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The effect of Hatha yoga on the shifting function of attention

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Kein Mensch schafft irgendetwas allein.

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Introduction

Like water erupting from a source and finding its way down the mountain via the path of least resistance, being directed this way and then the other, attention that remains unfocused and unharnessed would enable us to deal with life's myriad challenges only by reflex, or by chance. Only when there are aqueducts, dams, and pipes, are we able to bend water to our will, enabling complex tasks, such as showering and watering crops. Executive functions are the hydraulic infrastructure of our cognition. They enable us to direct attention willingly, to suppress irrelevant responses and stimulation, and to keep in mind what we wish to keep in mind. Their impairment has dire consequences for our inner and outer lives, making impossible the most basic tasks. Impaired executive functions are implicated in most psychological pathologies (for a review, see Snyder et al., 2015), and play a central role in disorders including autism spectrum disorder (ASD), obsessive-compulsive disorder (OCD), depression, anxiety, and, of course, attention-deficit/hyperactivity disorder (ADHD) (Zelazo, 2020). Fortunately, there is hope: a number of interventions have been shown to improve executive functions (for reviews, see Diamond, 2013; Diamond & Ling, 2016). In the present manuscript, we assess the specific effectiveness of one such intervention, Hatha yoga, on the shifting function of attention, one of three main components of executive function (Diamond, 2013). In our metaphor, the shifting function can be imagined as the system of pipes, faucets, and other water outlets in your house, taking the stream coming from the municipal water supply, and directing it wherever it may be needed at the moment.

In a randomized control trial, we implemented an eight-week Hatha yoga intervention and assessed the difference in behavioral performance measures, pre- to posttest, on two task-switching paradigms, one testing participants' ability to switch between an auditory and a visual task, and another assessing the ability to switch between feature-directed control representations, which in this case constituted switching between searching for target stimuli defined by different colors. The present manuscript will only cover procedure and findings of the first, the modality-switching paradigm. In this experimental setup, participants were simultaneously presented with a visual and an auditory two-back task. This meant that they had to react to target sequences, consisting of a target stimulus, followed by a non-target stimulus, again followed by a target stimulus. A bimodal cue signaled when to switch from attending the task in one modality to the other. Electrophysiological activity was recorded in addition to behavioral measures by use of an electroencephalogram (EEG) to gain an objective measure for which modality was currently attended and to assess the intervention's effect on neural oscillations implicated in task-switching. To lay out the theoretical framework upon which our intervention is based, the following sections will outline executive functions, with a focus on the shifting function of attention. Subsequently, yoga, its benefits, and possible mechanisms by which yoga influences executive functioning, and the shifting function in particular, are presented. Finally, theoretical background to our method, especially our electrophysiological measures, is provided.

Executive Functions

As a set of top-down mental processes, executive functions are indispensable for the proper allocation of attentional resources, coming into play whenever intuitive “autopilot” action is not advisable for the task at hand. They enable us to, among other things, exercise self-control, solve complex problems, and adapt to new and changing situations (Diamond, 2013). A seminal paper by Miyake et al. (2000), using a latent variable analysis based on literature review, proposed three main components of executive function, which are correlated with, yet clearly distinct from, one another: updating of working memory, response inhibition, and shifting between task sets. Further analyses have confirmed this proposal (e.g., Lehto et al., 2003). Working memory describes the mechanism enabling us to not just reflexively let information flow in and out of our consciousness, but to selectively keep in mind what we require at a specific moment (e.g., Miller et al., 2018). Updating of working memory describes the process by which this information is managed in relation to changing task demands. Response inhibition describes the ability to suppress currently unnecessary actions, reflexive or otherwise, that would hinder proper execution of the task at hand (Mostofsky & Simmonds, 2008). In this paper we will focus specifically on the third component of executive control, the shifting function of attention. The shifting function enables us to shift our attention back and forth between different operations, tasks, or attentional control sets (e.g., searching for a certain color, then searching for a certain shape), facilitating our adaptation to the ever-changing requirements of the world around us (Kiesel et al., 2010).

To illustrate the role executive functions play in our day-to-day lives, consider a waiter in a busy pub. He must keep in mind the drink orders of an entire table, while forgetting the irrelevant ones from a previous table (updating of working memory); on the way to the bar he has to inhibit his reflexive reactions to the shouts from other tables, wishing to order as well (inhibition); finally, he needs to switch between drawing beer, pouring wine, and keeping a list of what needs to be paid later (shifting).

The Shifting Function of Attention

Consider again the waiter, who has successfully arrived back at the bar with his orders. Each action that he now has to perform in order to keep track of and prepare the different drinks, will require a specific configuration of mental resources. Pouring wine will require a very different configuration to, for example, cutting lemon slices to serve with Tequila. These configurations are termed task-sets, and executive control is required for the selection of task sets appropriate to the task at hand (Monsell, 2003). The implementation of this executive control is the role of the shifting function of attention.

The shifting function is typically investigated in task-switching paradigms (for reviews, see Koch et al., 2018; Monsell, 2003), where in some trials, participants have to switch between tasks (switch trials), and in others the same task is repeated (repeat trials). Participants' shifting abilities are then typically judged through an assessment of switching costs, meaning the difference in performance between switch and repeat trials. Some authors have argued that different task-switching paradigms may measure shifting as an element of executive function to varying degrees. Ravizza and Carter (2008), for example, differentiated between paradigms employing perceptual shifts (i.e., where attention should be focused) and those using rule shifts (i.e., requiring different actions or operations), concluding that rule shifts allow more of a measure of executive function, likely due to the involvement of working memory for keeping in mind the differing rule sets. Although the paradigm employed in the present study, which will be outlined in more detail below, employs tasks with the same rules in both the visual and the auditory modality, the switch in modality constitutes a complete change of the nature of the task and thus the task rules, placing it in the second category of experimental setups.

Yoga

Yoga is the term for a collection of physical and spiritual practices of Indian origin, whose main components are exercises (asanas), breathing (pranayama), and mediation, and which are aimed at cultivating awareness, mindfulness, self-control, and higher states of consciousness (Büssing et al., 2012). There is no lack of findings outlining the positive effects of yoga on both physical and mental health: Yoga has been shown to lower blood pressure (Selvamurthy et al., 1998), other risk markers of circulatory disease such as blood cholesterol (Damodaran et al., 2002), and inflammatory markers in patients with chronic heart failure (Pullen et al., 2008). Yoga interventions have been found to reduce symptoms of depression (e.g., Pilkington et al., 2005) and, with certain limitations, show promise in reducing symptoms of anxiety disorders (e.g., Kirkwood et al., 2005).

Pertaining to our study, the most important findings regarding the benefits of yoga are those concerning its effect on executive function. Overall, Hatha yoga shows promise in benefitting executive function in children, adolescents, adults, as well as certain clinical populations (for a review, see Luu & Hall, 2016). These improvements have been reported for both acute and long-term interventions. Authors employing a single yoga session have reported, for example, a significant increase of cognitive performance compared to an aerobic exercise and a passive control condition (Gothe et al., 2013) and a significant improvement on the Stroop task (Stroop, 1992) compared to a control condition (Luu & Hall, 2017). The effects of long-term interventions include significant performance improvements on the Tower of London task in school children following a one-month yoga intervention, compared to a physical exercise condition (Manjunath & Telles, 2001) and general improvement of executive functions after a two-month yoga intervention, which was however not stronger than the improvements after a physical exercise intervention (Vhavle et al., 2019). Similarly, Telles et al. (2013) found that a 3-month yoga intervention improved performance on the Stroop task significantly from baseline, an improvement that was also matched by the effects of a physical exercise intervention. It is important to note here however, that the physical exercise interventions involved rigorous training sessions including rapid repetitive movements, jogging in place, and relay races, whereas the yoga intervention consisted to a large part of chanting, guided relaxation, and breathing techniques, suggesting distinct mechanisms through which the improvements took place.

Hatha Yoga

Hatha yoga is the most widely practiced form of yoga in the west (Burley et al., 2005). Compared to other forms of yoga, it is more physical, and focuses less on breathing and meditation exercises (although these also play a role), enabling us to relate potential results more to the physical practice, as opposed to other, mindfulness-based, components of yoga. Mindfulness can be defined as a state in which attention is placed on one’s present experience without judgement (Creswell, 2017; Tang et al., 2015). It is an integral component of the practice of yoga, where practitioners are often explicitly encouraged to focus on current mental and physical sensations. However, some separation between physical and mindfulness-based components seems possible: Dong et al. (2023), for example, found that mindfulness training improved inhibitory control, but did not improve working memory or cognitive flexibility, which is closely related to the shifting function of attention. These findings suggest that any improvements in participant’s shifting due to our intervention may not be attributable to mindfulness-based components of the intervention but may in fact be directly caused by the physical yoga practice. It is important to note at this point, however, that due to the self-attentive nature of yoga, a definitive delineation between physical and mindfulness-based components is not possible. This ambivalence, however, does not only bear challenges, but also offers a possible explanation as to how yoga may influence the shifting function of attention.

Mechanisms of Influence

Self-Attentive Nature of Yoga

A plausible explanation for the improvements in executive function may arise from the self-attentive nature of yoga (Gard et al., 2014). Yoga requires attention be placed on interoceptive, bottom-up stimulation. Concentration and attention on the body parts involved in a certain asana are as important as the posture itself, and often explicitly encouraged in yoga classes. The repeated practice of shifting attention between body parts, switching between different asanas, and switching between observation of the body and observation of one's thoughts may in fact be training the executive functions, leading to an increase in performance, especially in the shifting function of attention, the mechanism underlying these attentional shifts.

Decrease in Stress and Anxiety

Another possible mechanism explaining the effect of yoga on executive function is mediation by decreased stress and/or anxiety. Previous studies have found ample evidence of the negative influence of stress and anxiety on executive functioning (e.g., Berggren & Derakshan, 2013; Derakshan & Eysenck, 2009; Liston et al., 2009). The basic mechanisms through which this impairment occurs are outlined in Attentional Control Theory (ACT; Eysenck et al., 2007) which posits that in an anxious state, attentional resources are shifted from goal-oriented top-down processes, such as executive functions, to stimulus-oriented bottom-up processes to increase perception of potentially threatening stimuli. Neuroscience offers additional support for the notion that stress reduces executive functioning, as stress significantly impairs function in prefrontal cortex (PFC), both acutely, and long-term, even eventually altering PFC architecture (Arnsten, 2009). Considering these mechanisms, the investigation of stress-relief interventions is of great interest when trying to find ways to improve executive functioning. Yoga constitutes one such intervention, as its potential to decrease stress and anxiety is a common finding: Hewett et al. (2018), for example, found significant improvement in perceived stress, self-efficacy, and health-related quality of life following a 16-week Bikram yoga intervention. Szaszkó et al. (2023) found similar results, with perceived stress levels and stress reactivity decreasing significantly following an eight-week Hatha yoga intervention. Thus, through a decrease in stress and anxiety, yoga may help free up attentional resources, benefitting executive function, as well as activating the parasympathetic nervous system through relaxation and deep breathing, leading to an improvement in PFC activity (Zaccaro et al., 2018).

Steady-State Potentials (SSPs)

This investigation was supplemented by EEG recordings, using the approach of frequency tagging (Saupe et al., 2009; Vialatte et al., 2010) to identify potentials typical for each modality. In particular, we looked for the occurrence of SSPs which have previously been identified as specific to either the visual or the auditory modality (e.g., Norcia et al., 2015; Stapells et al., 1984): the steady-state visual evoked potential (SSVEP) and the auditory steady-state response (ASSR). SSVEP and ASSR are reactions of the brain to visual or auditory stimulation at a certain frequency, whereby electrophysiological signals are created in the brain at the same frequency as that of the stimulus or its harmonics. In our case visual stimuli were presented at 20 Hz and auditory stimuli were presented at 24 Hz. Consequently, we expected EEG recordings to show 20 and 40 Hz activity when attention was placed on the visual task, and 24 Hz activity when it was placed on the auditory task, giving us an objective measure of attentional attendance, as opposed to sole approximation through behavioral measures. We did not investigate the second harmonic of the auditory stimulation frequency at 48 Hz, as this was too close to the local utility frequency, which generally leads to large amounts of EEG-noise around 50 Hz.

