relevance of individual differences in responsiveness to transcranial electrical stimulation. *Frontiers in Systems Neuroscience*, 8. <https://doi.org/10.3389/fnsys.2014.00025>
- Krause, B., Márquez-Ruiz, J., & Cohen Kadosh, R. (2013). The effect of transcranial direct current stimulation: A role for cortical excitation/inhibition balance? *Frontiers in Human Neuroscience*, 7. <https://doi.org/10.3389/fnhum.2013.00602>
- Kucyi, A., Esterman, M., Riley, C. S., & Valera, E. M. (2016). Spontaneous default network activity reflects behavioral variability independent of mind-wandering. *Proceedings of the National Academy of Sciences*, 113(48), 13899–

"References"

13904. <https://doi.org/10.1073/pnas.1611743113>
- Kumle, L., Vö, M. L.-H., & Draschkow, D. (2021). Estimating power in (generalized) linear mixed models: An open introduction and tutorial in R. *Behavior Research Methods*, 53(6), 2528–2543. <https://doi.org/10.3758/s13428-021-01546-0>
- Laczó, B., Antal, A., Rothkegel, H., & Paulus, W. (2014). Increasing human leg motor cortex excitability by transcranial high frequency random noise stimulation. *Restorative Neurology and Neuroscience*, 32(3), 403–410. <https://doi.org/10.3233/RNN-130367>
- Langner, R., & Eickhoff, S. B. (2013). Sustaining attention to simple tasks: A meta-analytic review of the neural mechanisms of vigilant attention. *Psychological Bulletin*, 139(4), 870–900. <https://doi.org/10.1037/a0030694>
- Lema, A., Carvalho, S., Fregni, F., Gonçalves, Ó. F., & Leite, J. (2021). The effects of direct current stimulation and random noise stimulation on attention networks. *Scientific Reports*, 11(1), 6201. <https://doi.org/10.1038/s41598-021-85749-7>
- Lenartowicz, A., Simpson, G. V., & Cohen, M. S. (2013). Perspective: Causes and functional significance of temporal variations in attention control. *Frontiers in Human Neuroscience*, 7. <https://doi.org/10.3389/fnhum.2013.00381>
- Lorenz, R., Hampshire, A., & Leech, R. (2017). Neuroadaptive bayesian optimization and hypothesis testing. *Trends in Cognitive Sciences*, 21(3), 155–167. <https://doi.org/10.1016/j.tics.2017.01.006>
- Lorenz, R., Simmons, L. E., Monti, R. P., Arthur, J. L., Limal, S., Laakso, I., Leech, R., & Violante, I. R. (2019). Efficiently searching through large tACS parameter spaces using closed-loop bayesian optimization. *Brain Stimulation*, 12(6), 1484–1489. <https://doi.org/10.1016/j.brs.2019.07.003>
- Luna, F. G., Marino, J., Roca, J., & Lupiáñez, J. (2018). Executive and arousal vigilance decrement in the context of the attentional networks: The ANTI-vea task. *Journal of Neuroscience Methods*, 306, 77–87. <https://doi.org/10.1016/j.jneumeth.2018.05.011>
- Ma, X., Monfared, R., Grant, R., & Goh, Y. M. (2024). Determining Cognitive Workload Using Physiological Measurements: Pupillometry and Heart-Rate Variability. *Sensors*, 24(6), 2010. <https://doi.org/10.3390/s24062010>
- Macdonald, K. T., Barnes, M. A., Miciak, J., Roberts, G., Halverson, K. K., Vaughn, S., & Cirino, P. T. (2021). Sustained Attention and Behavioral Ratings of Attention in Struggling Readers. *Scientific Studies of Reading*, 25(5), 436–451. <https://doi.org/10.1080/10888438.2020.1826950>

"References"

