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The influence of hatha yoga on stress, anxiety, and executive functioning

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Abstract

Yoga is commonly practiced for its reported benefits on health, well-being, and cognition. Despite numerous studies exploring these effects, few have investigated the nexus between cognition and health, with even fewer utilizing randomization and/or a control groups. Therefore, we conducted a Randomized Controlled Trial with 98 subjects, building the backbone of this dissertation, to answer the questions whether practicing hatha yoga at least three times weekly over a period of eight weeks enhances executive functioning, and whether this effect was due to a potential decrease in measures of stress and/or anxiety, a direct result of improved executive control, or both. We used three experiments (two of which additionally employed electrophysiological measures) to operationalize executive functioning; physiological measures and self-report measures of stress- and anxiety-related variables were collected using an innovative ecological momentary assessment approach.

We found neither behavioral, nor electrophysiological evidence for changes in participants' switching function; instead, increased frontocentral theta activity and decreased mixing costs indicated that participants' ability to hold multiple task sets at the same time in mind improved, pointing to changes related to working memory functioning. Our experiment dedicated to investigating inhibitory control showed no effects of the intervention; however, increased modality-specific alpha power when attending visual and ignoring auditory stimuli (that is likely to represent inhibition of distracting visual input) speaks for increased inhibition through the intervention under conditions of high cognitive load. The intervention did lower levels of self-reported perceived stress and stress reactivity, and enhanced mindfulness, with individuals already high in trait mindfulness profiting the most from the stress-decreasing effects of the intervention. However, hatha yoga showed no effect on salivary stress biomarkers and self-reported measures of trait or state anxiety. Corroborating contemporary research, these outcomes point to improved psychological coping with stress due to the intervention, together with increased nonreactivity. Although evidence for a stress-mediated effect on executive functioning is merely correlational in the present dissertation, in which a role of relatively direct effects of yoga via increased executive control seemed more evident, an interaction between both of these mechanisms or principles cannot be safely ruled out. As the philosophy of yoga keeps telling us: Everything is connected.

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Introduction

1.1 The Science of Yoga

The ancient tradition of yoga has been present on our globe for thousands of years: Its origins date back to between 2,500 and 5,000 years ago, with the earliest known reference to yogic practices of meditation and discipline in the Rig Veda, written around 1,500 BC or earlier (Jamison & Brereton, 2014). The word yoga itself comes from the same root (yuj) as the English word yoke (Nayak & Shankar, 2004), and means "unification", directed towards a goal, in Sanskrit – representative for the connection of body, mind, and spirit (Muller, 2001), like a yoke of a chariot (the body) connecting it to the horses (senses and mind), with the spirit as the coachman (Pandurangi et al., 2017). The ultimate goal of unity, seen as the unification of all dimensions of our being with god, as well as the steps towards it, freeing us from the material world, are traditionally called yoga (von Brück, 2007); this process is extensively explained in the traditional Hindu scripture Bhagavad Gita, arguably one of the most important religious-philosophical works of Hinduism: During the process of yoga, the yogi aims to reveal the true nature of themselves through detachment from the outer world perceived through the senses (Pandurangi et al., 2017), which, in turn, helps to alleviate suffering (Feuerstein, 2011).

In the contemporary Western context, yoga is often recognized for its benefits to mental, emotional, and physical well-being, primarily through the practice of physical postures (*Asanas*). This emphasis on physical exercise, along with some elements of meditation (*Dhayana*) and breath control (*Pranayama*), has popularized yoga as a holistic health practice. While focusing on these aspects has made yoga accessible to a broader audience, it represents a departure from the traditional scope of yoga, which encompasses a system of ethical-moral teachings (Yamas/Niyamas) together with more diverse forms of breath regulation and meditation and the aforementioned Asanas, in the pursuit of one's "true self" (Feuerstein, 2011;

Gard et al., 2014). Thus, this shift in focus may not fully capture the depth and breadth of the ancient teachings of yoga as outlined in classical texts.

Nowadays, a key term to understanding yoga is mindfulness. Mindfulness, arising by nonjudgmental, nonreactive attention focusing on the present experience (Kabat-Zinn, 2003; Tang et al., 2015), is rooted in the Buddhist concept "sati" and its Sanskrit counterpart "smrti" (both of which can be translated as mindfulness). Originating in India between 600 and 400 BCE with the teachings of Siddharta Gautama, better known as Buddha (Conze, 1993), Buddhism shares a common cultural and philosophical background with other Indian religious traditions, such as Hinduism (Harvey, 2012); consequently, the concept of mindfulness closely aligns with the ancient teachings of yoga, as evidenced in Patanjali's Yoga Sutras, one of the foundational texts of yoga (Bryant, 2009). This perception — that yoga and mindfulness are closely related — is further reinforced by the way mindfulness has been popularized in the Western world. Notably, the programs of mindfulness-based stress reduction (MBSR; Kabat-Zinn, 1990) and mindfulness-based cognitive therapy (MBCT; Segal et al., 2002) have played a significant role. MBSR and MBCT, both integrating elements adapted from traditional Eastern philosophies and religions (meditation, yoga postures, breathing techniques) to a varying degree, have significantly contributed to the widespread view of yoga and mindfulness as interconnected concepts.

There is a vast amount of distinct yoga styles that have developed over the centuries and millennia since the first texts on yoga were written. Hatha yoga, today probably the most popular yoga style, is centered around various postures and breathing techniques that were originally intended to prepare the mind for meditation (Gard et al., 2014). The word hatha comes from "hath", meaning "to oppress" or "treat with violence", hence the meaning of hatha yoga can be seen as "the discipline of bodily exertion" (Larson & Bhattacharya, 2011). The origin of hatha yoga is somewhat unclear, but is often associated with Goraksha, the founder of the Natha movement in India combining ideas of Buddhism, Shaivism and Yoga, and his mentor Matsyendranathâ, who lived in the 10th or 11th century (Larson & Bhattacharya, 2011; but see Mallinson, 2013). However, the organization of hatha yoga into a coherent practice and philosophy came significantly later, with a crucial role of Svâtmârâma, who lived in the 14th century CE and is the author of the most influential hatha yoga manual, the *Hatha Yoga Pradipikâ* (Feuerstein, 2011). According to the Hatha Yoga Pradipikâ, the main goal of hatha yoga is to enable the mastery of the mind by purifying and controlling the body (Svâtmârâma, 2007). To achieve this goal, Svâtmârâma originally describes 16 postures (asanas), most of them variations of the cross-legged sitting posture and eight types of breath control along other purificatory practices. Svâtmârâma sees the roots of hatha yoga in three concepts: Ayurveda, the oldest known health system in the world (with the exercise of hatha yoga aimed to combat disease and achieve spiritual and physical health), in kundalini yoga (a form of yoga aiming to awaken the "serpent", Kundalini, that can be described as the power of creation in a person), and raja yoga (commonly seen as the yoga of the mind and its mastery). Raja yoga is a form of yoga already described by Patanjali in the Yoga Sutras (Bryant, 2009), aimed toward self-regulation and cognitive mastery, with its eight limbs (moral observances, physical postures, breath regulation, sensory withdrawal, meditation, concentration, and self-transcendence; Stone, 2009) included in Svâtmârâma's work. In the Hatha Yoga Pradipikâ, but also in other influential manuals like the Gheranda-Samhitâ and the Shiva-Samhitâ, hatha yoga is seen as a stairway to raja yoga (Feuerstein, 2011), here synonymous with samadhi, a state of pure realization, often associated with enlightenment: a boundless, infinite, divine experience, namely that of pure being, in which ego and consciousness dissolve (Shankman, 2008).