Alpha and Theta Activity

In addition to frequency-tagging, EEG measurements were used to investigate the effect of the intervention on alpha (8-12 Hz) and theta (4-7 Hz) frequency bands. The alpha band has been repeatedly implicated in the suppression of task-irrelevant stimuli during task-switching, with increased parietooccipital alpha power being associated with the formation of a biased attentional state in anticipation of an upcoming switch (e.g., Foxe et al., 1998; Fu et al., 2001). Furthermore, when a switch is anticipated, alpha oscillations play a direct role in the inhibition of brain areas irrelevant to task performance (Gladwin & de Jong, 2005). Activity in the theta band is implicated in a wide range of processes connected to successful task-switching including, for example, mechanisms necessary for the maintenance of task-control representations in working memory (e.g., Itthipuripat et al., 2013; Sauseng et al., 2002), the ability to cope with increased cognitive control demands (e.g., Cavanagh & Frank, 2014; Popescu et al., 2023; Sauseng et al., 2019), as well as cognitive flexibility more broadly (e.g., Cao et al., 2023; L. Wang et al., 2024). One neurofeedback study even produced findings in support of theta oscillations playing a causal role in task-switching performance directly (Enriquez-Geppert et al., 2014).

Hypotheses

Generally, an improvement in the shifting function of attention (in particular in participants' ability to switch back and forth between modalities), facilitated by the intervention, was expected due to the mechanisms outlined above. Behaviorally we expected this to manifest in an interaction between group (intervention vs. control) and time-point of measurement (pre- vs. posttest measurement) in an analysis of the switching costs, meaning that we expected the intervention group to show lower switching costs at posttest measurement compared to the control group at posttest. Switching costs were defined as the difference in reaction times (RTs) and accuracy rates between trials following a switch in modality (switch trials) and those in which the same modality was attended as in the previous trial (repeat trials). In the event of asymmetrical switching costs (meaning different switching costs in switch trials in one modality compared to the other), we would expect to see a threefold interaction between group, time-point, and modality (auditory vs. visual), meaning that we expected the intervention group to show less switch costs compared to the control group, at posttest, in the modality that showed a larger decrease of switching costs through the intervention.

Concerning the electrophysiological data, we expected the intervention group to show larger posttest differences, as compared to pretest baseline differences, in spectral power of the tagging frequency corresponding to the currently attended modality (or its second harmonic), as compared to the control group. Following a switch in modality, we expected an increase in power of the tagging frequency of the modality that is being switched to, combined with a decrease in power of the tagging frequency of the modality that is being switched away from. Finally, following a switch in modality, we expected a power increase at theta-band frequencies, consigned to significant clusters, in the intervention group, compared to the control group, at posttest. As outlined above, in contrast to the direct involvement of theta oscillations in task-switching, the literature suggests more of an auxiliary role of alpha oscillations, which contribute primarily to related processes. Therefore, to identify potential mechanisms connecting alpha activity to task-switching, our analyses of alpha-band frequencies were of an exploratory nature.

Methods

Participants

345 individuals were assessed for eligibility between December 2nd, 2021 and April 27th, 2022. 116 were admitted into the study, of which 98 (83 female; M_{Age} = 25.03 years; SD_{Age} = 4.18 years; range 18-40 years) were part of the study once the intervention started,

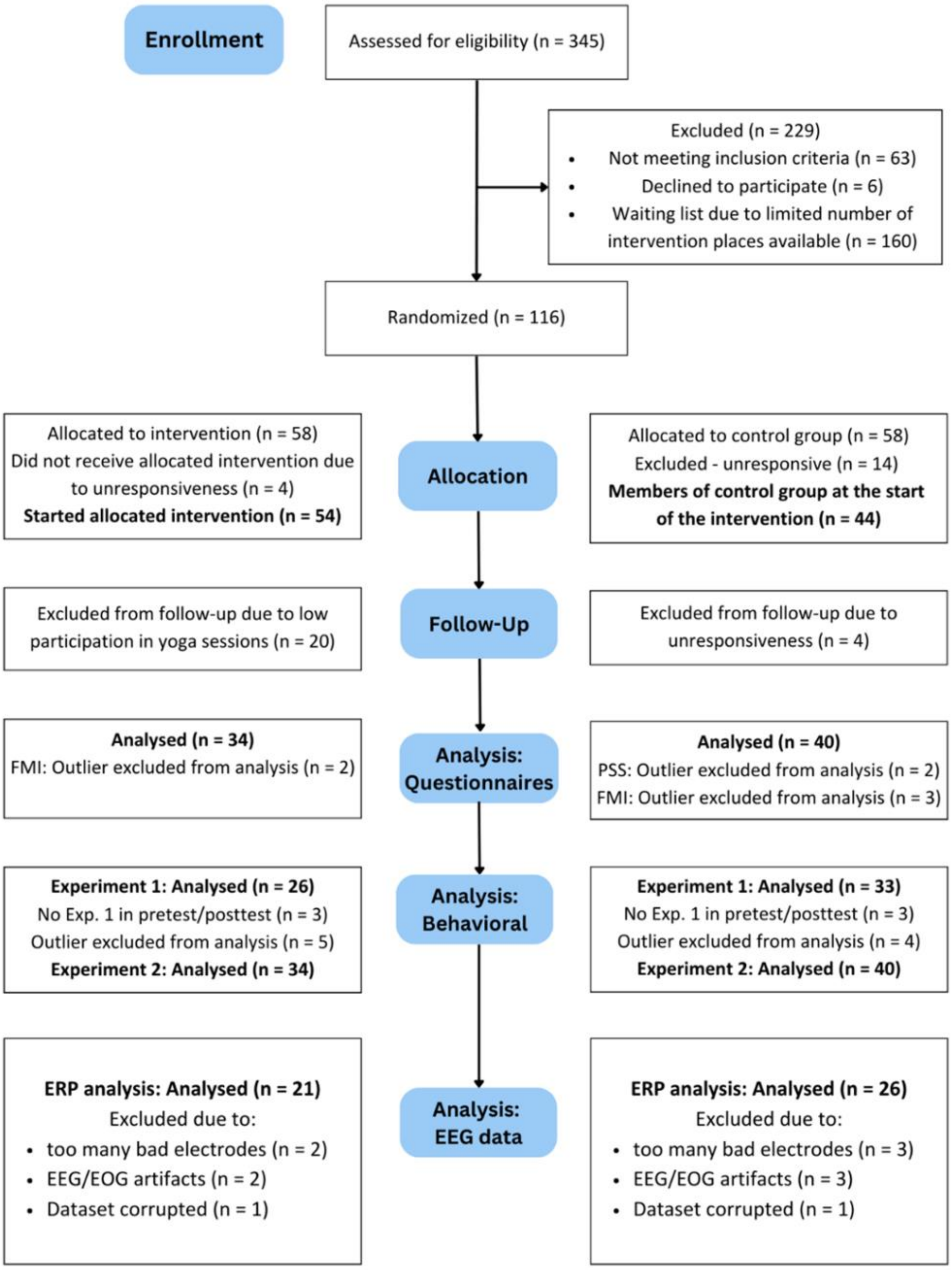
having completed baseline questionnaires and both pretest sessions. We aimed for a sample size of 102 in order to achieve 80% power, $d = 0.5$ and an alpha error probability of .05, for both EEG and behavioral data. Dropout and exclusions were considerably high, leading to 47 participants being included in the final analyses. Figure 1 shows the CONSORT diagram, outlining dropouts/exclusions at different levels of the study.

Participants were recruited online using the University of Vienna's Laboratory Administration for Behavioral Science (LABS) platform and Vienna Cognitive Science Hub's Study Participant Platform (SPP). Additionally, the study was advertised on social media and through flyers posted throughout the University of Vienna. Potential participants were screened using a shortened version of the Diagnostic Interview for Mental Disorders (Mini-DIPS; Margraf, 1994). Participants showing possible current or past psychological or psychiatric disorders were excluded. Participants were also excluded on the basis of age, with only those between the ages of 18 and 40 being asked to participate. Further exclusion criteria were level of German proficiency (level C1 required) and uncorrected, impaired vision or hearing as well as recent (within the past six weeks) injuries to the skull (skull fraction or concussion). Finally, due to regulations at the time of data collection, failure to provide proof of COVID-19 recovery or vaccination also led to exclusion.

Participants were pseudo-randomly assigned to a control and an intervention group, in order to ensure that the groups were of the same size. Due to the nature of the intervention blinding was not possible, as participants and instructors were both fully aware that they were participating in yoga classes. Written, informed consent was obtained from all participants during the first pretest session and compensation occurred through payment of 30 EUR at the start of the study and a further 30 EUR upon completion. The possibility of a bonus payment of 10 EUR was provided, given that participants attended an average of four yoga classes per week for the duration of the intervention, or 20 EUR for attending an average of five classes per week.

Figure 1

CONSORT Diagram of the Present Study



Note. Taken from Szaszkó et al. (2024a). CONSORT diagram illustrating the number of dropouts at different stages of the study. The remaining number of participants at each stage are written in bold. If participants were excluded from the analysis of questionnaire data, this did not mean automatic exclusion from the other analyses. EEG: Electroencephalography; EOG: Electrooculography.

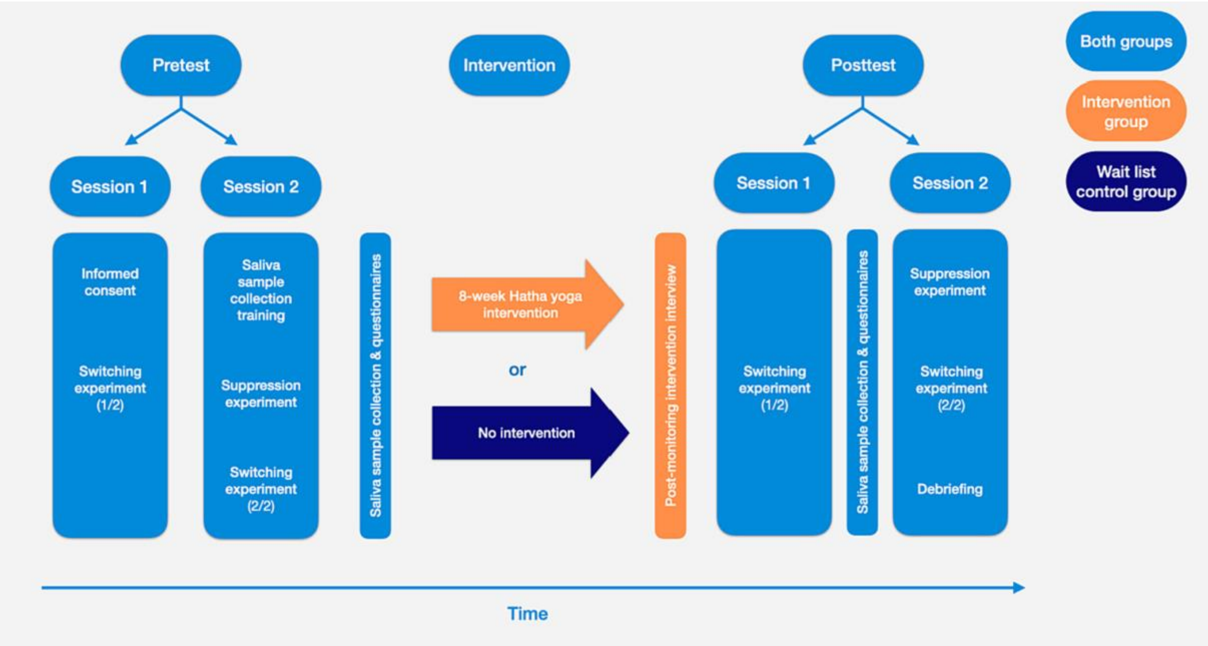
Study Design

This experiment was part of a larger study assessing the effect of Hatha yoga on the executive functions inhibition (Szaszkó et al., 2023) and task-switching (Szaszkó et al., 2024a). Furthermore, changes in self-reported stress and anxiety, as well as a number of other measures, such as mindfulness and quality of sleep, pre- to posttest, were collected using a battery of questionnaires (Szaszkó et al., 2023). Additionally, to attain an objective measure of participants' stress levels, pre- and posttest salivary cortisol and alpha-amylase levels, which have been regularly implicated as reliable markers for stress (e.g., Chatterton et al., 1996; Kirschbaum & Hellhammer, 1994), were compared (Szaszkó et al., 2024b).