- Machida, K., Murias, M., & Johnson, K. A. (2019). Electrophysiological Correlates of Response Time Variability During a Sustained Attention Task. *Frontiers in Human Neuroscience*, 13. <https://www.frontiersin.org/articles/10.3389/fnhum.2019.00363>
- Mackenzie, A. K., & Harris, J. M. (2017). A link between attentional function, effective eye movements, and driving ability. *Journal of Experimental Psychology: Human Perception and Performance*, 43(2), 381–394. <https://doi.org/10.1037/xhp0000297>
- Mackworth, J. F. (1964). Performance decrement in vigilance, threshold, and high-speed perceptual motor tasks. *Canadian Journal of Psychology / Revue Canadienne de Psychologie*, 18(3), 209–223. <https://doi.org/10.1037/h0083302>
- Mackworth, N. H. (1948). The Breakdown of Vigilance during Prolonged Visual Search. *Quarterly Journal of Experimental Psychology*, 1(1), 6–21. <https://doi.org/10.1080/17470214808416738>
- Magliacano, A., Fiorenza, S., Estraneo, A., & Trojano, L. (2020). Eye blink rate increases as a function of cognitive load during an auditory oddball paradigm. *Neuroscience Letters*, 736, 135293. <https://doi.org/10.1016/j.neulet.2020.135293>
- Makeig, S., & Inlow, M. (1993). Lapse in alertness: Coherence of fluctuations in performance and EEG spectrum. *Electroencephalography and Clinical Neurophysiology*, 86(1), 23–35. [https://doi.org/10.1016/0013-4694\(93\)90064-3](https://doi.org/10.1016/0013-4694(93)90064-3)
- Maness, E. B., Burk, J. A., McKenna, J. T., Schiffrino, F. L., Strecker, R. E., & McCoy, J. G. (2022). Role of the locus coeruleus and basal forebrain in arousal and attention. *Brain Research Bulletin*, 188, 47–58. <https://doi.org/10.1016/j.brainresbull.2022.07.014>
- Manly, T., Robertson, I. H., Galloway, M., & Hawkins, K. (1999). The absent mind:: Further investigations of sustained attention to response. *Neuropsychologia*, 37(6), 661–670. [https://doi.org/10.1016/S0028-3932\(98\)00127-4](https://doi.org/10.1016/S0028-3932(98)00127-4)
- Martínez-Pérez, V., Andreu, A., Sandoval-Lentisco, A., Tortajada, M., Palmero, L. B., Castillo, A., Campoy, G., & Fuentes, L. J. (2023). Vigilance decrement and mind-wandering in sustained attention tasks: Two sides of the same coin? *Frontiers in Neuroscience*, 17. <https://www.frontiersin.org/articles/10.3389/fnins.2023.1122406>
- Martínez-Pérez, V., Baños, D., Andreu, A., Tortajada, M., Palmero, L. B., Campoy, G., & Fuentes, L. J. (2021). Propensity to intentional and unintentional mind-wandering differs in arousal and executive vigilance tasks. *PLOS ONE*, 16(10),

"References"

- e0258734. <https://doi.org/10.1371/journal.pone.0258734>
- Matthews, G., & Davies, D. R. (2001). Individual differences in energetic arousal and sustained attention: A dual-task study. *Personality and Individual Differences*, 31(4), 575–589. [https://doi.org/10.1016/S0191-8869\(00\)00162-8](https://doi.org/10.1016/S0191-8869(00)00162-8)
- McMillan, R., Kaufman, S. B., & Singer, J. L. (2013). Ode to positive constructive daydreaming. *Frontiers in Psychology*, 4. <https://doi.org/10.3389/fpsyg.2013.00626>
- McVay, J. C., & Kane, M. J. (2013). Dispatching the wandering mind? Toward a laboratory method for cuing “spontaneous” off-task thought. *Frontiers in Psychology*, 4. <https://doi.org/10.3389/fpsyg.2013.00570>
- Mechler, K., Banaschewski, T., Hohmann, S., & Häge, A. (2022). Evidence-based pharmacological treatment options for ADHD in children and adolescents. *Pharmacology & Therapeutics*, 230, 107940. <https://doi.org/10.1016/j.pharmthera.2021.107940>
- Melnychuk, M. C., Robertson, I. H., Plini, E. R. G., & Dockree, P. M. (2021). A bridge between the breath and the brain: Synchronization of respiration, a pupillometric marker of the locus coeruleus, and an EEG marker of attentional control state. *Brain Sciences*, 11(10), 1324. <https://doi.org/10.3390/brainsci11101324>
- Minkow, K., & Fuerst, F. (2024). *Linking Health and Well-Being to Financial Performance in Commercial Real Estate*. <https://doi.org/10.2139/ssrn.5042836>
- Molloy, R., & Parasuraman, R. (1996). Monitoring an automated system for a single failure: Vigilance and task complexity effects. *Human Factors*, 38(2), 311–322.
- Monastra, V. J., Lubar, J. F., Linden, M., VanDeusen, P., Green, G., Wing, W., Phillips, A., & Fenger, T. N. (1999). Assessing attention deficit hyperactivity disorder via quantitative electroencephalography: An initial validation study. *Neuropsychology*, 13(3), 424–433. <https://doi.org/10.1037/0894-4105.13.3.424>
- Moret, B., Camilleri Gorrieri, R., Grassi, M., & Campana, G. (2021). Cognitive exergame training and transcranial random noise stimulation effects on executive control in healthy young adults. *Neuropsychology*, 35(5), 568–580. <https://doi.org/10.1037/neu0000745>
- Moret, B., Donato, R., Nucci, M., Cona, G., & Campana, G. (2019). Transcranial random noise stimulation (tRNS): A wide range of frequencies is needed for increasing cortical excitability. *Scientific Reports*, 9(1), 15150. <https://doi.org/10.1038/s41598-019-41510-1>