Over the centuries, hatha yoga has been increasingly integrated with other yogic paths like jnana yoga and bhakti yoga (Larson & Bhattacharya, 2011). In the early to mid-20th century, influential figures like Swami Sivananda, Swami Kuvalayananda, and his student Tirumalai Krishnamacharya were crucial in introducing yoga to Western audiences, with the latter two intermingling hatha yoga asanas with gymnastic exercises from the 20th century, leading to the development of a flowing style of yoga with less emphasis on spiritual goals (Singleton, 2010). Along with their followers, including K. Pattabhi Jois (ashtanga vinyasa yoga) and B. K. S. Iyengar (Iyengar yoga), they also developed unique approaches to the practice, further fragmentizing the teachings (Mallinson, 2011). Making hatha yoga appealing to a Western audience also posed challenges in maintaining its depth and integrity; this trend has contributed to the increased emphasis on the physical aspects of hatha yoga. The road from this point to the Western scientific community intending to capitalize on the popularity of (hatha) yoga was anything but long.

1.2 The Impact of Yoga on Executive Functioning

1.2.1 Executive Functions

While its effects on general health parameters, emotional states, and psychological and physiological well-being have been seemingly prioritized in contemporary studies, there has been an increasing amount of research on yoga's effect on cognitive functioning, acknowledging the fact that a functional mind is integral to one's well-being and that the cognitive and emotional effects of mindfulness practices, such as yoga, are intricately connected. Executive functions are effortful top-down cognitive processes used, for example, when employing automatic, instinctive, or intuitive processes does not constitute the best choice for a given task or when they are simply unavailable (Burgess & Simons, 2005; Diamond, 2013; Espy, 2004; Miller & Cohen, 2001). Current literature agrees on three core executive functions (Miyake et al., 2000): updating (often also called, somewhat generalized, working memory), inhibition (also called inhibitory control or suppression), and cognitive flexibility (also called [set] shifting). There are also several higher-order executive functions, like problem solving or planning, that are built from the three core EFs (Diamond, 2013). For example, planning requires working memory to keep the goal in mind, cognitive flexibility to adjust plans as needed, and inhibitory control to resist impulsive actions and distractions not aligning with the plan. In the following, I will address all three in a short overview, before showing how yoga could potentially affect executive functioning.

Updating involves the manipulation of information while holding it in one's mind, without it actually being perceptually present (Baddeley & Hitch, 1994). In order to achieve this, incoming information has to be categorized and then replaced with up-to-date information when outdated (Morris & Jones, 1990). Updating is separable from the other two factors (Miyake et al., 2000), although they work in close collaboration with each other, with, for example, shifting between distinct components of working memory being an important factor determining performance (Conway & Engle, 1996; Towse et al., 1998). At least two types of working memory can be distinguished: verbal and visuospatial working memory (Alloway et al., 2006). Sustained neural activity, often in higher cortical areas and especially widespread in the prefrontal cortex (PFC; Asaad et al., 2000; Roy et al., 2010), is often reported in behavioral experiments believed to utilize working memory (Miller, 2013). It does most likely reflect task demands and flexible adaptation to them, frequently prioritized over corresponding sensory information (Cromer et al., 2010; Rigotti et al., 2013). Separate networks in prefrontal cortex have been held responsible for the manipulation and holding of information (Eldreth et al., 2006). One common experimental protocol assessing updating is the N-back task (Kirchner, 1958), in which participants are presented with a sequence of stimuli (letters, numbers, shapes, etc.), and are asked to indicate whether the current stimulus matches the one that appeared N items before in the sequence.

The second executive function, inhibition, allows humans to not be prisoners of their impulses and habits, or strong environmental inputs alone. Salient stimuli generate a priority signal, calling for attention to be directed to them (Franconeri & Simons, 2003; Theeuwes, 1992, 1994; for a review of the literature, see Luck et al., 2021); however, if humans would attend to every potentially salient stimulus in the environment, or give in to their most pressing impulses every time (like the last time you watched that YouTube video instead of focusing on work, although you really wanted to), normal human functioning would become impossible and lives hard to manage by humans. Thus, it is the role of inhibition to sort out whether to yield or not to give in to a current inclination, enabling humas to prevent attentional capture, even in the face of a priority signal (Gaspelin & Luck, 2018a; Vatterott & Vecera, 2012).

These considerations imply at least three types of inhibition: attentional inhibition (essentially the flipside of selective attention), behavioral (or: response) inhibition, and cognitive inhibition. For example, attentional inhibition would, in best case, help you to ignore passing traffic on the road besides you when you walk safely on the pavement, while behavioral inhibition would hinder you to reflexively jump away from the cars coming down the street and roughly towards you. In addition, a third type of inhibition, namely cognitive inhibition, would help you resist unwanted thoughts about scenarios you can possibly imagine such as a driver on the street losing control of her vehicle to drive on the pavement (Anderson & Levy, 2009). Behavioral inhibition and attentional inhibition can be reduced to a single factor (called interference control; Diamond, 2016). In the experiments of the present thesis, I and my colleagues mainly focused on interference control. Interference control is commonly investigated by using a Stroop protocol, in which participants are presented with color words printed in congruent (word “red” printed in red) or incongruent (word “blue” printed in red) ink colors (Stroop, 1935), flanker tasks (Eriksen & Eriksen, 1974), involving the suppression of flanking stimuli adjacent to the target, or go/no-go tasks, all assessing the ability to withhold a response to some input (e.g. irrelevant word meaning) while responding to others (naming the word color; e.g., Van Royen et al., 2022; Wright et al., 2014).

In addition to these more traditional ways of measuring (mainly response) inhibition, attentional inhibition can also be investigated by utilizing either performance differences between trials with and without a to-be-suppressed salient distractor (as in the additional singleton protocol by Theeuwes, 1992), and, importantly for the current work, by electrophysiology. Here, increased alpha band (8-12 Hz) activity has been shown to be related to gating of sensory input, implying reduced processing in sensory areas (Zumer et al., 2014). Multiple studies have shown that lateralized alpha power, with a decrease contralateral to the unattended location, is a reliable indicator of suppressing (visual) input (e.g., Bauer et al., 2012; Foster & Awh, 2019; Haegens et al., 2011; Pomper & Chait, 2017; Romei et al., 2010; Thut et al., 2006). Besides the (time-)frequency domain, this can also be observed in the time domain through a positive deflection to a to-be-ignored stimulus in event-related potentials at electrodes over visual cortex contralateral (Gaspelin & Luck, 2018b), called distractor positivity (Pd; Hickey et al., 2009).