Due to space restraints in the yoga studio, participants in both groups were divided into two cohorts of roughly the same size, which underwent the different stages of the study shifted by eight weeks, the duration of the yoga intervention. The second intervention cohort thus started the first pretest while the first intervention cohort was starting the intervention. Other than that, the procedure was identical for the two groups. First, a pretest examination was conducted, where participants were asked to fill out questionnaires and complete both task-switching paradigms. In the days after the pretests were completed, participants were asked to submit saliva samples. Then the eight-week yoga intervention started, followed by posttest measurements and tasks, which comprised, except for a few exceptions, the same tasks and questionnaires as those at pretest. After this, saliva samples were collected once more. The control group cohorts completed pre- and posttest measurements eight weeks apart without attending any yoga classes in between. As a further incentive for completing both measurements, following posttest measurements and tasks, participants in the control group were offered the opportunity to also participate in 8 weeks of yoga classes free of charge for their own benefit. Figure 2 illustrates the order of all elements of the overarching study for one cohort of intervention and control group each.

Figure 2

Elements of the Overarching Study



Note. Taken from Szaszkó et al. (2023). Progression of elements of the overarching study for one cohort of the intervention and control group each. Light blue elements were completed by both groups, orange elements only by the intervention group, and dark blue elements only by the control group. During two pre- and two posttest sessions, participants of both groups completed two task-switching and one inhibition experiment. The first task-switching experiment, labelled *switching experiment (1/2)*, is covered in the present manuscript. Additionally, at both timepoints, participants of both groups were asked to collect saliva samples and fill out a number of questionnaires. Between the two measurement timepoints, only the intervention group participated in the eight-week Hatha yoga intervention.

Intervention

Participants were required to attend 60 min long Hatha yoga classes at least three times a week for a duration of 8 weeks. These courses were offered in collaboration with “FREIRAUM” yoga studio in Vienna. Classes were instructed by certified yoga teachers and involved no breathing or meditation exercises in order to isolate, to the degree that this is possible, the effects of the physical yoga practice. Participants had to preregister online for each class, but their attendance was additionally tracked by employees of the studio.

Apparatus, Task, and Stimuli

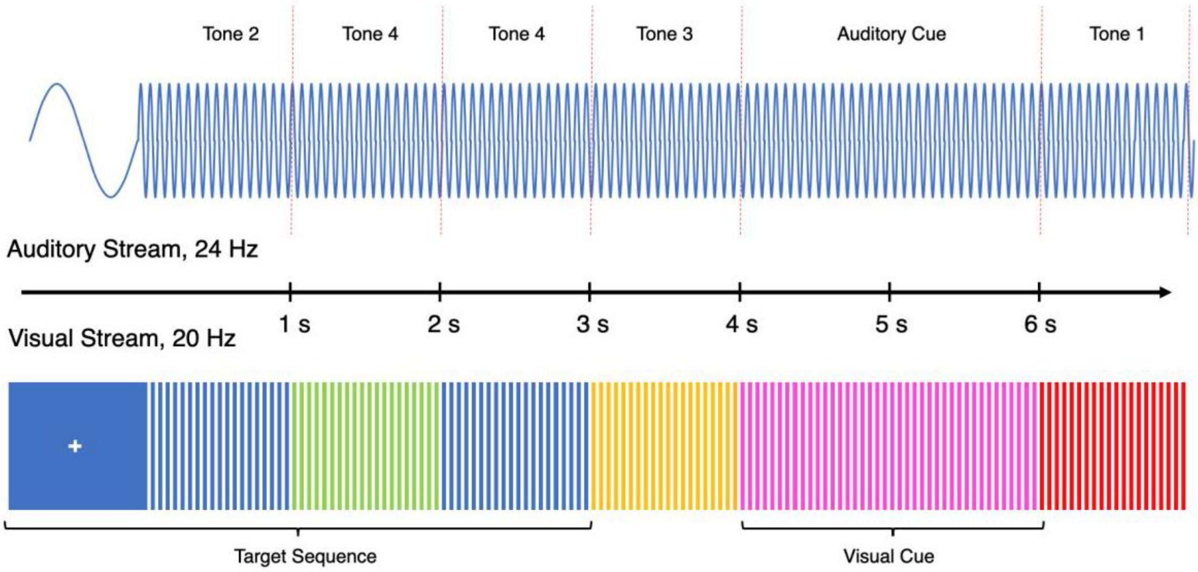
To assess the influence of Hatha yoga on participant’s task-switching abilities, participants were given a two-back task before and after the intervention. The experiment took place in the university’s soundproof and dimly lit EEG laboratory, where participants completed the task alone, with experimental staff monitoring from outside the room. The task was presented on a 19" CRT Monitor (Sony Multiscan) with a resolution of 1,280 x 1,024 pixels, an aspect ratio of 4:3, and a refresh rate of 100 Hz. Participants were asked to place their chin on a chinrest, in order to keep the distance between their eyes and the screen constant at 57 cm. The task was presented using PsychoPy 3 (Peirce & MacAskill, 2018), and responses were given on a conventional QWERTZ-keyboard. In this task, visual and auditory flickering stimuli were presented simultaneously (visual at 20 Hz, auditory at 24 Hz), with visual stimuli oscillating against a black background. Participants were asked to respond to a target sequence by pressing the "down arrow" key on the keyboard as quickly and accurately as possible, with a bimodal cue signaling which modality should currently be attended to. Stimuli in the visual domain comprised four equiluminant (CIE L*a*b*, L* = 60), colored rectangles (orange: a* = 61, b* = 71, blue: a* = 12, b* = −71, red: a* = 80, b* = 69, green: a* = −54, b* = 55) against a black (L* = 3.3, a* = 0.1, b* = −6.5) background, presented at the center of the screen. A sequence of a blue rectangle, followed by a non-blue rectangle, again followed by a blue rectangle constituted the target in the visual domain (two-back task). In the auditory domain stimuli consisted of six pure tones (at frequencies of 311 Hz, 440 Hz, 622 Hz, 880 Hz, 1244 Hz, 1760 Hz), played over headphones at participants' individual comfort level. A sequence of a 1,760 Hz tone, followed by a tone at one of the other five frequencies, again followed by a 1,760 Hz tone constituted the target in the auditory domain. In both modalities, stimuli changed once per second. Figure 3 illustrates an exemplary trial.

At the start of the block participants were cued as to which modality they had to attend first. Throughout the block, participants were signaled when to switch the attended modality. This occurred through presentation of a bimodal cue, with both visual and auditory conditions switching simultaneously to stimuli reserved for this purpose. In the visual domain this meant that the color of the rectangle changed to either turquoise (L* = = 60, a* = −28, b* = −13) or pink (L * = = 60, a* = 80, b* = 13). Simultaneously, in the auditory domain, one of two distinct tones was played. Which modality was indicated by which color/tone was counterbalanced across participants. This bimodal switching cue was presented for 2 s, as opposed to all other stimuli, which were presented for 1 s. The number of times that participants had to attend visual and auditory conditions were counterbalanced so that per experimental block, exactly 40 switches took place to each modality.

The experiment started with a 3 min practice block, which could be repeated if the participant chose to do so. This was followed by a total of 15 experimental blocks with a duration of 180 s each. Breaks between experimental blocks ended when the participant chose to continue. Each participant was subjected to a single-task baseline condition for each modality before and after the experimental blocks, to assess baseline ASSR and SSVEP, and whether these were in fact present and occurred only in the modality's respective conditions.

Figure 3

Schematic Diagram of an Exemplary Trial of the Task-Switching Paradigm



Note. From Szaszkó et al. (2024a). This figure illustrates an exemplary trial of the task-switching paradigm. The blue wave illustrates the continuous stream of auditory stimuli, being presented at 24 Hz, and changing tone once every second. The colored rectangles illustrate the continuous stream of visual stimuli, changing color once every second, being presented at 20 Hz, and simultaneous to the auditory stream. A blue rectangle at position *n*, followed by a rectangle of another color at position *n*-1, being followed once more by a blue rectangle at position *n*-2, constituted the target sequence in the visual domain, to which participants were asked to respond by keypress. In the auditory domain, the target sequence (not illustrated here) similarly consisted of a target tone at *n*, followed by a non-target tone at *n*-1, and once again followed by a target tone at *n*-2. The auditory and visual cues, lasting for 2 s, consisting of a color and a tone not presented otherwise, and being presented simultaneously to one another, signaled that participants should now switch from attending to the task in one modality to attending to the task in the other modality.

Data Recording and Analysis

Behavioral Analysis

All analyses of behavioral data were conducted using RStudio (Version 1.4.1717; RStudio Team, 2021) with R (version 4.1.2; R Core Team, 2021). Packages used were: data.table (Version 1.14.2; Dowle & Srinivasan, 2021), ez (Version 4.4.-0.; Lawrence, 2016), rstatix (Version 0.7.2; Kassambara, 2023), schoRsch (Version 1.9; Pfister & Janczyk, 2020), and tidyverse (Wickham et al., 2019).

A comparative analysis of pre- and posttest reaction times, hit rates, and false-alarm rates was conducted. Hit rates were defined as the number of targets that participants reacted to correctly, divided by the total amount of targets. False-alarm rates were defined as the number of times that participants pressed the button indicating the presence of a target when there was in fact no target present, divided by the total amount of stimuli that could possibly provoke such a response. Additionally, we analyzed switching costs, meaning the extent to which the above variables changed when the task was to detect consecutive target stimuli in the same modality (repeat trials), compared to trials in which a switch in modality was necessary (switch trials).

Participants were excluded from behavioral analysis using a generalized Extreme Studentized Deviate, sensitive for multiple outliers (alpha level of .05; Rosner, 1983). Individual trials were excluded from RT analysis where participants' RTs exceeded ± 2.5 *SDs* from their individual RT mean.

EEG Recording

For collection of electrophysiological data, an ActiveTwo Biosemi™ electrode system (BioSemi B.V., Amsterdam, Netherlands) was used, recording at 512 Hz, with a total of 132 electrodes. Of these, two were used for the recording of the vertical and horizontal electrooculogram (EOG) on the right eye, two were used as offline reference electrodes, placed bilaterally on the mastoids. The remaining 128 were scalp electrodes, mounted equiradially in an ABC layout.

Preprocessing

Data were analyzed with custom code in MATLAB (The MathWorks Inc., 2022) with additional use of EEGLab (version 2022.1; Delorme & Makeig, 2004). Data were resampled to a sampling rate of 256 Hz and subsequently high-pass filtered at 1 Hz and low-pass filtered at 40 Hz. Following this, we separated data according to condition (visual baseline, auditory baseline, attend-visual, attend-auditory). Faulty channels were excluded manually by trained personnel. If more than 15% of channels had to be excluded for a given participant, they were excluded from further analysis (this was the case for five participants). Data was then epoched into periods of 2 s by first selecting the first 10 s after a switch in modality, to later perform spectral analysis assessing changes in SSPs independent of modality switches. As the lengths of the conditions for each modality were pseudo-randomized, this was a necessary step to ensure comparability. Epochs of 3 s length, starting 1 s before the bimodal cue indicating modality switch, and ending 2 s after, were selected for time-frequency analysis, which was used to investigate the changes in the spectra over time, specifically following modality switches. Epochs containing artefacts other than eye blinks were again rejected manually by trained personnel. We excluded participants from further analysis completely, for which more than 25% of epochs had to be excluded in any condition (this was the case for a further five participants). An average of 4.13% of epochs were excluded from all other participants. Subsequently, an independent component analysis (ICA) was run to identify and exclude further artefacts, especially eye blinks. Finally, rejected channels were interpolated. This was done at the end in order to not cause rank deficiency problems in ICA, which can be caused by the addition of dimensions of previously interpolated near-zero eigenvalue channels.

Spectral Analysis

For further analysis, data were analyzed using the Fieldtrip toolbox (Oostenveld et al., 2011). A spectral analysis was conducted to assess potential changes in SSPs. Data was Fourier-transformed using multi-taper frequency transformation based on discrete prolate spheroidal sequences (Percival & Walden, 1993) and thus raw power for each subject at each timepoint was computed from 1 to 42 Hz in steps of 1 Hz. These raw power values were then transformed into signal-to-noise-ratio (SNR). This was done in order to increase visibility of SSPs (Derzsi, 2021) and to ensure that identified SSPs were significantly different from noise (Meigen & Bach, 1999). SNR was calculated by dividing raw power values of each subject and each respective timepoint, channel and frequency band, by the mean raw power of its two neighboring frequencies in both directions (−2 Hz, −1 Hz, +1 Hz, +2 Hz). From the resulting SNR a value of one was subtracted in order to permit its interpretation as a signal measure relative to the noise level.