"References"

[i.org/10.1038/s41598-019-51553-7](https://doi.org/10.1038/s41598-019-51553-7)

- Nawani, H., Mittner, M., & Csifcsák, G. (2023). Modulation of mind wandering using transcranial direct current stimulation: A meta-analysis based on electric field modeling. *NeuroImage*, 272, 120051. <https://doi.org/10.1016/j.neuroimage.2023.120051>
- Nelson, J. T., McKinley, R. A., Golob, E. J., Warm, J. S., & Parasuraman, R. (2014). Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). *NeuroImage*, 85, 909–917. <https://doi.org/10.1016/j.neuroimage.2012.11.061>
- Nuechterlein, K. H., & Dawson, M. E. (1984). Information Processing and Attentional Functioning in the Developmental Course of Schizophrenic Disorders. *Schizophrenia Bulletin*, 10(2), 160–203. <https://doi.org/10.1093/schbul/10.2.160>
- Nuechterlein, K. H., Parasuraman, R., & Jiang, Q. (1983). Visual Sustained Attention: Image Degradation Produces Rapid Sensitivity Decrement Over Time. *Science*, 220(4594), 327–329. <https://doi.org/10.1126/science.6836276>
- O’Connell, R. G., Bellgrove, M. A., Dockree, P. M., Lau, A., Fitzgerald, M., & Robertson, I. H. (2008). Self-alert training: Volitional modulation of autonomic arousal improves sustained attention. *Neuropsychologia*, 46(5), 1379–1390. <https://doi.org/10.1016/j.neuropsychologia.2007.12.018>
- O’Connell, R. G., Dockree, P. M., & Kelly, S. P. (2012). A supramodal accumulation-to-bound signal that determines perceptual decisions in humans. *Nature Neuroscience*, 15(12), 1729–1735. <https://doi.org/10.1038/nn.3248>
- Oken, B. S., Salinsky, M. C., & Elsas, S. M. (2006). Vigilance, alertness, or sustained attention: Physiological basis and measurement. *Clinical Neurophysiology*, 117(9), 1885–1901. <https://doi.org/10.1016/j.clinph.2006.01.017>
- Ostlund, B. D., Alperin, B. R., Drew, T., & Karalunas, S. L. (2021). Behavioral and cognitive correlates of the aperiodic (1/f-like) exponent of the EEG power spectrum in adolescents with and without ADHD. *Developmental Cognitive Neuroscience*, 48, 100931. <https://doi.org/10.1016/j.dcn.2021.100931>
- Pallier, C. (2002). *Computing discriminability and bias with the R software*.
- Pan, J., Klímová, M., McGuire, J. T., & Ling, S. (2022). Arousal-based pupil modulation is dictated by luminance. *Scientific Reports*, 12(1), 1390. <https://doi.org/10.1038/s41598-022-05280-1>
- Pani, S. M., Saba, L., & Fraschini, M. (2022). Clinical applications of EEG power spectra aperiodic component analysis: A mini-review. *Clinical Neurophysiology*, 143, 1–13. <https://doi.org/10.1016/j.clinph.2022.08.010>

"References"