The third executive function is cognitive flexibility or shifting. Cognitive flexibility is the ability to adapt to changing task demands (Diamond, 2013; Kiesel et al., 2010). Cognitive flexibility is essential for changing the focus of attention from one object, modality, or point of view to another, utilizing distinct top-down control representations to aid the executive control of behavior and coordinate thoughts and actions in line with one's own objectives (Miller & Cohen, 2001). The shifting function is essential: Without it, we would not be able, for example, to return to writing an e-mail after we put heat on to boil water for our lunch, leaving behind angry colleagues eagerly awaiting our response. In the example, both of these tasks would require a distinct configuration of mental resources, also called a "task set" (Monsell, 1996), with both tasks requiring the selection and implementation of their fitting task set (Monsell , 2003) because there are an infinite number of possible actions we could undertake with the laptop and a pot of hot water, making executive control of our behavior necessary for our optimal functioning.

The ability to switch between distinct task sets is, in general, investigated in task-switching experiments (Allport et al., 1994; Jersild, 1927; Rogers & Monsell, 1995; Rubin & Meiran, 2005; for reviews, see Kiesel et al., 2010; Monsell, 2003). In in each trial of these experiments, participants carry out a specific task. Between trials, they may switch between two or more tasks that they have generally practiced beforehand (referred to as switch trials). In contrast, a fraction of all trials requires participants to repeat one and the same task in consecutive trials (repeat trials). Switching between task sets generally results in decreased performance (higher response times and/or error rates), called *switching costs*, compared to repeatedly utilizing the same task set. A second type of costs, *mixing costs*, are observed when comparing the performance of mixed-task blocks (blocks in which task switches occur) with that in single-task blocks (blocks without task switches). However, mixing costs are calculated for task-repetition trials only so as not to conflate them with switching costs. Mixing costs are thought to represent the overhead of maintaining multiple task sets in working memory, representing the effort needed to keep track of multiple task sets even without actually switching between them (Kiesel et al., 2010; Los, 1996; Rubin & Meiran, 2005).

Considerably fewer experiments have investigated the neural correlates of task switching. In a landmark study by Braver et al. (2003), utilizing functional magnetic resonance imaging (fMRI), switch trials compared to repeat and single-task trials led to activation of the left lateral prefrontal cortex, potentially reflecting a general role in task-set representation and response preparation (Gilbert & Shallice, 2002; Wylie & Allport, 2000), as well as left superior parietal cortex, covarying with switching-cost magnitude, potentially involved in switch-related reconfiguration processes. Switch blocks compared to single-task blocks led to sustained activation in right anterior prefrontal cortex, covarying with mixing-cost magnitude, thus, potentially reflecting increased cognitive demands. Looking at corresponding evidence in electrophysiology, a primary method used in this dissertation, many studies attributed a similar role to theta oscillations (4-7 Hz): Theta oscillations are involved in various processes relevant for task switching, like proactive executive control (Cunillera et al., 2012; van Driel et al., 2015; van Noordt et al., 2016, 2017), as well as updating or reactivation of working memory and task sets (Gladwin & de Jong, 2005; Itthipuripat et al., 2013; Karayanidis et al., 2009). However, there is also causal evidence in form of neurofeedback that upregulating theta activity in frontocortical areas decreases behavioral costs in task-switching protocols (Enriquez-Geppert et al., 2014). Complementary to increased theta power and connectivity, reduced alpha activity in switch compared to repeat trials has been observed in multiple studies, reflecting shielding of goal-relevant against distracting information (Dreisbach & Haider, 2008; Verstraeten & Cluydts, 2002), as well as memory retrieval (Barlow et al., 2018; Sauseng et al., 2006; Wolff et al., 2017). Multiple studies have also reported increases in parietooccipital alpha under high cognitive load, indicating suppression of irrelevant visual information and working memory content (Jensen et al., 2002; Klimesch, 1999; Tuladhar et al., 2007; for causal evidence using transcranial magnetc stimulation, TMS, see Riddle et al., 2020). These results and their implications are discussed in more detail in Chapter 3 of this dissertation.

1.2.2 Improving Executive Functioning Through Self-Regulation

However, while mindfulness practices incorporating movement (e.g., taekwondo and t'ai chi) show the strongest results among all approaches for improving executive functions (for an extensive review, see Diamond, 2020), this does not apply to yoga, with comparatively few studies finding positive (or mixed) results (Gothe et al., 2014, 2016, 2017; Hariprasad et al., 2013; Manjunath & Telles, 2001; Purohit & Pradhan, 2016; Phansikar et al., 2023), and a multitude of other studies finding no effects on core EFs at all (Bilderbeck et al., 2013; Blumenthal et al., 1989; Oken et al., 2006; Sharma et al., 2006). In particular, assessing inhibitory control often produced null results (Bilderbeck et al., 2013; Phansikar et al., 2023; Telles et al., 2013). In fact, the most recent paper among the above-mentioned, by Phansikar et al. (2023), reported null results on behavioral costs for both inhibition and task switching, while finding positive effects for working memory. A review by Gothe and McAuley (2015), including 15 studies (also some with low ecological validity), quantified the impact of yoga on executive functions as moderate ($g = 0.27$).

To date, there are hardly any studies that intelligibly link the potential benefits and mechanisms of yoga on executive functioning under one theoretical framework, systematically presenting possible mechanisms. One such framework can be derived from the work of Gard et al. (2014), who attempted to demonstrate and systematize the effects of yoga on health and cognition, with increased self-regulation as a central concept. Self-regulation is the ability to control diverse endogenous systems, including behavioral and psychological networks to meet environmental demands (Blair & Raver, 2014). Improved self-regulation through yoga can be attributed to various changes in the integration and efficiency of higher-order (e.g., central executive) and lower-order (e.g., autonomic systems) brain networks in cooperation with available sensory information (Chiesa et al., 2013). Focused attention on the asanas, while blocking out distractions, may play a crucial role in these changes. This process is complemented by regulated breathing during their execution (Mendelson et al., 2010). These practices engage the central executive and the frontoparietal attentional network, while inhibiting potentially maladaptive activity in other networks, such as the default mode network (Vincent et al., 2008). Together with explicit prompts during yoga lessons encouraging practitioners to switch their focus of attention (e.g., from one body part to another), these properties may contribute to increased cognitive flexibility and inhibitory control, two executive functions that are at the focus of this dissertation. Practicing yoga can also lead to developing a non-reactive awareness of the body's own sensations and thoughts, implying that rather by diminishing distraction beforehand, yoga can assist in becoming fully aware of such distractions (may these be thoughts, feelings, or sensations), without becoming excessively absorbed by them (Bishop et al., 2004; Kabat-Zinn, 2003).