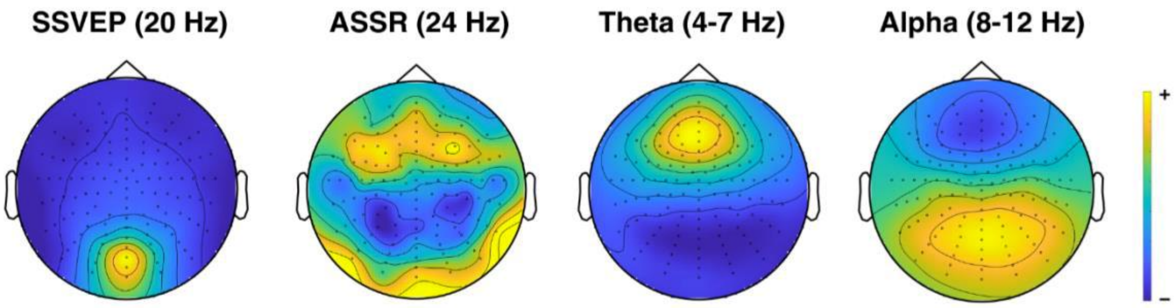
Those channels for which the SNR of the SSPs was the highest (fifteen frontocentral channels for ASSR, four occipital channels for SSVEP) were averaged for both attend-visual and attend-auditory conditions and compared pre- to posttest. To determine whether 1) SSPs were present at their respective stimulation frequencies, and 2) whether SNR of these SSPs changed significantly through the intervention, a repeated-measures ANOVA was conducted.

To assess a possible influence of the intervention on posterior alpha and frontocentral theta activity, an appropriate region of analysis had to be selected. For the analysis of posterior alpha activity, the spectral distribution of frequencies between 8 and 12 Hz for both attend-auditory and attend-visual conditions was averaged across timepoints and groups, and the electrodes with the highest power in these frequencies were selected for analysis. The same was done with frequencies between 4 and 7 Hz in order to select electrodes with highest theta activity. This led to a total of 44 electrodes being selected for the analysis of changes in posterior alpha activity, and 10 electrodes being selected for the analysis of changes in frontocentral theta activity. Topographies of SSPs, as well as theta- and alpha-band frequencies can be seen in Figure 4.

Again, a repeated measures ANOVA was conducted in order to determine a possible influence of the intervention on posterior alpha and frontocentral theta activity.

Figure 4

Topography of SSPs, Alpha Activity, and Theta Activity



Note. Taken from Szaszkó et al. (2024a). Spatial distributions of SSPs, theta activity, and alpha activity, averaged across all timepoints, groups, and conditions. Lowest activity is indicated by dark blue areas, highest activity by yellow areas. SSVEP: Steady State Visual Evoked Potential; ASSR: Auditory Steady State Response.

Time-Frequency Analysis

In order to analyze the relative change in power in one modality compared to the modality previously attended to, a time-frequency analysis using multitaper method convolution with Hanning tapers was conducted, using the Fieldtrip toolbox, on epochs starting 1 s before stimulus onset (the bimodal cue signaling a change in modality) and ending 2 s after. Data were normalized by subtracting the mean of a baseline (the period of time 1 s until 0.25 s before stimulus onset) from each data point and dividing each resulting value by the baseline.

Next, for each participant, channel, and timepoint, pretest was subtracted from posttest normalized power. Subsequently, in order to identify clusters of significant differences between intervention and control group, a cluster-based permutation test was conducted. This and all following cluster-based permutation tests were calculated with 1,000 permutations and an alpha level of .05. In order to analyze changes in the frequencies of the SSPs (20 Hz and 40 Hz for SSVEP; 24 Hz for ASSR), an average over those channels was taken in which the spectral analysis had identified a significant presence of SSPs.

For the analysis of significant clusters of alpha and theta activity, the distinct frequencies within these frequency bands (alpha: 8-12 Hz; theta: 4-7 Hz), and the time course of this activity, all 128 channels were included and treated as independent data points. A separate permutation test was run for each frequency band and, where significant clusters of differences in pre- to posttest activity were found, followed up by paired *t*-tests to separately test for significant clusters in both the intervention and the control group, limited to the timeframe of the significant interaction.

Results

Behavioral Results

After exclusion of participants based on too many false alarms or too many missed targets, out of 68 participants who had completed the experiment at both time points, 59 participants (51 female, $N_{\text{Intervention}} = 26$, $M_{\text{Age}} = 25.01$ years; $SD_{\text{Age}} = 4.57$ years; range 19-40 years) remained for behavioral analysis.

Response Times

Response times were analyzed using a 2 x 2 x 2 x 2 mixed ANOVA. Within-participant variables comprised *condition* (visual/auditory), *measurement* (pre/post), and *switching* (switch/repetition). *Group* (intervention/control) constituted the sole between-participant variable. Figure 5 illustrates the results of this analysis, combined with the results of the analysis of hit rates.

The most interesting significant effect found was the main effect of switching $F(1, 57) = 16.25$, $p < .001$, $\text{eta}_p^2 = .22$. Counter to our intuitions, this was not due to an increase in RTs after a switch, but rather due to 6 ms lower RTs in switch compared to repetition trials.

Furthermore, a significant main effect of condition was found, $F(1, 57) = 46.21$, $p < .001$, $\text{eta}_p^2 = .45$, with RTs in visual trials being 40 ms faster than in auditory trials. This is in line with previous findings (for a review, see Kiesel et al., 2010). Similarly, a learning effect, visible through the significant main effect of measurement $F(1, 57) = 6.25$, $p = .015$, $\text{eta}_p^2 = .10$, is commonly found in these kinds of experiments. Participants in both intervention and control groups were 13 ms faster in posttest compared to pretest trials.

The effect of the intervention on switching costs, as analyzed in the interaction between group, measurement, and switching, was marginally significant $F(1, 57) = 2.91$, $p = .060$, $\text{eta}_p^2 = .05$. Here, a trend could be observed that suggested an effect of the intervention, as differences between RTs in repetition and switch trials decreased in the intervention group from pre- to posttest (from 8 ms to 3 ms) but increased in the control group (from 5 ms to 9 ms). To further investigate this trend, an independent-samples *t*-test was conducted to compare RT differences between groups due to switching costs, by calculating RT differences between repetition and switch trials and their difference between pre- and posttest measurements. This interaction was not significant $M = 8$ ms, $t(73) = 1.71$, $p = .093$, $d = 0.44$. All other interactions and main effects of the ANOVA were not significant, with *p*s > .231.

Hit Rates

As in the analysis of response times, hit rates were analyzed using a 2 x 2 x 2 x 2 mixed ANOVA. Within-participant variables again comprised *condition* (visual/auditory), *measurement* (pre/post), and *switching* (switch/repetition). *Group* (intervention/control) again constituted the sole between-participant variable.

Here, the main effect of switching was marginally significant, $F(1, 57) = 3.56$, $p = .064$, $\text{eta}_p^2 = .05$, with, contrary to the direction of the effect found in RTs, participants being 1.13% more accurate in repetition, compared to switching trials.

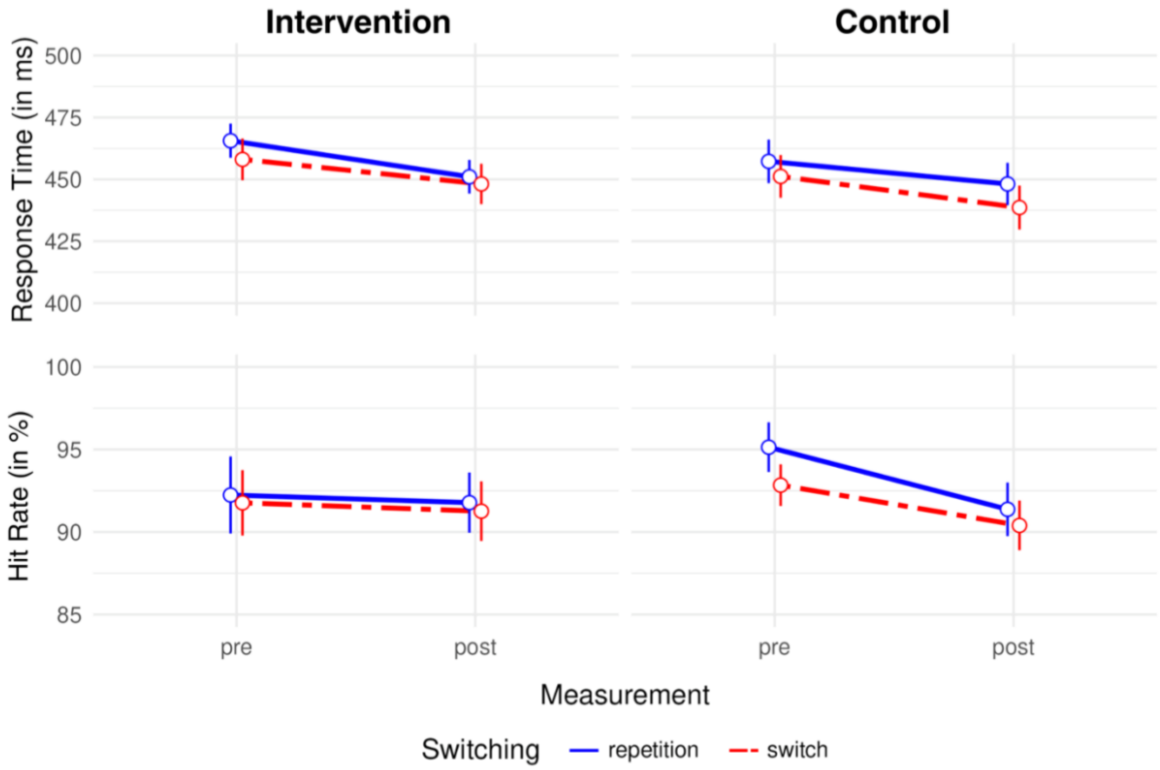
Like in RTs, the significant main effect of condition, $F\ (1, 57) = 38.96$, $p < .001$, $\text{eta}_p^2 = .41$, reflected higher accuracy in the visual compared to the auditory condition (3.2% better performance). Similarly, a significant main effect of measurement, $F(1, 57) = 5.56$, $p = 022$, $\text{eta}_p^2 = .09$, again reflected a learning effect (1.95% higher accuracy in post-, compared to pretest measurements, across both groups).

A significant interaction was found between switching and condition, $F(1, 57) = 4.04$, $p = 049$, $\text{eta}_p^2 = .07$, reflecting higher switching costs in the visual, compared to the auditory modality. In the visual modality, switching costs were significant, $M = 1.82$ %, $t(73) = 2.81$, $p < .001$, $d = 0.47$, in the auditory modality, however, they were not, $M = 0.45$% , $t(73) = 0.84$, $p = .203$, $d = 0.47$.

The effect of the intervention on hit rates, as analyzed in the interaction between group, measurement, and switching, was non-significant, $F(1, 57) = 0.78$, $p = .381$, $\text{eta}_p^2 = .01$. All other interactions and main effects of the ANOVA were not significant, with *p*s > .118.

Figure 5

Response Time and Hit Rates for Switch Versus Repeat Trials



Note. Taken from Szaszkó et al. (2024a). Blue lines indicate repetition trials, red dot-dashed lines indicate switch trials. Vertical red and blue bars represent 95% CIs. The top row illustrates changes in response times, and the bottom row changes in hit rates, both between pre- and posttest measurements. The left column illustrates these results for the intervention group, the right column for the control group.