- Parasuraman, R., Nestor, P., & Greenwood, P. (1989). Sustained-Attention Capacity in Young and Older Adults. *Psychology and Aging*, 4(3), 339–345.
- Parkin, B. L., Bhandari, M., Glen, J. C., & Walsh, V. (2019). The physiological effects of transcranial electrical stimulation do not apply to parameters commonly used in studies of cognitive neuromodulation. *Neuropsychologia*, 128, 332–339. <https://doi.org/10.1016/j.neuropsychologia.2018.03.030>
- Pasqualotto, A. (2016). Transcranial random noise stimulation benefits arithmetic skills. *Neurobiology of Learning and Memory*, 133, 7–12. <https://doi.org/10.1016/j.nlm.2016.05.004>
- Paulus, W. (2011). Transcranial electrical stimulation (tES – tDCS; tRNS, tACS) methods. *Neuropsychological Rehabilitation*, 21(5), 602–617. <https://doi.org/10.1080/09602011.2011.557292>
- Pavan, A., Ghin, F., Contillo, A., Milesi, C., Campana, G., & Mather, G. (2019). Modulatory mechanisms underlying high-frequency transcranial random noise stimulation (hf-tRNS): A combined stochastic resonance and equivalent noise approach. *Brain Stimulation*, 12(4), 967–977. <https://doi.org/10.1016/j.brs.2019.02.018>
- Perone, S., Anderson, A. J., & Weybright, E. H. (2021). It is all relative: Contextual influences on boredom and neural correlates of regulatory processes. *Psychophysiology*, 58(3), e13746. <https://doi.org/10.1111/psyp.13746>
- Pertermann, M., Moritz, M., Adelhöfer, N., Ziemssen, T., & Beste, C. (2019). On the interrelation of 1/f neural noise and norepinephrine system activity during motor response inhibition. *Journal of Neurophysiology*, 121(5), 1633–1643. <https://doi.org/10.1152/jn.00701.2018>
- Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, 35(1), 73–89. <https://doi.org/10.1146/annurev-neuro-062111-150525>
- Peterson, B. S., Trampush, J., Maglione, M., Bolshakova, M., Rozelle, M., Miles, J., Pakdaman, S., Brown, M., Yagyu, S., Motala, A., & Hempel, S. (2024). Treatments for ADHD in Children and Adolescents: A Systematic Review. *Pediatrics*, 153(4), e2024065787. <https://doi.org/10.1542/peds.2024-065787>
- Peysakhovich, V., Vachon, F., & Dehais, F. (2017). The impact of luminance on tonic and phasic pupillary responses to sustained cognitive load. *International Journal of Psychophysiology*, 112, 40–45. <https://doi.org/10.1016/j.ijpsycho.2016.12.003>
- Pi, Y., Yan, J., Pscherer, C., Gao, S., Mückschel, M., Colzato, L., Hommel, B., & Beste, C. (2024). Interindividual aperiodic resting-state EEG activity predicts

"References"

- cognitive-control styles. *Psychophysiology*, 61(8), e14576. <https://doi.org/10.1111/psyp.14576>
- Pinggal, E., Dockree, P. M., O'Connell, R. G., Bellgrove, M. A., & Andrillon, T. (2022). Pharmacological Manipulations of Physiological Arousal and Sleep-Like Slow Waves Modulate Sustained Attention. *The Journal of Neuroscience*, 42(43), 8113–8124. <https://doi.org/10.1523/JNEUROSCI.0836-22.2022>
- Plas, M. van der, & Hanslmayr, S. (2020). Entraining neurons via noninvasive electric stimulation improves cognition. *PLOS Biology*, 18(10), e3000931. <https://doi.org/10.1371/journal.pbio.3000931>
- Poerio, G. L., Sormaz, M., Wang, H.-T., Margulies, D., Jefferies, E., & Smallwood, J. (2017). The role of the default mode network in component processes underlying the wandering mind. *Social Cognitive and Affective Neuroscience*, 12(7), 1047–1062. <https://doi.org/10.1093/scan/nsx041>
- Popescu, T., Krause, B., Terhune, D. B., Twose, O., Page, T., Humphreys, G., & Cohen Kadosh, R. (2016). Transcranial random noise stimulation mitigates increased difficulty in an arithmetic learning task. *Neuropsychologia*, 81, 255–264. <https://doi.org/10.1016/j.neuropsychologia.2015.12.028>
- Ralph, B. C. W., Thomson, D. R., Seli, P., Carriere, J. S. A., & Smilek, D. (2015). Media multitasking and behavioral measures of sustained attention. *Attention, Perception, & Psychophysics*, 77(2), 390–401. <https://doi.org/10.3758/s13414-014-0771-7>
- Raposo, I., Szczepanski, S. M., Haaland, K., Endestad, T., Solbakk, A.-K., Knight, R. T., & Helfrich, R. F. (2023). Periodic attention deficits after frontoparietal lesions provide causal evidence for rhythmic attentional sampling. *Current Biology*, 33(22), 4893–4904.e3. <https://doi.org/10.1016/j.cub.2023.09.065>
- Raz, A., & Buhle, J. (2006). Typologies of attentional networks. *Nature Reviews Neuroscience*, 7(5), 367–379. <https://doi.org/10.1038/nrn1903>
- Reed, T., & Cohen Kadosh, R. (2018). Transcranial electrical stimulation (tES) mechanisms and its effects on cortical excitability and connectivity. *Journal of Inherited Metabolic Disease*, 41(6), 1123–1130. <https://doi.org/10.1007/s10545-018-0181-4>
- Rees, A., Wiggins, M. W., Helton, W. S., Loveday, T., & O'Hare, D. (2017). The Impact of Breaks on Sustained Attention in a Simulated, Semi-Automated Train Control Task. *Applied Cognitive Psychology*, 31(3), 351–359. <https://doi.org/10.1002/acp.3334>
- Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). "Oops!": Performance correlates of everyday attentional failures in traumatic