A third pillar, beyond increased focal attention and improved emotional nonreactivity, through which increased self-regulation can contribute to better (executive) functioning, is the effect of yoga on stress and anxiety. For thousands of years, yoga has been said by thinkers to have positive effects on mental and physical health. Nowadays, a multitude of studies suggest that yoga is particularly effective in allowing humans to control and cope with stress (for findings pertaining mainly to physical yoga practice, see Tulloch et al., 2018; Yoshihara et al., 2014; for findings pertaining to both physical and pranayama practice, see Hewett et al., 2018; Park et al., 2017; for reviews, see Li & Goldsmith, 2012; Wang & Szabó, 2020), as well as decreasing anxiety (mainly physical yoga practice: McNamara et al., 2016; Shohani et al., 2018; Streeter et al., 2010; pranayama or both: Gupta et al., 2006; Khalsa et al., 2013; Nemati, 2013; for reviews, see Breedvelt et al., 2019; Hofmann et al., 2016). However, before further elaborating on how decreasing stress and anxiety may improve self-regulation and, thus, aid proper executive functioning, let us take a step back to first define what stress and anxiety are and what happens in the body when they are present.

1.3 Connecting the Dots: Yoga, the Stress Systems of the Body, and Executive Functioning

1.3.1 Mechanisms and Implications of Acute and Chronic Stress, and Anxiety

Stress arises when individuals perceive that they cannot cope with demands or threats placed on them (Lazarus, 1966). Imagine that your supervisor reminds you that you have to give a talk in front of the entire company in 30 minutes, a talk that you forgot is today. What happens in your body and mind during these 30 minutes?

First, the situation leads to a psychological stress response which is primarily cognitive (Thornton & Andersen, 2006): the event must be perceived as stressful to lead to stress. During the evaluation of the situation, you appraise the threat value of the presentation (primary appraisal), as well as your individual capacity to put up with the situation (secondary appraisal) (Lazarus & Folkman, 1984); the results of this process then determine the nature of the emotional response in reaction to the potential stressor (Lazarus, 1993) – in this case, you may start to feel anxious, because you fear failure and its consequences, but also angry towards your supervisor having put you in this situation in the first place. This can greatly vary based on your personality, past experiences, and available resources (Lazarus & Folkman, 1984). Subjective stress can not only be momentary (and by that, fluctuate over time), but also ongoing, involving a sustained feeling of being unable to cope over extended periods. This can be the case when you have the feeling that your supervisor is constantly trying to set a trap for you (possibly leading to a sustained perception of job insecurity), but also due to other long-term factors such as health issues diminishing your resources available to cope with acute stressors like the reminder about your upcoming presentation.

Based on the evaluation of the current situation, in case of a stressor being present, your body reacts using two distinct, but interrelated systems constituting the physiological stress response (Charmandari et al., 2005): the hypothalamic-pituitary-adrenal (HPA) axis and the autonomic nervous system (ANS), both of which closely interact with the immune system to maintain homeostasis (Nater et al., 2013; Sternberg, 2006). Before we take a closer look how these two systems influence your behavior and your physiological sensations, it must be mentioned that there are significant differences between individuals when it comes to the psychiobiological reactivity to stress (Boyce et al., 1995), with high stress reactivity potentially increasing the risk for an individual's health (Schlotz et al., 2011).

Along the HPA axis, acute stress triggers the secretion of corticotropin-releasing hormone (CRH) in the hypothalamus. This prompts the pituitary gland below the hypothalamus to release adrenocorticotropic hormone (ACTH) (Charmandari et al., 2005). ACTH then stimulates the adrenal glands on the top of each kidney to produce glucocorticoids (GC), in humans mainly cortisol, a stress hormone that, among other behavioral effects, increases glucose availability, suppresses the immune system, boosts metabolism, and increases attention and arousal (Herman et al., 2016; Katsu & Baker, 2021). These mechanisms are additionally mediated by GCs inducing the release of glutamate, an excitatory neurotransmitter, in several areas of the brain like the prefrontal cortex and the amygdala (Lowy et al., 1993, 1995). This can result in positive or negative cognitive effects, depending on the task. For instance, it has been repeatedly demonstrated that acute stress or the administration of GCs facilitates working memory performance (Henckens et al., 2011; Lupien et al., 2007). On a physical level, a rise in GC concentrations results in a decrease of the inflammatory/immune response, but also in increased blood pressure, heart rate, and respiratory rate (Chrousos & Gold, 1992), all helping (or in some aspects hindering) you to finish your presentation slides on time. Importantly, glucocorticoids also play a crucial role in the termination of the stress response by negative feedback on CRH and ACTH secretion to mitigate negative effects of sustained exposure to GC on reproduction, the immune system, but also on body composition (Christiansen et al., 2007; Chrousos & Gold, 1992; Habib et al., 2001). Cortisol follows a diurnal rhythm, with elevated morning levels and a peak 30-40 minutes after waking up, before decreasing swiftly in the hours following this initial surge. Levels continue to decline gradually until they reach their lowest point around the time of going to sleep (Adam & Kumari, 2009; Pruessner et al., 1997). Additionally, salivary cortisol levels exhibit relative peaks around 25-30 minutes after the occurrence of a stressor (Dickerson & Kemeny, 2004; Kirschbaum & Hellhammer, 2007), remaining elevated for a variable amount of time depending on the stressor and the individual. Richter et al. (1996) found that salivary cortisol levels were still elevated 1 h after a parachute jump, while the most commonly used paradigm to investigate psychobiological stress, the Trier Social Stress Test (Kirschbaum et al., 1993), showed similar results, with cortisol levels down to prestimulation values 90 min after exposure to a stressor. Thus, a while after you have held the talk, everything should go back to normal. To summarize, GC secretion as an end product of HPA axis activity constitutes a relatively slow, but also relatively long-lasting adaptive mechanism in reaction to a stressor.

GC levels can remain persistently elevated due to exposure to an inescapable stressor and in response to chronic stress, as revealed by animal studies (Brennan et al., 2000; Pickering & Pottinger, 1989). Elevated levels of cortisol in response to an acute stressor or as a result of chronic stress can directly impair prefrontal activity in the brain by binding to glucocorticoid and mineralocorticoid receptors, both of which can be found extensively in the prefrontal cortex (PFC), leading to reduced executive control (Lupien et al., 2007; Shields et al., 2016). Dopaminergic and noradrenergic processes within the PFC also seem to mediate stress-induced impairments in executive functioning (Arnsten, 1997; 2000; Arnsten & Li, 2005; Murphy et al., 2005). In addition, chronic stress can lead to structural and functional changes in the brain, particularly in the PFC, reducing its volume and disrupting its connections to other regions, thus, impairing proper executive functioning (Arnsten, 2009). While acute stress may facilitate certain cognitive functions by enhancing glutamatergic synaptic transmission in the prefrontal cortex and other limbic regions through the regulation by GCs, chronic stress is associated with a loss of regulatory abilities of both glutamate release and glutamate clearance (Popoli et al., 2011), leading to chronically elevated glutamate levels. For instance, Liston and colleagues (2009) could show that chronic psychosocial stress leads to increased switching costs in a paradigm measuring changes of the shifting function, as well as disrupted prefrontal connectivity. These changes constitute one potential mechanism accounting for the impairment of cognitive functions relying on prefrontal cortex due to chronic stress or glucocorticoid treatment (Liston et al., 2006; Young et al., 1999), potentially contributing to the pathophysiology of various psychiatric disorders.