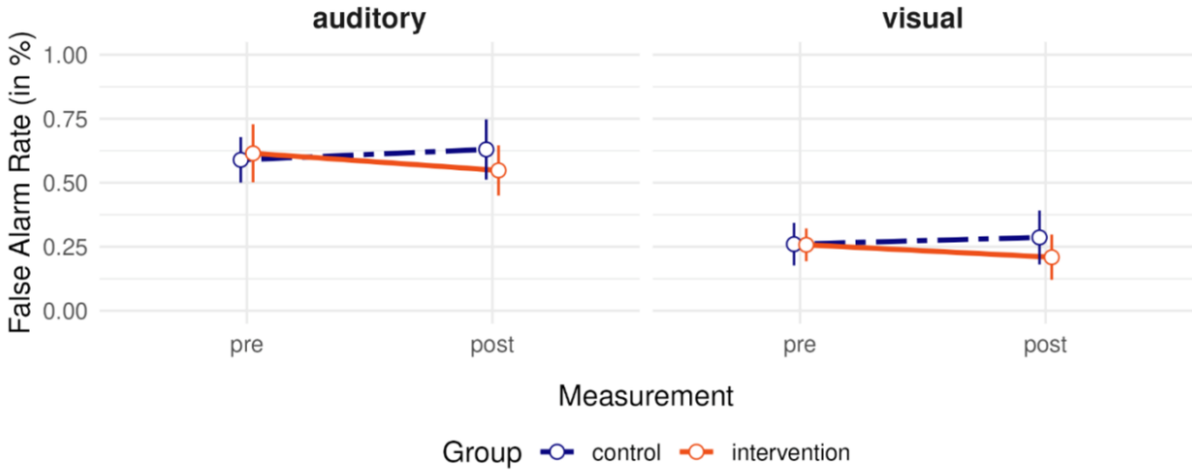
False Alarm Rates

For the analysis of false alarm rates, a 2 x 2 x 2 mixed ANOVA was conducted. Within-participant variables were *condition* (visual/auditory) and *measurement* (pre/post), with *group* (intervention/control) once more constituting the sole between-participant variable. Figure 6 illustrates the results of this analysis.

A significant main effect of condition was found, $F(1, 57) = 63.32$, $p < .001$, $\text{eta}_p^2 = .53$, but no changes in false alarm rates independent of modality, as indicated by the non-significant interaction between group and measurement, $F(1, 57) = 2.13$, $p = .150$, $\text{eta}_p^2 = .04$. Furthermore, the absence of a significant interaction between group, measurement, and condition, $F(1, 57) = 0.10$, $p = .750$, $\text{eta}_p^2 < .01$, indicated that there were no changes pre- to posttest in false alarm rates specific to one or the other modality, in either group. All other interactions and main effects of the ANOVA were not significant, with all *p*s > .694.

Figure 6

False Alarm Rates for Switch Versus Repeat Trials



Note. Taken from Szaszkó et al. (2024a). Differences in false alarm rates shown between pre- and posttest measurements, and separately for auditory and visual trials. Blue dot-dashed lines indicate repetition trials, orange solid lines indicate switch trials. Vertical orange and blue bars represent 95% CIs.

Electrophysiological Results

All subjects excluded from behavioral analysis were also excluded from the analysis of electrophysiological data. Of the remaining 59 participants, five participants had to be excluded due to the number of faulty channels, and a further five due to the number of epochs that had to be deleted. Additionally, the data of two participants had to be excluded, as these data sets had been corrupted and could not be used. The remaining 47 participants (38 female, $N_{Intervention} = 21$, $M_{Age} = 24.64$ years; $SD_{Age} = 4.39$ years; range 19-40 years) were included in the following analyses.

Spectral Analyses of SSPs

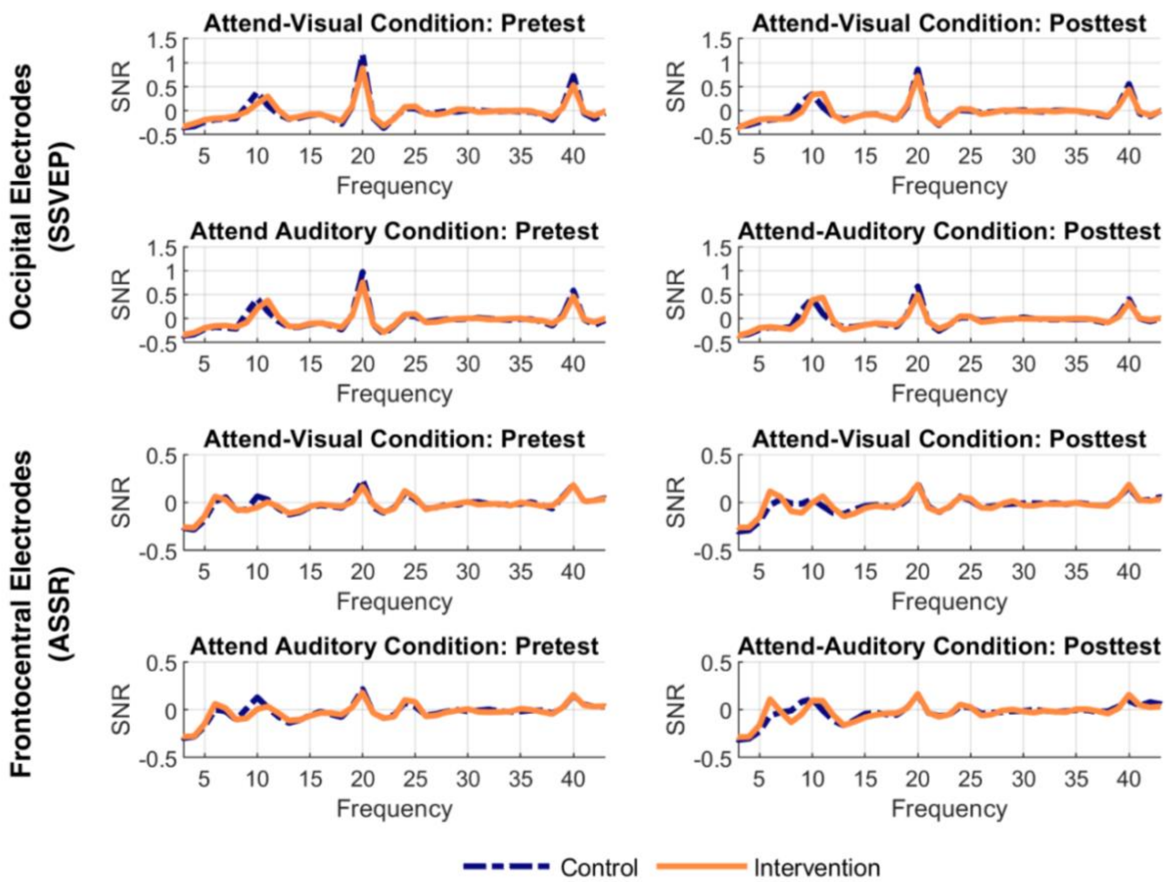
Spectral analysis was performed on frequencies between 1 and 45 Hz. Findings from this analysis are visualized in Figure 7. To assess whether the desired SSPs could actually be detected in the data, data from the baseline conditions was analyzed first. Three repeated-measures ANOVAs were calculated with the independent variables *measurement*, *condition*, and *group*, and spectral SNR at frequencies and locations sensitive to 1) the visual stimuli (posterior-occipital electrodes at 20 Hz and 40 Hz) and 2) the auditory stimuli (frontocentral electrodes at 24 Hz), as dependent variables.

As expected, a significant main effect of condition was found for frequencies sensitive to the visual stimuli, 20 Hz: $F(1, 45) = 113.11$, $p < .001$, $\text{eta}_p^2 = .72$; and 40 Hz: $F(1, 45) = 84.21$, $p < .001$, $\text{eta}_p^2 = .65$, as well as for the frequency sensitive to the auditory stimuli, 24

Hz: $F(1, 45) = 15.56$, $p < .001$, $\eta_p^2 = .26$, indicating the presence of the respective relevant SSPs. Furthermore, no threefold interactions were observed (all *p*s > .596), indicating that the presence of the SSPs may only be attributed to the main effect of condition, and thus the reactions to the visual or auditory stimuli when attention was placed on the respective modality.

Figure 7

Spectral Distributions for Control Versus Intervention Group



Note. Taken from Szaszkó et al. (2024a). For frequencies between 3 and 45 Hz, grand average SNR is shown for both attend-auditory and attend-visual conditions, as well as both pre- and posttest measurement timepoints. The top two rows show spectra at occipital electrodes, where at around 20 and 40 Hz the steady-state visual evoked potential is visible, the bottom two rows show spectra at frontocentral electrodes, where at around 24 Hz, the auditory steady-state response is visible. SSVEP: Steady State Visual Evoked Potential; ASSR: Auditory Steady State Response.

In a next step, using data from the experimental condition, the question was addressed whether the intervention had an effect on the change in magnitude of the SSPs, between attend-auditory and attend-visual conditions. Three 2 x 2 x 2 mixed ANOVAs were computed, once more including *measurement*, *condition*, and *group* as independent variables, and spectral SNR at frequencies and locations sensitive to 1) the visual stimuli (posterior-occipital electrodes at 20 Hz and 40 Hz) and 2) the auditory stimuli (frontocentral electrodes at 24 Hz), as dependent variables.

Significant threefold interactions were observed for neither SSVEP frequencies 20 Hz: $F(1, 45) = 0.47$, $p = .273$, $eta_p^2 = .03$; and 40 Hz: $F(1, 45) = 0.07$, $p = .637$, $eta_p^2 < .01$, nor ASSR frequency 24 Hz: $F(1, 45) = 0.99$, $p = .325$, $eta_p^2 = .02$. This lack of a significant interaction indicated that the intervention had no significant effect on participants' SSVEP or ASSR. Results also indicated that there were no changes in SSPs due to the intervention which were not specific to a modality, as shown by the lack of significant interactions between measurement and group (all *p*s > .479).

A significant main effect of measurement was found for SSVEP frequencies both at 20 Hz: $F(1, 45) = 17.21$, $p < .001$, $eta_p^2 = .28$, and at 40 Hz: $F(1, 45) = 9.59$, $p = .003$, $eta_p^2 = .18$, indicating lower SNRs at posttest than at pretest. Such an effect could not be found for the ASSR frequency at 24 Hz: $F(1, 45) = 3.03$, $p = .089$, $eta_p^2 = .01$.

A significant main effect of condition was found at all frequencies: 20 Hz, $F(1, 45) = 34.72$, $p < .001$, $eta_p^2 = .44$; 40 Hz, $F(1, 45) = 30.88$, $p < .001$, $eta_p^2 = .41$; 24 Hz ASSR, $F(1, 45) = 6.64$, $p = .013$, $eta_p^2 = .13$. This effect illustrates that SNRs at 20 Hz and 40 Hz were significantly higher in the attend-visual condition, compared to the attend-auditory condition and that SNRs at 24 Hz were significantly higher in the attend-auditory, compared to the attend-visual condition. This was to be expected as it means that when a modality was attended, the respective SSPs of that modality were higher than those of the non-attended modality. There were no other significant main effects or interactions at 20 Hz, 40 Hz, or 24 Hz (all *p*s > .194).

Spectral Analyses of Alpha and Theta Activity

Spectral Analysis of Alpha Activity. For the analysis of alpha activity, a 2 x 2 x 2 mixed ANOVA was conducted. Independent variables were *condition* (visual/auditory), *measurement* (pre/post), and *group* (intervention/control). The dependent variable was participants mean SNR, averaged over alpha-band frequencies of 8 to 12 Hz. Figure 8 illustrates the findings of this analysis.

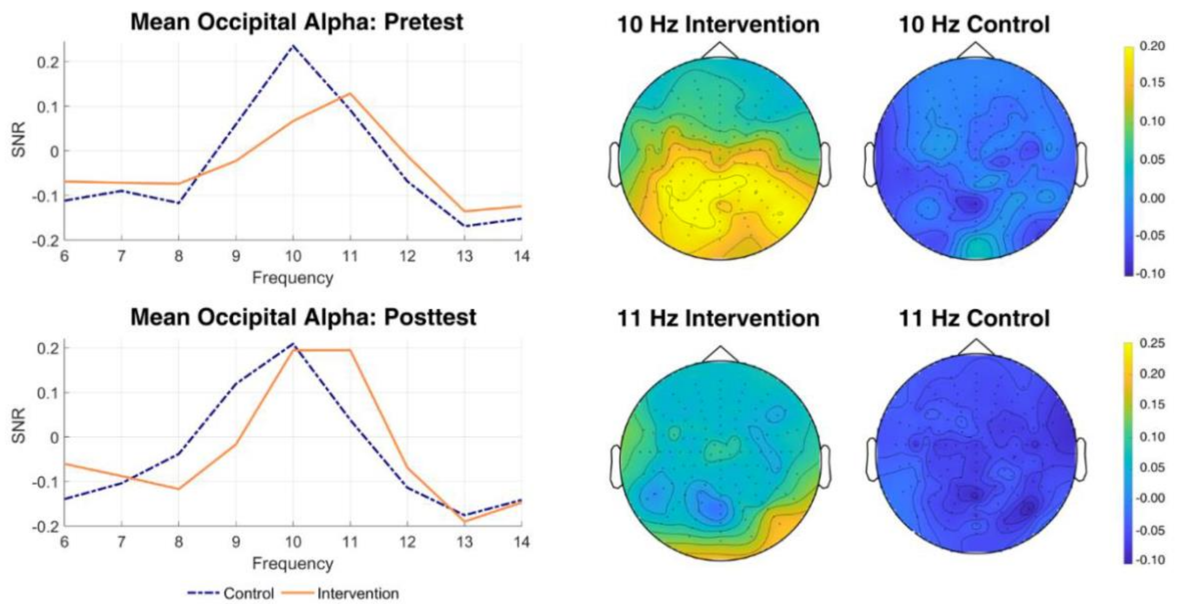
A significant interaction between group and measurement was found, $F(1, 45) = 5.39$, $p = .025$, $eta_p^2 = .11$, indicating a significant effect of the yoga intervention. Following up these findings with *t*-tests to determine the direction of this interaction showed a significant increase in SNR at alpha frequencies in the intervention group from pre- to posttest, *M* = 0.02, *t*(45) = 3.21, *p* = .004, *d* = 0.29, and at the same time no significant change in the control group, *M* = 0.00, *t*(45) = 0.09, *p* = .932, *d* = 0.02.