"References"

- brain injured and normal subjects. *Neuropsychologia*, 35(6), 747–758. [https://doi.org/10.1016/S0028-3932\(97\)00015-8](https://doi.org/10.1016/S0028-3932(97)00015-8)
- Robertson, M. M., Furlong, S., Voytek, B., Donoghue, T., Boettiger, C. A., & Sheridan, M. A. (2019). EEG power spectral slope differs by ADHD status and stimulant medication exposure in early childhood. *Journal of Neurophysiology*, 122(6), 2427–2437. <https://doi.org/10.1152/jn.00388.2019>
- Rosvold, H. E., Mirsky, A. F., Sarason, I., Bransome Jr., E. D., & Beck, L. H. (1956). A continuous performance test of brain damage. *Journal of Consulting Psychology*, 20(5), 343–350. <https://doi.org/10.1037/h0043220>
- Saad, J. F., Kohn, M. R., Clarke, S., Lagopoulos, J., & Hermens, D. F. (2018). Is the Theta/Beta EEG Marker for ADHD Inherently Flawed? *Journal of Attention Disorders*, 22(9), 815–826. <https://doi.org/10.1177/1087054715578270>
- Safati, A. B., Carr, T. H., Lowe, C. J., & Smilek, D. (2024). Mind wandering on command. *Frontiers in Psychology*, 15. <https://doi.org/10.3389/fpsyg.2024.1448226>
- Schepers, A. M., Schorrepp, L., Vries, J. D. de, Kloe, T. de, Linden, D. van der, & Bijleveld, E. (2023). Revisiting the link between the sustained attention to response task (SART) and daily-life cognitive failures. *Consciousness and Cognition*, 114, 103558. <https://doi.org/10.1016/j.concog.2023.103558>
- Schie, M. K. M. van, Lammers, G. J., Fronczek, R., Middelkoop, H. A. M., & Dijk, J. G. van. (2021). Vigilance: Discussion of related concepts and proposal for a definition. *Sleep Medicine*, 83, 175–181. <https://doi.org/10.1016/j.sleep.2021.04.038>
- Schooler, J. W., Smallwood, J., Christoff, K., Handy, T. C., Reichle, E. D., & Sayette, M. A. (2011). Meta-awareness, perceptual decoupling and the wandering mind. *Trends in Cognitive Sciences*. <https://doi.org/10.1016/j.tics.2011.05.006>
- Seli, P., Cheyne, J. A., Xu, M., Purdon, C., & Smilek, D. (2015). Motivation, intentionality, and mind wandering: Implications for assessments of task-unrelated thought. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 41(5), 1417–1425. <https://doi.org/10.1037/xlm0000116>
- Seli, P., Ralph, B. C. W., Konishi, M., Smilek, D., & Schacter, D. L. (2017). What did you have in mind? Examining the content of intentional and unintentional types of mind wandering. *Consciousness and Cognition*, 51, 149–156. <https://doi.org/10.1016/j.concog.2017.03.007>
- Seli, P., Smallwood, J., Cheyne, J. A., & Smilek, D. (2015). On the relation of

"References"