Conversely to the mechanisms of the HPA axis, the autonomic nervous system functions akin to a sprinter when a stressor is present. Within seconds after your boss has said the dreadful words to you, you can feel their effect on yourself. The ANS is composed of two complementary systems, the sympathetic (SNS) and the parasympathetic nervous system (PNS) (Charmandari et al., 2005). The former is also responsible for the activation of the so-known "fight or flight" response, activated within seconds of perceiving a stressor (Sapolsky et al., 2000). In the course of this response, the ANS quickly releases various catecholamines (among which are epinephrine and norepinephrine) from the adrenal medulla, the inner part of the adrenal glands (Goldstein, 2010). This then leads to rapid physiological changes, such as increased heart rate, blood pressure, airway dilation, redirection of blood flow to essential muscles, and the mobilization of energy stores, preparing the body for an immediate reaction to a potential threat (Cannon, 1914, 1915, 1932; McCarty, 2016). The PNS can counteract these effects caused by the SNS by enhancing its activity but can also serve as an amplifier of sympathetic effects by decreasing its activity (Chrousos, 2007; McEwen, 2007; Thayer & Lane, 2000). While SNS activation can be measured in distinct ways (e.g., through heart rate monitoring, skin conductance measurements), salivary alpha-amylase (sAA) constitutes a reliable and easily attainable indicator of SNS activity (Nater & Rohleder, 2009; Speirs et al., 1974). A study by Ehlert et al. (2006), during which the authors used yohimbine injections to trigger sympathetic nervous system activity, proposed that fluctuations in sAA levels reflect the interaction between sympathetic and parasympathetic activation, mediated by adrenergic mechanisms. sAA, like cortisol, follows a distinct diurnal rhythm, with sAA levels dropping sharply in the first 30 min of awakening before steadily rising until bedtime (Nater et al., 2007). Persistently elevated or reduced sAA levels are often present in patients with major depressive disorder (Bauduin et al., 2018; Jezova & Herman, 2020), anxiety disorders (van Veen et al., 2008) and somatic diseases, with ANS dysfunctions being a potential link between both (Xu et al., 2018).

High correlations have been reported between sAA and state anxiety levels (Noto et al., 2005; Takai et al., 2004). Anxiety represents a complex emotional state, influenced by the interplay of internal psychological dynamics and external situational stressors impacting an individual; it is further characterized by both physical (described above) and mental symptoms, like feelings of tension, worry, and heightened SNS activity (Spielberger, 1966; VandenBos, 2007); anxiety can be distinguished by fear, with the former focused on anticipation of future, diffuse dangers (corresponding to a state of uncertainty), while the latter being a reaction to a known or immediate threat.

Two aspects of anxiety can be distinguished: state anxiety and trait anxiety; state anxiety reflects the immediate emotional, cognitive, and physiological response to perceived threats, while trait anxiety is a rather stable aspect of one's personality predisposing the affected individual to experience state anxiety. Persons more prone to experience an anxious state are referred to as high in trait anxiety, leading to a differentiation between trait and state anxiety (Spielberger, 1971).

Anxiety can be both adaptive (for instance, by improving the ability to detect and counteract looming danger) and maladaptive (e.g., by leading to rumination about negative life events) (Robinson et al., 2013). The implications of anxiety are profound, affecting various cognitive processes and behavior. Anxiety biases the attentional system towards a more reactive setup, preparing for imminent danger (Bar-Haim et al., 2007; Eysenck et al., 2007), by increasing sensitivity for sensory input and, thereby, impairing goal-driven task performance (Bishop, 2009; Pacheco-Unguetti et al., 2010). During states of high anxiety, as well as in patients with anxiety disorders (such as generalized anxiety disorder and panic disorder), some cognitive functions (e.g. long-term memory and decision making) are typically enhanced to adapt the organism to the potential occurrence of a threat (Clark et al., 2012; McNally et al., 1989; Mueller et al., 2010), while others, like visuospatial working memory, are impaired (Boldrini et al., 2005; Shackman et al., 2006) – the latter most probably due to an overlap in prefrontal structures devoted to both anxiety and short-term memory processes and the effect of stress hormones on them (Robinson et al., 2013).

1.3.2 Improving Executive Functioning by Reducing Stress and Anxiety

By mitigating the negative effects of stress and anxiety, yoga can increase self-awareness and quality of life (Akdeniz & Kaştan, 2023), a characteristic that is becoming increasingly important in our fast-paced world. By focusing on deep breathing during yoga, the control of the parasympathetic nervous system is strengthened, improving self-regulation (Vempati & Telles, 2002; Zaccaro et al., 2018), one potential variable for decreasing perceived stress (although it has been argued that other variables positively influenced by yoga, such as increased mindfulness, interoceptive awareness, self-compassion and spiritual wellbeing, may rather contribute to decreased stress and stress reactivity than self-regulation; Park et al., 2021). It has also been shown that mindfulness training increases goal-driven regulatory activity of the prefrontal cortex (Hölzel et al., 2013) while reducing reactivity in the amygdala, the anterior cingulate cortex, and the hypothalamus (Ulrich-Lai & Herman, 2009) – all regions associated with increased emotional processing –, ultimately leading to reduced cortisol secretion (Carlson et al., 2003; Matousek et al., 2010; but cf. Gex-Fabry et al., 2012) and stress reduction (Wager et al., 2008).

Both physical and emotional stress and anxiety are assumed to negatively affect self-regulation (Gard et al., 2014), as well as core executive functions (Berggren & Derakshan, 2013; Derakshan & Eysenck, 2009; Liston et al., 2009; Shields et al., 2016): Attentional Control Theory (Eysenck et al., 2007) states that anxiety impairs inhibitory control and the shifting function, while a meta-analysis by Shields and colleagues (2016) found detrimental effects of stress on working memory and shifting, but more nuanced effects on inhibition. Yoga has the potential to counter these adverse effects via its aforementioned effects of increased parasympathetic activity and nonreactivity to distracting input. Decreased stress and anxiety levels, in turn, can liberate resources for executive control, otherwise occupied with distressing contents of the mind (Folkman et al., 1986; McRae & Gross, 2020), which can lead to further decreased levels of stress and anxiety through a greater sense of control in a given situation. Gothe et al. (2016) found that self-reported stress and anxiety levels predicted performance on several executive function tasks (n-back task, task switching paradigm, running span task). This result is consistent with findings by Gothe et al. (2014; 2016; 2017) and Purohit and Pradhan (2016), as well as Voss et al. (2023), who attribute the improvements in cognitive performance to improvements in stress regulation, as well as increased efficiency of neurocognitive resources (although their findings are restricted to older adults).