Furthermore, a significant main effect of condition was found, *F*(1, 45) = 13.70, *p* = .001, eta_p^2 = .23. SNRs at 8 to 12 Hz were higher in attend-auditory conditions, *M* = 0.084, *SD* = 0.026, than in attend-visual conditions, *M* = 0.073, *SD* = 0.020. There were no other significant main effects or interactions at 8 to 12 Hz (all *p*s > .118).

Additionally, in order to determine in which areas of the brain changes in alpha activity were most prominent, a topographical analysis of the changes pre- to posttest, compared between intervention and control group, was conducted. Figure 8 illustrates the results of this analysis.

Figure 8

Changes in Alpha Activity



Note. Taken from Szaszkó et al. (2024a). On the left, spectral distributions for mean occipital alpha activity for both pre- and posttest measurements are shown, with the dot-dashed blue line representing spectral distributions in the control group, and the orange solid line representing spectral distributions in the intervention group. On the right, changes in topography from pre- to posttest are shown separately for intervention and control groups and for the frequencies of 10 and 11 Hz. Frequencies were chosen for exhibiting the largest changes. Areas with the highest increase in activity are yellow, those with the highest decrease are dark blue. Light blue areas indicate no change. Topography plots only indicate the distribution of changes in activity. General alpha activity was similar for both frequencies and across groups, concentrated around central parietal electrodes.

Frequencies at 10 and 11 Hz were used for the topographical analysis of alpha activity, as these exhibited the largest changes in SNR. At 10 Hz, the intervention group showed an increase in activity in parietooccipital cortex, and at 11 Hz an increase in activity in the right occipital cortex. The control group showed neither an increase nor a decrease in activity.

Spectral Analysis of Theta Activity. For the analysis of theta activity, a 2 x 2 x 2 mixed ANOVA was conducted. Independent variables were once more *condition* (visual/auditory), *measurement* (pre/post), and *group* (intervention/control). The dependent variable was participants mean SNR, averaged over theta-band frequencies of 4 to 7 Hz. Figure 9 illustrates the findings of this analysis.

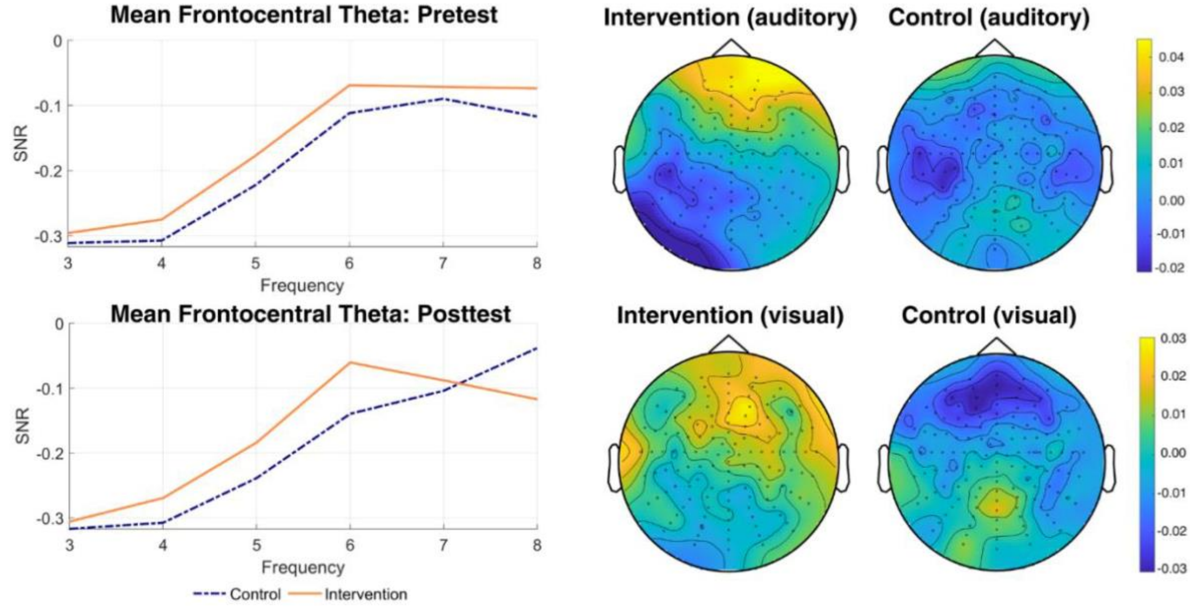
Again, a significant interaction between group and measurement was found, $F(1, 45) = 1.98$, $p = .018$, $\text{eta}_p^2 = .12$, indicating an effect of the intervention on theta activity. A follow-up *t*-test was conducted on the differences in group means pre- to posttest, and confirmed the findings of the ANOVA, $M = 0.04$, $t(45) = 2.44$, $p = .018$, $d = 0.71$. The three-fold interaction between condition, measurement and group was non-significant, $F(1, 45) = 0.06$, $p = .812$, etap2 < .01, indicating that the effect of the intervention was independent of condition.

Again, a significant main effect of condition was found, $F(1, 45) = 10.24$, $p = .003$, $\text{eta}_p^2 = .19$, this time however with lower SNR at 4 to 7 Hz in attend-auditory conditions, $M = -0.103$, $SD = 0.055$, than in attend-visual conditions, $M = -0.078$, $SD = 0.045$. There were no other significant main effects or interactions at 4 to 7 Hz (all *p*s > .135).

Additionally, in order to determine in which areas of the brain changes in theta activity were most prominent, a topographical analysis of the changes pre- to posttest, compared between intervention and control group, was conducted. Averaged across the entire theta frequency band of 4 to 7 Hz, the intervention group showed an increase in activity in prefrontal cortex. At the same time, the control group showed a decrease in activity in the same area, with a simultaneous increase in activity in parietal cortex which was especially pronounced in the visual condition. Figure 9 illustrates the results of this analysis.

Figure 9

Changes in Theta Activity



Note. Taken from Szaszkó et al. (2024a). On the left, spectral distributions for mean frontocentral theta activity for both pre- and posttest measurements are shown, with the dot-dashed blue line representing spectral distributions in the control group, and the orange solid line representing spectral distributions in the intervention group. On the right, changes in topography of frequencies across the entire theta band (4-7 Hz), from pre- to posttest are shown separately for intervention and control groups and for the visual and auditory conditions. Areas with the highest increase in activity are yellow, those with the highest decrease are dark blue. Light blue areas indicate no change.

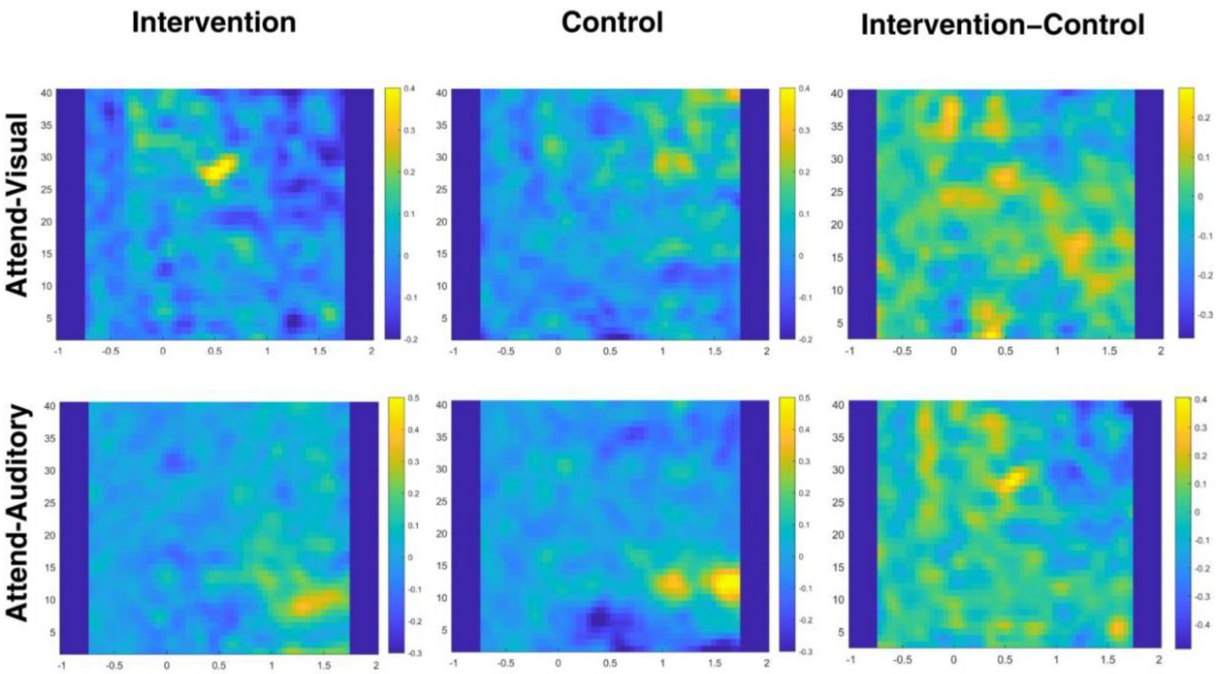
Time-Frequency Analyses

Time-Frequency Analyses of SSPs. In order to determine whether there were significant differences between groups in the changes in power of the SSP frequencies (SSVEP: 20 Hz, 40 Hz; ASSR: 24 Hz), following a modality switch, time-frequency analyses were conducted using the period of 1,000 to 250 ms before onset of the bimodal cue as baseline. Then, cluster-based permutation tests were computed comparing, between groups, change in power after bimodal cue onset, from pre- to posttest, for the first 2,000 ms following onset of the bimodal cue. Figure 10 illustrates these results.

A significant cluster (p = .017), indicating a decrease in SSVEP in attend-visual condition, compared to the attend-auditory baseline, in the intervention group, relative to the control group, was found at 40 Hz between 1,150 and 1,400 ms after bimodal cue onset.

Figure 10

Time-Frequency Plots for Both Experimental Groups and Their Differences



Note. Taken from Szaszkó et al. (2024a). Time-frequency plots showing change in activity relative to a baseline (the previously attended condition) for intervention group (left column) and control group (middle column), as well as for the difference between the two groups (right column) are shown. The top row shows plots for attend-visual trials, the bottom row for attend-auditory trials. The time locking stimulus is the bimodal cue indicating a switch in modality. Frequency (2 to 45 Hz) is represented on the y-axis. Time (from 1 s before, until 2 s after the time locking stimulus) is represented on the x-axis. Yellow areas indicate the largest relative increase in activity, dark blue areas the largest relative decrease.

Cluster-based permutation tests were then calculated to assess differences pre- to posttest for each group separately and limited to the time frame of the significant cluster, 1,150 to 1,400 ms after bimodal cue onset. Results showed that there were no significant clusters in the intervention group, but that there was in fact a significant increase in 40 Hz SSVEP power for this timeframe in the control group.

No other significant clusters, indicating differences between groups, in the changes in power following bimodal cue onset were found (all *p*s > .103).