- mind wandering and ADHD symptomatology. *Psychonomic Bulletin & Review*, 22(3), 629–636. <https://doi.org/10.3758/s13423-014-0793-0>
- Shalev, L., Ben-Simon, A., Mevorach, C., Cohen, Y., & Tsal, Y. (2011). Conjunctive Continuous Performance Task (CCPT)—A pure measure of sustained attention. *Neuropsychologia*, 49(9), 2584–2591. <https://doi.org/10.1016/j.neuropsychologia.2011.05.006>
- Shalev, N., De Wandel, L., Dockree, P., Demeyere, N., & Chechlacz, M. (2018). Beyond time and space: The effect of a lateralized sustained attention task and brain stimulation on spatial and selective attention. *Cortex*, 107, 131–147. <https://doi.org/10.1016/j.cortex.2017.09.009>
- Sheffield, J. G., Raz, G., Sella, F., & Cohen Kadosh, R. (2020). *How can noise alter neurophysiology in order to improve human behaviour? A combined tRNS and EEG study*. <https://doi.org/10.1101/2020.01.09.900118>
- Shen, I.-H., Tsai, S.-Y., & Duann, J.-R. (2011). Inhibition control and error processing in children with attention deficit/hyperactivity disorder: An event-related potentials study. *International Journal of Psychophysiology*, 81(1), 1–11. <https://doi.org/10.1016/j.ijpsycho.2011.03.015>
- Shirama, A., Takeda, T., Ohta, H., Iwanami, A., Toda, S., & Kato, N. (2020). Atypical alert state control in adult patients with ADHD: A pupillometry study. *PLOS ONE*, 15(12), e0244662. <https://doi.org/10.1371/journal.pone.0244662>
- Singh-Curry, V., & Husain, M. (2009). The functional role of the inferior parietal lobe in the dorsal and ventral stream dichotomy. *Neuropsychologia*, 47(6), 1434–1448. <https://doi.org/10.1016/j.neuropsychologia.2008.11.033>
- Smallwood, J., & O'Connor, R. C. (2011). Imprisoned by the past: Unhappy moods lead to a retrospective bias to mind wandering. *Cognition and Emotion*, 25(8), 1481–1490. <https://doi.org/10.1080/02699931.2010.545263>
- Smallwood, J., & Schooler, J. W. (2015). The Science of Mind Wandering: Empirically Navigating the Stream of Consciousness. *Annual Review of Psychology*, 66(Volume 66, 2015), 487–518. <https://doi.org/10.1146/annurev-psy-010814-015331>
- Smilek, D., Carriere, J. S. A., & Cheyne, J. A. (2010). Failures of sustained attention in life, lab, and brain: Ecological validity of the SART. *Neuropsychologia*, 48(9), 2564–2570. <https://doi.org/10.1016/j.neuropsychologia.2010.05.002>
- Smith, Z. R., Langberg, J. M., Cusick, C. N., Green, C. D., & Becker, S. P. (2020). Academic Motivation Deficits in Adolescents with ADHD and Associations with

"References"

- Academic Functioning. *Journal of Abnormal Child Psychology*, 48(2), 237–249. <https://doi.org/10.1007/s10802-019-00601-x>
- Snowball, A., Tachtsidis, I., Popescu, T., Thompson, J., Delazer, M., Zamarian, L., Zhu, T., & Cohen Kadosh, R. (2013). Long-term enhancement of brain function and cognition using cognitive training and brain stimulation. *Current Biology*, 23(11), 987–992. <https://doi.org/10.1016/j.cub.2013.04.045>
- Snyder, A. C., Morais, M. J., & Smith, M. A. (2016). Dynamics of excitatory and inhibitory networks are differentially altered by selective attention. *Journal of Neurophysiology*, 116(4), 1807–1820. <https://doi.org/10.1152/jn.00343.2016>
- Snyder, S. M., & Hall, J. R. (2006). A meta-analysis of quantitative EEG power associated with attention-deficit hyperactivity disorder. *Journal of Clinical Neurophysiology*, 23(5), 441. <https://doi.org/10.1097/01.wnp.0000221363.12503.78>
- Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, & Computers*, 31(1), 137–149. <https://doi.org/10.3758/BF03207704>
- Stawarczyk, D., François, C., Wertz, J., & D’Argembeau, A. (2020). Drowsiness or mind-wandering? Fluctuations in ocular parameters during attentional lapses. *Biological Psychology*, 156, 107950. <https://doi.org/10.1016/j.biopsycho.2020.107950>
- Stawarczyk, D., Majerus, S., Maj, M., Van der Linden, M., & D’Argembeau, A. (2011). Mind-wandering: Phenomenology and function as assessed with a novel experience sampling method. *Acta Psychologica*, 136(3), 370–381. <https://doi.org/10.1016/j.actpsy.2011.01.002>
- Steinmayr, R., Ziegler, M., & Träuble, B. (2010). Do intelligence and sustained attention interact in predicting academic achievement? *Learning and Individual Differences*, 20(1), 14–18. <https://doi.org/10.1016/j.lindif.2009.10.009>
- Stevenson, H., Russell, P. N., & Helton, W. S. (2011). Search asymmetry, sustained attention, and response inhibition. *Brain and Cognition*, 77(2), 215–222. <https://doi.org/10.1016/j.bandc.2011.08.007>
- Strayer, D. L., Robison, M. K., & Unsworth, N. (2023). Effects of goal-setting on sustained attention and attention lapses. *Attention, Perception, & Psychophysics*. <https://doi.org/10.3758/s13414-023-02803-4>
- Sturm, W., & Willmes, K. (2001). On the Functional Neuroanatomy of Intrinsic and Phasic Alertness. *NeuroImage*, 14(1), S76–S84. <https://doi.org/10>