Thus, we hypothesized that an eight-week hatha yoga intervention would not only decrease levels of self-reported stress, stress reactivity and anxiety, as well as levels of the measured stress biomarkers salivary cortisol and alpha-amylase, but also increase the ability of participants to inhibit task-irrelevant stimuli and to switch between distinct tasks and modalities more efficiently. We focused on these two core executive functions based on findings obtained by Attentional Control Theory, even though we believe that our results have meaningful implications for the updating function as well. We wanted to know whether these effects on executive functioning can be related to (or are mediated by) decreased stress levels, or rather reflected effects that have to do with the direct (if far) transfer of abilities from the yoga intervention, such as the controlled deployment of attention.

1.4 Chapter Overview

Each of the following three chapters consists of an original manuscript that focuses on a subtopic of the interventional study, which forms the backbone of this dissertation. Chapter 2 describes the effects of our hatha yoga intervention on self-reported stress, anxiety, and mindfulness levels, while also examining potential changes in inhibitory control using electrophysiology. Chapter 3 focuses on the effects of our intervention on the shifting function using electrophysiological and behavioral evidence from two experiments: The first experiment focused on the question whether yoga improves the ability to switch between distinct feature representations (here: the colors green and red), while the second experiment investigated if frequent switching between distinct objects of attention successfully transferred to the ability to efficiently switch between distinct (here: the auditory and visual) modalities. The final manuscript involved in Chapter 4 of this dissertation aims to demonstrate whether our intervention successfully decreased biological markers of stress, salivary cortisol and alpha-amylase, together with perceived momentary stress levels. For this, we used an ecological momentary assessment (EMA) approach (Trull & Ebner-Priemer, 2013), with participants reporting their momentary stress levels on a visual analogue scale (VAS) at the time of salivary assessment (five times per day, for three days before and after the intervention) to achieve a high correlation between both dimensions of measurement. The general discussion aims to summarize the main findings and connect the links between stress-related variables and executive functions, providing a comprehensive interpretation of our findings, while outlining open questions remaining to be solved by future studies. At the beginning of Chapters 2-4, the publication status of the respective manuscript indicates if it is under revision, meaning that the final, published version might deviate from the version contained in this dissertation.

2

The Influence of Hatha Yoga on Stress, Anxiety, and Suppression: A Randomized Controlled Trial

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Results of this manuscript were presented in a talk at the European Conference of Visual Perception (ECVP) 2023 in Paphos, Cyprus, as well as a poster presentation at the 3rd Stress and Cognition Summer School in Nijmegen, Netherlands in 2023.

Abstract

Engaging in yoga may mitigate stress and anxiety in individuals while potentially enhancing one's capacity to manage distractions. Our research aimed to explore the relation between these two outcomes: Can an eight-week yoga program foster distraction suppression, thereby reducing stress and discomfort? To answer this question, we used hatha yoga, the most commonly practiced form of yoga. We tested if the intervention improved participants' ability to suppress distractions and selectively decrease self-reported stress and stress reactivity. In Addition, we investigated whether such an intervention would increase participants' mindfulness. Our study included 98 healthy yoga novices between 18 and 40 years who were randomly assigned to either an experimental or a waitlist condition, with each participant completing pre- and post-intervention assessments, including questionnaires, as well as electrophysiological and behavioral measures. After eight weeks of yoga practice, significant reductions in self-reported stress and stress reactivity levels, as well as increased mindfulness, were observed among those participating in the intervention relative to those in the waitlist control group. There were, however, no significant changes in state or trait anxiety due to the intervention. Changes in stress measures could not be explained by changes in participants' ability to suppress distractors, which was not affected by the intervention. Overall, our findings suggest that regular participation in hatha yoga can improve mental health outcomes without impacting cognitive functioning directly related to distractor suppression.

Keywords: anxiety, mental health, mindfulness, proactive inhibition, stress, yoga
Clinical trial registration number: NCT05232422

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Introduction

The Effect of Yoga on Stress and Anxiety

Yoga is a collective term that describes a group of physical, spiritual, and mental practices of Indian origin (Büssing et al., 2012). It can contribute to increased mindfulness, defined as a nonjudgmental focus of attention on one's present experience (Tang et al., 2015). In recent decades, yoga has become increasingly popular in Western societies, with a particular focus on yoga poses (*asanas*).

Yoga is often practiced for its beneficial health effects. In the present study, we focus on two: its potential to reduce anxiety and its ability to decrease stress (e.g., Breedvelt et al., 2019; Gallegos et al., 2017; Pascoe & Bauer, 2015). Anxiety is defined as "an aversive emotional and motivational state occurring in threatening circumstances" (Eysenck et al., 2007, p. 336), while psychological stress is defined by Lazarus and Folkman (1984, p. 19) as "a particular relationship between the person and the environment that is appraised by the person as taxing or exceeding his or her resources and endangering his or her well-being." Both states or responses can either be of a more transitory or of a more sustained nature. More specifically, one's current experienced level of anxiety (*state anxiety*) is a product of situational stress and *trait anxiety* (an individual's stable tendency to experience negative emotions (Eysenck, 1992; Gidron, 2013)); stress can either be acute (experienced as a direct consequence of a stressor) or, mainly as a result of long-term physiological and psychological changes, chronic (e.g., Marin et al., 2011; Rohleder, 2019). Stress and anxiety can also negatively affect physical and mental health and well-being (e.g., Glaser & Kiecolt-Glaser, 2005; Swinbourne & Touyz, 2007). The potential stress-decreasing effect of yoga might also be related to individual levels of trait mindfulness, the inherent ability to attend and experience the present moment (Brown et al., 2007), with individuals showing higher trait mindfulness levels experiencing lower amounts of stress (Lu et al., 2019).

Yoga and Executive Functions

At the same time, yoga may influence executive functions in a positive way (e.g., Diamond & Lee, 2011; Gothe et al., 2013; Luu & Hall, 2016). In this context, executive functions typically denote the mental abilities associated with the control of (human) information processing, such as suppression, shifting, and updating functions (Miyake et al., 2000), where suppression is responsible for the inhibition of distracting information (e.g., ignoring the sound of the vacuum cleaner while reading a book) while shifting allows voluntary switches between tasks (e.g., stopping to look for an exit sign in an unknown airport at which you just arrived, and turning to the digital map in your smartphone), and updating would be necessary to replace outdated task-related information by currently relevant one (e.g., noticing that the last two kids that dropped by your daughter's birthday party were Gene and Tyrone so that only Sarah would still be expected to arrive before you can serve cake). This is interesting, as lowered anxiety and stress levels due to yoga may be related to improved cognitive functioning (e.g., Gothe et al., 2016).