Time-Frequency Analyses of Alpha and Theta Activity. To compare changes in alpha and theta power after bimodal cue onset between groups, cluster-based permutation tests were computed once more, for the period of 2,000 ms following bimodal cue onset, again using the time frame of 1,000 to 250 ms preceding cue onset, and thus activity in the previous modality, as baseline.

For theta power and in attend-auditory trials, this analysis yielded two positive clusters, indicating a higher increase in theta power following a switch in modality in the intervention compared to the control group. The first significant cluster ($p = .035$) was found starting at 6-7 Hz, spreading to 4-7 Hz and finally ending again at 6-7 Hz, between 150 and 500 ms, and the second significant cluster ($p = .026$) was found exclusively at 6-7 Hz, between 1,000 and 1,300 ms following the onset of the bimodal cue.

Cluster-based permutation tests were then calculated to assess differences pre- to posttest for each group separately and limited to the timeframe of the significant clusters. Results for the time frame of the first significant cluster, 150 to 500 ms after onset of the bimodal cue, showed a significant decrease in theta activity in the control group ($p < .001$), lasting the entire duration of the time frame, and no change in theta activity in the intervention group. Results for the timeframe of the second significant cluster, 1,000 to 1,300 ms following onset of the bimodal cue, showed a significant increase in theta activity in the intervention group ($p = .004$), lasting from 1,000 to 1,250 ms after bimodal cue onset.

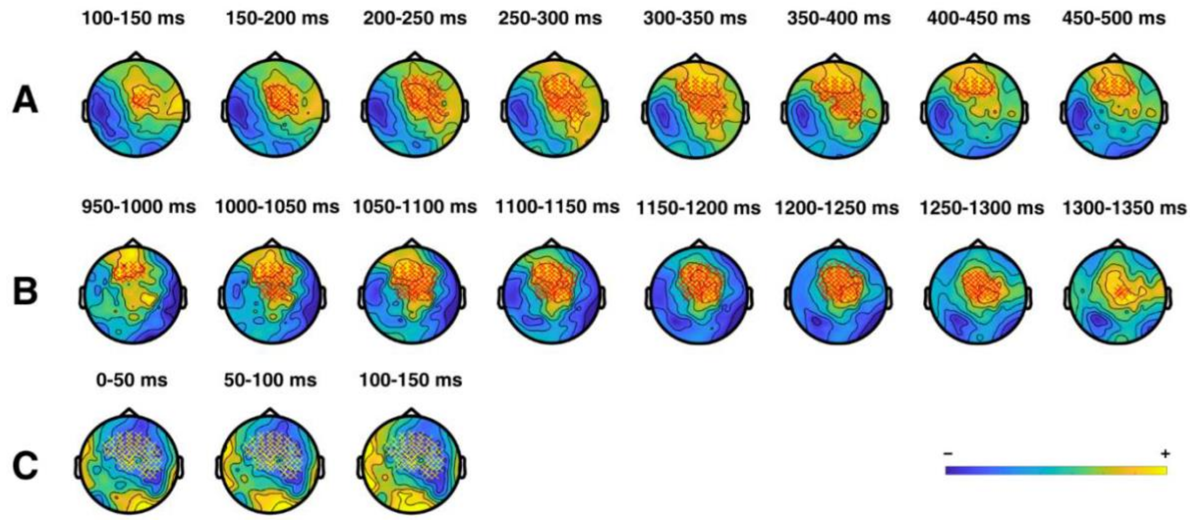
For theta power and in attend-visual trials, this analysis yielded one negative cluster, indicating a higher decrease in theta power following a switch in modality in the intervention compared to the control group. This significant cluster ($p = .037$) was found at 4-5 Hz, between 0 and 100 ms following the onset of the bimodal cue.

Cluster-based permutation tests were then calculated once more to assess differences pre- to posttest for each group separately and limited to the time frame of the significant cluster, 0 to 100 ms following onset of the bimodal cue. Results showed a significant decrease in theta activity in the intervention group ($p = .019$), lasting for the entire timeframe of the original significant cluster, and a significant increase in theta activity in the control group ($p = .027$). lasting from 0 to 50 ms following onset of the bimodal cue. Figure 11 illustrates the topography and time course of all significant clusters of theta activity.

For alpha power, no significant clusters were found (all *p*s > .103).

Figure 11

Significant Clusters of Theta Activity.



Note. Taken from Szaszkó et al. (2024a). Significant clusters of electrodes are shown across different timepoints and for two different frequencies. Yellow areas show greater, and dark blue areas show lower activity in the intervention group compared to the control group. Clusters A and B show activity at 7 Hz, and cluster B shows activity at 5 Hz, both after a switch to the auditory condition, compared to a switch to the visual condition.

Discussion

The present results did not directly support the hypotheses outlined in the introduction of this manuscript. They did, however, yield some interesting findings supporting the notion of an improvement, through our yoga intervention, of executive function in general, and the shifting function in specific.

A Non-Significant Trend in Switching Costs

Concerning the interaction between group and time point in the analysis of switching costs, contrary to our expectations that the intervention would lead to a decrease in switching costs in the intervention group, no significant interaction between group, measurement, and switching was found for hit rates. For RTs however, a marginally significant threefold interaction was found, indicating a significant difference in switching costs, pre- to posttest, between groups. Although a trend, potentially supporting our hypothesis, could be observed, with switching costs decreasing in the intervention group and increasing in the control group, this trend was non-significant. However, in combination with other behavioral findings and electrophysiological results examined throughout the following sections, this trend may point in an interesting direction.

Faster RTs in Switch Trials

The finding that RTs were significantly lower in switch compared to repetition trials, may be explained by the activating effect of the bimodal cue, which may have jolted tired participants' attention back on task. As participants were seated in a dimly lit room for over 45 min and were constantly exposed to parallel flickering stimulation in the auditory and visual domains, it is not unlikely that some grew fatigued over the course of the experiment. The non-significant trend towards a decrease in switching costs in the intervention group, described above, suggests that through the intervention, participants' reactivity to the bimodal cue might have been reduced through a more appropriate allocation of cognitive resources. This may have led to less of an activating effect of the cue, resulting in lower switching costs at posttest measurement in the intervention group.

Another possible explanation for the significantly lower RTs in switch trials may be the reduction in processing load following a switch in modality. This reduction may have come about as participants no longer had to keep the sequence of current cues, possibly leading to a target sequence, in memory.

SSVEP Increase in the Control Group Following a Switch to the Visual Modality

Contrary to our expectations, we did not observe changes in the spectra of the SSPs due to the intervention, nor did the time-frequency analysis show the expected increase in power of the SSP associated with the modality that was being switched to, paralleled by a decrease in power of the SSP associated with the modality that was being switched away from. Considering the change in spectral activity over time did however yield a significant window between 1,150 and 1,400 ms after onset of the bimodal cue, in which 40 Hz SSVEP activity increased significantly in the control group, compared to the intervention group. Considering the findings of numerous previous studies that suggest that the amplitude of the SSVEP reflects the amount of attentional resources allocated to a stimulus (e.g., Kim et al., 2007; Malinowski et al., 2007; Toffanin et al., 2008; J. Wang et al., 2007) and further considering that there were only minor differences in the performance of the intervention and the control group, reflected, for example, in the absence of a significant threefold interaction between group, measurement and switching for hit rates, it stands to reason that, after the intervention, participants in the intervention group required less attentional resources than those in the control group to achieve similar results. This suggests that the intervention enabled participants to use cognitive resources more efficiently. In a similar vein, Schöne et al. (2018), for example, found a decrease in SSVEP amplitude following an eight-week meditation intervention, which they too explained through more efficient use of attentional resources.

Reactivity to the cue offers an explanation for the absence of switching costs in the analysis of reaction times. For hit rates, however, switching costs were in fact observed (1,13% higher accuracy in repetition compared to switch trials), but only in switches to the visual modality. This may point to a further interesting mechanism: switching costs specific to a switch from auditory to visual modality, explained by a reduction in cognitive flexibility when switching from a more challenging to an easier task.

Significant Switching Costs Only When Switching to the Visual Modality

Results showed clear performance advantages for tasks in the visual condition. The significant main effect of condition for RTs illustrated 40 ms faster RTs in visual compared to auditory trials, and the significant main effect of condition for hit rates illustrated 3,2% higher accuracy in visual compared to auditory trials. Nonetheless, switching costs were significantly higher when switching to the visual condition. Numerous previous studies have found asymmetrical switching costs in task-switching paradigms (for a review, see Kiesel et al., 2010). In one such experimental setup, for example, involving switching between visual and auditory modalities, Murphy et al. (2016) also reported higher switching costs when switching to the visual modality, compared to switching to the auditory modality. They posited that this was due to suppression of the visual task, which is necessary while attending to the auditory task, persisting after a switch back to the visual task, a concept known as task-set inertia.

The task-set inertia explanation, originally posited by Allport et al. (1994), states that in a task-switching paradigm, in a given trial, the current task is activated while the competing task is suppressed. As an easier task is more readily activated, it requires stronger suppression. This heightened suppression then persists for a while after a switch, leading to higher switching costs when switching from the more difficult to the easier task. In the case of the present study this means that as the visual task was easier, it took more energy to suppress its interference while attending to the auditory task. Once a switch to the visual task occurred, this suppression carried over, resulting in the observed switching costs.

The task-set inertia explanation does not hold true in all situations, with relative task difficulty playing a decisive role (e.g., Arbuthnott, 2008; Monsell et al., 2000), as well as the degree of delay between tasks. Yeung and Monsell (2003), for example, varied the delay of the onset of a word relative to its colored background in a Stroop task and found that starting from a delay of 160 ms, the asymmetry in switch costs predicted by task-set inertia was reversed, and larger switching costs were observed while switching to the more challenging, the color-naming task, compared to switches to the easier, the word-naming task. When there was no delay between colored background and word onset, however, they also observed switching costs compatible with the task-set inertia explanation.

The fact that in the present study the bimodal cue signaling a switch in modality lasted for 2000 ms suggests that our results may not be explained by task-set inertia, as this delay between tasks is well above the threshold described by Yeung and Monsell. Nonetheless, considering that there were clear differences in difficulty between the two tasks, as reflected in the differences in performance, combined with further support from the analyses of frontocentral theta and posterior alpha activity, which will be discussed in more detail in the following sections, we believe that our results are well explained by task-set inertia. In any case, due to these partially conflicting findings, further research into task-set inertia as an explanatory mechanism behind ours and similar results may be a fruitful avenue for future research.

Yoga Increases Frontocentral Theta Activity

In the time-frequency analysis of theta activity, two significant clusters of theta-band activity were identified following switches in modality. The first was a cluster of decreased theta-band activity in the control group compared to the intervention group, lasting from 150 ms to 500 ms after onset of the bimodal cue signaling a switch in modality. The second was a cluster of increased theta band activity in the intervention group, compared to the control group, lasting from 1,000 ms to 1,300 ms after onset of the bimodal cue. Analyses of the neural sources of this activity located it in frontocentral regions.

Midfrontal theta activity has been associated with cognitive control mechanisms more broadly (e.g., Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Duprez et al., 2020; Eisma et al., 2021; Sauseng et al., 2019) and task-switching more specifically, with findings indicating higher theta power being associated with improved task-switching performance (e.g., Cunillera et al., 2012; McKewen et al., 2021; Sauseng et al., 2006; Verbeke et al., 2021). Enriquez-Geppert et al. (2014), for example, found that increasing participants' midfrontal theta oscillations through biofeedback training led to reduced mixing and shifting costs in a letter/number task-switching paradigm. Proposed roles of theta oscillations in task-switching include the tracking of task rules (Verbeke et al., 2021), and the facilitation of communication between regions of the brain relevant to solving the task at hand (Fries, 2005, 2015).

The increase in theta activity in the intervention group from 1,000 ms to 1,300 ms following the onset of the bimodal cue, as well as the significant interaction between group and measurement in the spectral analysis indicating a significant effect of the intervention on frontocentral theta activity, can thus be interpreted as increased cognitive resources having been made available for the tracking of task rules and the facilitation of communication between task-relevant areas through the intervention.

The decrease in theta activity in the control group, from 150 ms to 500 ms after onset of the bimodal cue, could be explained by bottom-up processes decreasing attentional control (Corbetta & Shulman, 2002). This explanation would be in line with the finding outlined in more detail further below, that alpha activity, as a facilitator of suppression of bottom-up processing (Benedek et al., 2014), increased in the intervention group, but did not change in the control group.