"References"

- .1006/nimg.2001.0839
- Teigen, K. H. (1994). Yerkes-Dodson: A Law for all Seasons. *Theory & Psychology*, 4(4), 525–547. <https://doi.org/10.1177/0959354394044004>
- Terney, D., Chaieb, L., Moliadze, V., Antal, A., & Paulus, W. (2008). Increasing Human Brain Excitability by Transcranial High-Frequency Random Noise Stimulation. *Journal of Neuroscience*, 28(52), 14147–14155. <https://doi.org/10.1523/JNEUROSCI.4248-08.2008>
- Thayer, R. E. (1990). *Arousal: A Basic Element of Mood and Behavior*. Oxford University Press. <https://doi.org/10.1093/oso/9780195068276.003.0003>
- Thomson, D. R., Besner, D., & Smilek, D. (2015). A Resource-Control Account of Sustained Attention: Evidence From Mind-Wandering and Vigilance Paradigms. *Perspectives on Psychological Science*, 10(1), 82–96. <https://doi.org/10.1177/1745691614556681>
- Tiego, J., Testa, R., Bellgrove, M. A., Pantelis, C., & Whittle, S. (2018). A Hierarchical Model of Inhibitory Control. *Frontiers in Psychology*, 9. <https://doi.org/10.3389/fpsyg.2018.01339>
- Tyler, S. C., Contò, F., & Battelli, L. (2018). Rapid improvement on a temporal attention task within a single session of high-frequency transcranial random noise stimulation. *Journal of Cognitive Neuroscience*, 30(5), 656–666. https://doi.org/10.1162/jocn_a_01235
- Unsworth, N., & McMillan, B. D. (2013). Mind wandering and reading comprehension: Examining the roles of working memory capacity, interest, motivation, and topic experience. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39(3), 832–842. <https://doi.org/10.1037/a0029669>
- Unsworth, N., & McMillan, B. D. (2014). Similarities and differences between mind-wandering and external distraction: A latent variable analysis of lapses of attention and their relation to cognitive abilities. *Acta Psychologica*, 150, 14–25. <https://doi.org/10.1016/j.actpsy.2014.04.001>
- Unsworth, N., & Robison, M. K. (2016). Pupillary correlates of lapses of sustained attention. *Cognitive, Affective, & Behavioral Neuroscience*, 16(4), 601–615. <https://doi.org/10.3758/s13415-016-0417-4>
- Unsworth, N., & Robison, M. K. (2017). A locus coeruleus-norepinephrine account of individual differences in working memory capacity and attention control. *Psychonomic Bulletin & Review*, 24(4), 1282–1311. <https://doi.org/10.3758/s13423-016-1220-5>
- Unsworth, N., & Robison, M. K. (2018). Tracking arousal state and mind wandering with pupillometry. *Cognitive, Affective, & Behavioral Neuroscience*, 18(4),

"References"