For example, practicing yoga involves paying attention to one's breath, physical sensations, and thoughts and feelings as they arise, without judgment (Mendelson et al., 2010). This might support an individual's ability to focus on task-relevant features and stimuli selectively, thus potentially helping to suppress and reduce the influence of unwanted distraction willingly (Gard et al., 2014; Lutz et al., 2008). In more general terms, according to Attentional Control Theory, anxiety decreases processing efficiency in two of three executive functions, inhibition and shifting (cf. Derakshan & Eysenck, 2009), the idea being basically that the regulation of anxiety corresponds to a task in itself, leaving less cognitive capacity to handle other executive tasks. To the extent that yoga decreases trait anxiety or ongoing stress levels, it would, thus, also liberate resources to handle executive tasks (and improved executive functioning further alleviating stress and anxiety through improved self-regulation, e.g., Folkman et al., 1986; McRae & Gross, 2020). In the current study, we wanted to understand if a yoga intervention improves suppression as one primary executive function, and if such an improvement goes hand in hand with a reduction of experienced anxiety and stress, a correlation predicted by several theories and findings.

Attentional Suppression

The ability to selectively attend to relevant information while suppressing irrelevant information is crucial for everyday functioning. Attentional suppression is the ability to minimize or block out interference from processing task-irrelevant or distracting information to focus on relevant input (Coombes et al., 2009; Wöstmann et al., 2022). In the current study, we were interested in understanding the relationship between suppression, anxiety, and stress. To start with, behavioral findings show that a salient singleton can lead to distraction and automatically attract spatial attention, even if irrelevant to the current task (e.g., Jonides & Yantis, 1988; Theeuwes, 1992). Here, salience is defined as the local feature contrast between an object and adjacent objects or even the background (e.g., in vision, in terms of color, luminance, or line orientation; cf. Itti et al., 1998), and a singleton would be an object standing out by one of its features (e.g., its color) among several more similar nonsingletons (e.g., one green apple in a bowl of red apples; cf. Bacon & Egeth, 1994).

Notably, in the context of the present study, it has been shown that this type of attentional capture can be prevented, given supporting circumstances. For example, once an observer has established an attentional control set (e.g., to search for a target by one particular target-defining feature in a goal-directed fashion; Folk et al., 1992), irrelevant singletons that do not match the control set (e.g., that do not carry the searched-for feature) do not seem to capture attention anymore and can be proactively suppressed by downweighting signals converging to the attentional priority map (e.g., Gaspelin & Luck, 2018b; Goller et al., 2020; see Luck et al., 2021, for a review).

In many behavioral studies, where participants search for a pre-defined target, slower response times (RTs) in trials with an additional singleton distractor presented away from the visual target are taken as direct evidence for the capture of visuospatial attention by the irrelevant singleton (e.g., Gaspelin et al., 2015; Theeuwes, 1992). Conversely, if the singleton distractor is proactively suppressed, no RT differences are expected between distractor-present and distractor-absent conditions. Additional evidence for suppression and attentional capture comes from electrophysiological, magnetoencephalographical, and brain stimulation studies. Many have shown that increased alpha power (as well as its lateralization) is related to suppressing unattended stimuli (e.g., Haegens et al., 2011; Pomper & Chait, 2017; Romei et al., 2010).

In neurophysiological studies on event-related potentials (ERPs), suppression is often indicated by an ERP called *distractor positivity* (*Pd*), a posterior positive deflection at electrode sites contralateral compared to ipsilateral to the suppressed visual stimulus (Hickey et al., 2009). The Pd appears 100-400 ms after stimulus onset (Hilimire et al., 2012; Sawaki et al., 2012) and is essentially the result of the lateralization of alpha oscillations in occipital cortex, indicating proactive suppression. It thereby serves as an easily measurable indicator of distractor suppression. Conversely, attentional capture is indicated by another ERP called *N2pc*, a more negative deflection contra- than ipsilateral to an attended-to visual stimulus appearing 200-300 ms after stimulus onset at occipital electrodes (Eimer, 1996; Hickey et al., 2006).

Hypotheses

In the current study, we used a yoga intervention and a passive waiting-list control group to test whether yoga decreases anxiety and stress levels, increases suppression, and to study whether the two effects are related. We were also interested in whether higher levels of trait mindfulness before the intervention led to an additional decrease in participants' stress levels. For our test, we used a passive control condition to increase the likelihood of finding any beneficial effects of the intervention (cf. Breedvelt et al., 2019). We used a randomized controlled trial, including an eight-week hatha yoga intervention. Hatha yoga is the most commonly practiced form of yoga and includes stretching exercises, postures, and mindful breathing (Shapiro et al., 1998). We decided to specifically focus on hatha yoga for two critical reasons: First, due to its physically oriented nature and by focusing less on meditative aspects than common mindfulness-based interventions, it provides reliable separation from those practices; and second, due to its popularity, we expected facilitated recruitment of participants.

Materials and Methods

Participants

We used a shortened online version of the Diagnostic Interview for Mental Disorders (Mini-DIPS; Margraf, 1994) to screen potential participants for any existing or past psychological or psychiatric disorders, which served as an exclusion criterion. We also excluded participants if they were below 18 or over 40 years old (aiming to minimize potential confounding effects of age-related cognitive decline), if they practiced yoga more than twice a month in the past 12 months before the study, if their German level was below C1, they had an uncorrected visual or hearing impairment, or a skull fraction/concussion within the past six weeks, or if they did not provide a COVID-19 recovery or vaccination certificate.

Using G*Power (version 3.1, Erdfelder et al., 1996), we aimed for a sample size of 102 participants to achieve 80% power with d = 0.5 and an alpha error probability of .05. These calculations were based on the method with the potentially lowest power, namely the questionnaires, while EEG and behavioral measurements would have needed a sample size of 70 for 80% power due to the high number of trial repetitions (Brysbaert, 2019). Our expected effect size was based on previous studies examining yoga's effects on stress and anxiety (Della Valle et al., 2020; Pascoe et al., 2017). We started recruiting in November 2021 (for Cohort 1) and finished recruiting in April 2022 (for Cohort 2) via social media advertisement, as well as the participant recruiting systems of the University of Vienna. All participants were briefed in written and oral form and signed an informed consent before participating. They also received detailed written debriefing after their participation had ended. We recruited 116 participants, out of which 98 (54 intervention, 44 control; 83 female; M_{Age} = 25.03 years; SD_{Age} = 4.18 years; range 18-40 years;) were part of the study as the intervention started.