It is important to note that contrary to our expectations, in the first 100 ms following a switch from auditory to visual modality, the time-frequency analysis showed a significant decrease of activity in the lower theta band (4-5 Hz) in the intervention group, as well as a significant increase in the control group between 0 and 50 ms following a switch. Although these findings run contrary to our hypothesis that clustered theta activity would increase following a switch, they provide further support for the task-set inertia explanation by implying that generally, less cognitive resources needed to be employed in the visual condition. Furthermore, these results show that the intervention group was able to use resources more economically following the intervention, as demonstrated by similar behavioral performance measures in both groups, paralleled by significantly less theta activity in the intervention group.

Yoga Increases Alpha Activity

The exploratory analysis of alpha activity further supports the notion that the intervention led to improved deployment of cognitive resources and thus an improvement in task-shifting ability. The ANOVA conducted on the spectral analysis of posterior alpha activity showed a significant interaction between group and measurement, indicating a significant effect on alpha activity through the intervention, with follow-up *t*-tests confirming that this effect was due to an increase in alpha SNR in the intervention group, and finding no significant change in the control group. This change in alpha activity was located in parietal and occipital regions.

There is general consensus that activity in the alpha frequency band (8-12 Hz) is associated with inhibition of task-irrelevant processes (e.g., Engel et al., 2001; Foxe &

Snyder, 2011; Jensen et al., 2012; Klimesch et al., 2007; Knyazev, 2007). More specifically, alpha activity in parietal regions has been linked to increased internal attention and decreased bottom-up processing (Benedek et al., 2014). Alpha activity in occipital regions has been implicated in the blocking of irrelevant sensory input from moving to downstream areas (Zumer et al., 2014), as well as improved working memory function (Tuladhar et al., 2007), which plays an essential role in task-switching by facilitating the holding of different task-control representations (Vandierendonck, 2012).

In the present paradigm, stimulation occurred simultaneously in the visual and in the auditory modality, making active inhibition of the not-to-be-attended modality vital for optimal task performance, making it highly likely that the general increase in alpha SNR in the intervention group is indicative of improved inhibition of the opposite modality. In the ANOVA conducted on the spectral analysis of alpha-band SNR, the main effect of condition was also significant, with higher SNR in the auditory modality. Similar results concerning higher alpha activity in auditory trials have been reported in a number of previous studies (e.g., Fu et al., 2001; Gomez-Ramirez et al., 2007; Mazaheri et al., 2014).

This finding further supports the notion posited in the task-set inertia explanation, that increased inhibition, reflected by increased alpha SNR, is required during the more challenging task for the suppression of the easier task, in this case the visual stimulation while attending to the auditory task, which then carried over after a switch to the visual modality, leading to increased switching costs as reflected in the behavioral results. Here it is important to note that alpha activity has been associated with the suppression of visual processing in particular (e.g., Clements et al., 2023; Yamagishi et al., 2005). Additionally, increased alpha SNR in the intervention group may be explained by an increase in working memory function, facilitating an improvement in task-switching.

Limitations

As outlined in the introduction, delineating the specific effects of yoga against those of physical exercise or mindfulness practice is one of the major challenges when working with yoga interventions. The lack of active control groups participating in physical and mindfulness interventions of similar duration as the yoga intervention is therefore one of the major shortcomings of this study.

As intervention studies, in which large numbers of participants take part in classes taught by professionals over a relatively long period of time, come with high financial costs for, among others, instructors and instruction spaces, a possible solution for future research would be to conduct classes remotely, thus freeing resources for, for example, additional control groups. Phansikar et al. (2023) showed that this is feasible by conducting an eight-week, remote yoga intervention, in which, similar to our design, participants had to take part in three 50 min yoga sessions per week. Their results showed that when classes were taught synchronously (as opposed to through pre-recorded videos), attendance was as high as 97.5%, making remote instruction an interesting possibility for future research using yoga interventions.

The composition of the sample poses a challenge to the generalizability of results. As we recruited a majority of participants through university channels, the sample consisted mostly of female students (80%) working less than 20 hrs per week. The fact that most participants were enrolled in university, paired with some self-selection bias for individuals wishing to positively influence their health or improve daily habits, leads us to suspect a relatively high level of average baseline cognitive performance with low variance, which may have contributed to the study yielding less significant findings. In a study assessing the influence of high- and low-intensity exercise on executive functions, including the shifting function, Mou et al. (2023), for example, found significantly larger effects of their interventions for participants with lower baseline cognitive performance compared to those with higher baseline performance.

The high number of dropouts and exclusions also poses a challenge to the interpretability of the findings, as statistical power decreased dramatically, leading to, among other things, a number of marginal results that might have been significant under different circumstances. While applying strict cut-off criteria may have curtailed some interesting findings, it did however secure internal validity, allowing us to confidently attribute found effects to our intervention. Similarly, the use of per-protocol analysis, where only those participant's data are analyzed that are still part of the study at posttest, compared to intention-to-treat analysis, where missing data are imputed at posttest (Tripepi et al., 2020), led to an increase in internal validity: By using per-protocol analysis, we prevented large numbers of imputed data, which would have jeopardized randomization and thus generalizability.

Future Directions

Besides accounting for this study's methodological challenges outlined above, future research could try to implement longer interventions, as effects may only be visible after some time. Parkinson and Smith (2023), in an analysis of the difference in measures of psychological well-being between non-practitioners, medium-, and long-term practitioners of yoga, found that intermittent practitioners (practicing at least once a week for several months or years, followed by several months or years without any practice) scored higher than none-practitioners on only a few markers of psychological well-being, with much larger differences being observed between long-term (practicing at least once a week for 3 years or more) and intermittent practitioners. Based on these findings, it seems plausible that some of the beneficial effects of yoga may only reach a detectable level after several years of practice.

Another area in which future research could build on findings from the present study concerns the influence of acutely induced stress on the shifting function of attention. A recent paper by Morava et al. (2023) reported that task-switching performance actually increased after the induction of acute stress using the Trier Social Stress Test (TSST; Kirschbaum et al., 1993). The protocol employed in the present study was a two-back task in which auditory and visual stimuli were presented simultaneously, with visual stimuli oscillating against a black background with a frequency of 20 Hz. Combined with auditory stimuli presented at 24 Hz, this led to a demanding setup in which subjects were constantly stimulated and had to, at the same time, stay focused to meet task demands. It is plausible/conceivable that this high level of perceptual and cognitive demand may have led to an acute stress response which, following the findings of Morava et al. (2023), may in turn have caused an improvement in task-switching performance. Future research could incorporate psychosocial or physiological stress induction paradigms such as the TSST or the cold pressor test (CPT; Hines & Brown, 1936), in order to control for possible effects caused by such an acute stress response.

Finally, an interesting avenue of research that could be incorporated into the investigation of interventions influencing task-switching, and which may potentially change our basic understanding of the shifting function, concerns mind wandering. Combining existing theories on mind wandering with findings from research concerning cognitive flexibility in older populations, Wong et al. (2023) propose that the shifting function is in fact responsible for mind wandering, working counter to focusing one's attention on the current task. Strengthening the shifting function could thus lead to a decrease in task performance overall, as it would make mind wandering away from the experimental task more probable. This is a new and interesting perspective, the consideration of which may lead to the uncovering of more pronounced effects of improved task-switching following an intervention, which may previously have been partially diminished by an overall decrease in task-performance.

Concluding Remarks

In the present study we showed that an eight-week yoga intervention increased frontocentral theta activity generally, as well as following a switch in modality in a task-switching paradigm. We believe that these findings point to globally increased executive control, as well as a specific increase in the ability to track task rules, and an improvement in the facilitation of communication between brain areas involved in task-switching. Furthermore, we were able to show that our intervention increased posterior alpha activity, facilitating suppression as an auxiliary mechanism to task-switching.

Undoubtedly more research into the effects of yoga on executive functions, and specifically on the shifting function is necessary. But to end on a positive note concerning the present study, it is important to take into account that the restrictions caused by the relatively high baseline cognitive performance, as well as the decreased statistical power through the large number of dropouts, led to a measurement under quite conservative conditions, with the fact that clearly significant effects were found nonetheless speaking for the strength of the intervention's influence.

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List of Figures

List of Abbreviations

ACT:	Attentional Control Theory
ANOVA:	Analysis of Variance
ASSR:	Auditory steady state response
CPT:	Cold pressor test
EEG:	Electroencephalogram
EOG:	Electrooculogram
ICA:	Independent Components Analysis
LABS:	Laboratory Administration for Behavioral Science
Mini-DIPS:	Short Version of the Diagnostic Interview for Mental Disorders
PFC:	Prefrontal cortex
RT:	Reaction time
SNR:	Signal to noise ratio
SPP:	Study Participant Platform
SSP:	Steady state potential
SSVEP:	Steady state visual evoked potential
TSST:	Trier Social Stress Test

Appendix

Abstract: English

The shifting function of attention is an essential component of executive control, enabling us to switch between different tasks and the diverse sets of requirements needed for their successful execution. In the present study, in a randomized controlled trial, we employed an eight-week Hatha yoga intervention and investigated its effect on participants' shifting abilities through a task-switching paradigm, in which participants switched between attending n-back tasks in the visual and in the auditory modality. We supplemented behavioral analyses with electroencephalogram measures of steady state responses to gain an objective measure of the currently attended modality. Furthermore, the intervention's effect on neural oscillations in the alpha and theta frequency bands, which are commonly associated with task-switching, was assessed. We expected improved shifting abilities to manifest in lower switching costs (i.e., differences between trials with a switch in modality, compared to trials where there was no switch) for reaction times and accuracy rates in the intervention group compared to the control group at posttest measurement. Although we found none of the expected significant interactions at the behavioral level, in the electrophysiological data we found a significant increase in frontocentral theta (indicating the increased deployment of attentional resources to the task), as well as a significant increase in parietooccipital alpha activity (indicating increased suppression of the task-irrelevant modality). Both findings point to an improvement of the shifting function through the intervention, with further investigation being recommended, as in the present study high dropouts and exclusions led to diminished statistical power.

Keywords: alpha, executive functions, switching costs, task-switching, theta, yoga

Abstract: German

Die verlagernde Funktion der Aufmerksamkeit ist eine Kernkomponente der Exekutivfunktionen, die es uns erlaubt schnell und effizient zwischen unterschiedlichen Aufgaben und deren vielseitigen, individuellen Anforderungen zu wechseln. In der vorliegenden randomisiert-kontrollierten Studie, wurde der Einfluss einer achtwöchigen Hatha Yoga Intervention auf die verlagernde Funktion der Aufmerksamkeit untersucht. Dabei wurde die Leistung in einem Versuchsaufbau analysiert, in dem zwischen einer Aufgabe in der visuellen und einer Aufgabe in der auditorischen Modalität gewechselt werden musste. Behaviorale Maße wurden mit Messungen der Gehirnaktivität per Elektroenzephalogramm ergänzt, um ein objektives Maß der momentan attendierten Modalität zu erlangen. Des Weiteren wurden neuronale Oszillationen im Alpha und Theta Bereich untersucht, die häufig mit Aufmerksamkeitsverlagerung in Verbindung gebracht werden. Unter der Annahme, dass die Intervention die Fähigkeit Aufmerksamkeit zu verlagern verbessern würde, erwarteten wir niedrigere Wechselkosten (Unterschiede zwischen Durchgängen, in denen die Modalität gewechselt wurde im Vergleich zu Durchgängen, in denen kein Wechsel stattfand) für Reaktionszeiten und Genauigkeitsmaße in der Interventionsgruppe im Vergleich zur Kontrollgruppe zum zweiten Messzeitpunkt, nach der Intervention. Obwohl keine der erwarteten behavioralen Interaktionen signifikant ausfielen, konnten wir einen signifikanten Anstieg an frontozentralem Theta (als Indikator für erhöhte Verfügbarkeit kognitiver Ressourcen), sowie einen signifikanten Anstieg an parietooccipitalem Alpha (als Indikator für erhöhte Unterdrückung der jeweils nicht-relevanten Modalität) feststellen. Diese Ergebnisse deuten auf eine Verbesserung der Aufmerksamkeitsverlagerung durch die Intervention hin. Dies sollte jedoch weiterführend überprüft werden, da die hohe Anzahl an Ausschlüssen und Abbrüchen in der vorliegenden Studie zu beachtlichen Einbußen an statistischer Teststärke geführt hat.

Schlüsselbegriffe: Alpha, Aufgabenwechsel, Exekutivfunktionen, Theta, Wechselkosten, Yoga