- 638–664. <https://doi.org/10.3758/s13415-018-0594-4>
- Van Bueren, N. E. R., Reed, T. L., Nguyen, V., Sheffield, J. G., Ven, S. H. G. van der, Osborne, M. A., Kroesbergen, E. H., & Cohen Kadosh, R. (2021). Personalized brain stimulation for effective neurointervention across participants. *PLOS Computational Biology*, 17(9), e1008886. <https://doi.org/10.1371/journal.pcbi.1008886>
- Van Bueren, N. E. R., Van Der Ven, S. H. G., Hochman, S., Sella, F., & Cohen Kadosh, R. (2023). Human neuronal excitation/inhibition balance explains and predicts neurostimulation induced learning benefits. *PLOS Biology*, 21(8), e3002193. <https://doi.org/10.1371/journal.pbio.3002193>
- Van Der Groen, O., Potok, W., Wenderoth, N., Edwards, G., Mattingley, J. B., & Edwards, D. (2022). Using noise for the better: The effects of transcranial random noise stimulation on the brain and behavior. *Neuroscience & Biobehavioral Reviews*, 138, 104702. <https://doi.org/10.1016/j.neubiorev.2022.104702>
- Van Der Groen, O., Tang, M. F., Wenderoth, N., & Mattingley, J. B. (2018). Stochastic resonance enhances the rate of evidence accumulation during combined brain stimulation and perceptual decision-making. *PLOS Computational Biology*, 14(7), e1006301. <https://doi.org/10.1371/journal.pcbi.1006301>
- Van Der Groen, O., & Wenderoth, N. (2016). Transcranial Random Noise Stimulation of Visual Cortex: Stochastic Resonance Enhances Central Mechanisms of Perception. *The Journal of Neuroscience*, 36(19), 5289–5298. <https://doi.org/10.1523/JNEUROSCI.4519-15.2016>
- Van Son, D., De Blasio, F. M., Fogarty, J. S., Angelidis, A., Barry, R. J., & Putman, P. (2019). Frontal EEG theta/beta ratio during mind wandering episodes. *Biological Psychology*, 140, 19–27. <https://doi.org/10.1016/j.biopsycho.2018.11.003>
- Walcher, S., Körner, C., & Benedek, M. (2017). Looking for ideas: Eye behavior during goal-directed internally focused cognition. *Consciousness and Cognition*, 53, 165–175. <https://doi.org/10.1016/j.concog.2017.06.009>
- Walker, H. E. K., & Trick, L. M. (2018). Mind-wandering while driving: The impact of fatigue, task length, and sustained attention abilities. *Transportation Research Part F: Traffic Psychology and Behaviour*, 59, 81–97. <https://doi.org/10.1016/j.trf.2018.08.009>
- Wards, Y., Ehrhardt, S. E., Filmer, H. L., Mattingley, J. B., Garner, K. G., & Dux, P. E. (2023). Neural substrates of individual differences in learning generalization via combined brain stimulation and multitasking training. *Cerebral*

"References"

- Cortex*, bhad406. <https://doi.org/10.1093/cercor/bhad406>
- Waschke, L., Donoghue, T., Fiedler, L., Smith, S., Garrett, D. D., Voytek, B., & Obleser, J. (2021). Modality-specific tracking of attention and sensory statistics in the human electrophysiological spectral exponent. *eLife*, 10, e70068. <https://doi.org/10.7554/eLife.70068>
- Westwood, S. J., Criaud, M., Lam, S.-L., Lukito, S., Wallace-Hanlon, S., Kowalczyk, O. S., Kostara, A., Mathew, J., Agbedjro, D., Wexler, B. E., Kadosh, R. C., Asherson, P., & Rubia, K. (2023). Transcranial direct current stimulation (tDCS) combined with cognitive training in adolescent boys with ADHD: A double-blind, randomised, sham-controlled trial. *Psychological Medicine*, 53(2), 497–512. <https://doi.org/10.1017/S0033291721001859>
- Wilson, K. M., Finkbeiner, K. M., De Joux, N. R., Russell, P. N., & Helton, W. S. (2016). Go-stimuli proportion influences response strategy in a sustained attention to response task. *Experimental Brain Research*, 234(10), 2989–2998. <https://doi.org/10.1007/s00221-016-4701-x>
- Yamashita, A., Rothlein, D., Kucyi, A., Valera, E. M., Germine, L., Wilmer, J., DeGutis, J., & Esterman, M. (2021). Variable rather than extreme slow reaction times distinguish brain states during sustained attention. *Scientific Reports*, 11(1), 14883. <https://doi.org/10.1038/s41598-021-94161-0>
- Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Classics in the History of Psychology*, 18, 459–482. <https://psychclassics.yorku.ca/Yerkes/Law/>
- Zénon, A., Sidibé, M., & Olivier, E. (2014). Pupil size variations correlate with physical effort perception. *Frontiers in Behavioral Neuroscience*, 8. <https://www.frontiersin.org/articles/10.3389/fnbeh.2014.00286>
- Zuur, A. F., Ieno, E. N., & Elphick, C. S. (2010). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution*, 1(1), 3–14. <https://doi.org/10.1111/j.2041-210X.2009.00001.x>