Study Design

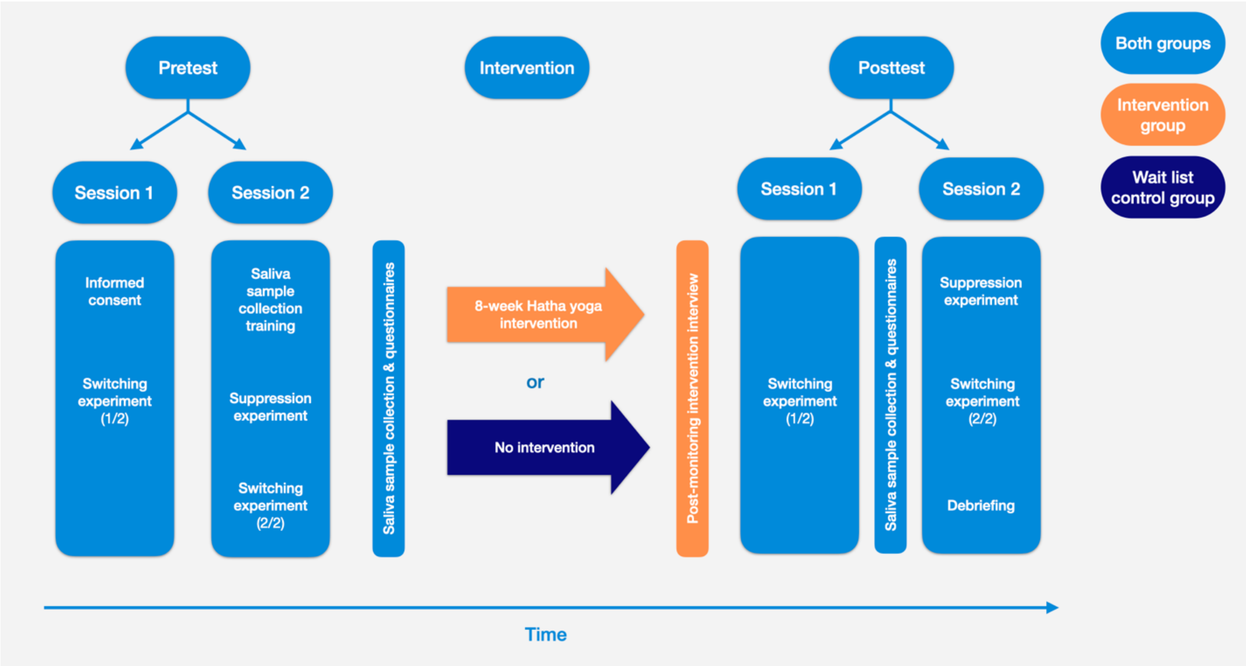
The results reported in this paper are part of a larger interventional study using a parallel design, including three experiments – one on inhibition and two on shifting. In the present manuscript, we focus on the effects of the intervention on stress, anxiety, and its potential relation to inhibition. In contrast, the effects on shifting are discussed in a second manuscript (currently under review). Nevertheless, we report characteristics of the study design for the entire study to allow readers to relate our current work on inhibition to the overarching framework of the study. Figure 1 shows all elements of the study in their full scope.

We divided participants into two roughly equally sized cohorts with different start dates. Data collection began in January 2022 and ended in August 2022. Members of each cohort had to follow the same procedure. Every participant had to complete two pretest and posttest sessions at the University of Vienna. After the first pretest session, participants were randomly assigned to a group using block randomization (block size: 4) using custom Python scripts by research team members. Members of the research team did enrollment and interventional assignment. During pretests (posttests), we instructed participants to fill out a series of online questionnaires, described below, assessing ongoing stress, trait and state anxiety, and trait mindfulness within a week after their second pretest (posttest) session. They were also required to collect saliva five times a day (immediately after waking up, 30 min after waking up, at 11 AM, 2 PM, and 7 PM) for three consecutive days each for pretest/posttest measurements to measure cortisol and alpha-amylase. Results from the analyses of these biomarkers will be reported in a follow-up manuscript assessing the switching function.

The intervention group (IG) received an eight-week hatha yoga course. The control group (CG) did not receive an intervention during this period; however, to counteract potentially harmful (psychological or physiological) effects resulting from members of the CG not being able to participate in the intervention, we invited them to participate in the eight-week intervention once posttests for both IG and CG were concluded. By this, we ensured that both groups sufficiently profited from the intervention. Participants were financially compensated with 30 EUR per measurement and could earn a 20 EUR bonus if they participated, on average, at least four times per week in the intervention. In addition, the intervention was free of any cost for the participants.

Figure 1

Study Design



Note. Participants completed two pretest and posttest appointments each. Tasks completed by both groups, yoga intervention and passive control, are colored light blue; tasks completed by only the intervention group (IG) are colored orange, while tasks completed by only the control group (CG) are colored dark blue. Members of the IG received an eight-week hatha yoga intervention after the pretests, while the waitlisted CG received no intervention in this time. During pre- and posttests, participants had to complete three experiments assessing inhibition and shifting functions, questionnaires measuring stress, anxiety, and mindfulness; they also had to collect saliva samples to assess cortisol and alpha-amylase.

Intervention

We employed four trained yoga instructors to guide the eight-week course at a yoga studio ($M_{\text{Job Experience}}$ = 4.00 years; $SD_{\text{Job Experience}}$ = 1.15 years; range 3-5 years of job experience). We asked participants to join the sessions at least three times a week (leading to an average participation of 2.55 sessions per week (SD = 0.55) and excluded them if they did not participate at least twice for three consecutive weeks. To ensure consistency, the instructors were jointly briefed by the experimenters and followed a strict program designed by the yoga instructors in cooperation with the research team. Each week, the sessions had a different focus, outlined in Table 1. While this weekly focus, as well as some of the key exercises was set commonly by the instructors and the research team, the instructors were still provided with the necessary freedom to implement modifications to a certain degree where the overall achievement of class objectives and inter-instructor comparability were not jeopardized. Yoga classes were also spot-checked by experimenters to ensure that protocols were followed. Participants could attend a maximum of five sessions per week, held eight to nine times a week (in the morning and late afternoon/evening). Attendance was recorded. Each 60-min session consisted of 5 to 10 min of warm-up exercises, 40 to 50 min of asanas, and 5 to 10 min of *savasana* (relaxing while lying flat on the back).

After the intervention ended, the instructors were asked to fill out the Essential Properties of Yoga Questionnaire, which consists of 62 items with a Cronbach's alpha of 0.70-0.90 (Grössl et al., 2015). This helped us to ensure a proper characterization of the intervention. The items were rated on a scale of one (not at all) to five (to a substantial amount), with higher scores indicating a higher level of mentioning/inclusion of the corresponding yoga element. Our analysis focused on five critical components assessed in the questionnaire: Acceptance/compassion, breathwork, physicality, body awareness, and meditation/mindfulness. While acceptance/compassion and meditation/mindfulness are considered classic components of mindfulness-based interventions in general (Kabat-Zinn, 2015; Park et al., 2021), breathwork, physicality, and body awareness are more specific to hatha yoga (Shapiro et al., 1998).

According to the outcomes of the EPYQ filled out by our yoga instructors (N = 4), breathwork, M = 4.28, SD = 0.61, 95% CI [3.03, 4.97], body awareness, M = 4.00 [3.25, 4.75], SD = 0.47, 95% CI [3.25, 4.75], as well as acceptance/compassion, M = 3.85, SD = 0.72, 95% CI [1.85, 4.15], were moderately-to-largely included in our eight-week hatha yoga intervention. In contrast, meditation/mindfulness, M = 2.96, SD = 0.95, 95% CI [1.45, 4.77], as well as physicality, M = 2.94, SD = 0.52, 95% CI [2.11, 3.77], were a moderate part of the intervention.

Table 1

Focus of Yoga Sessions per Week and Exemplary Asanas (Yoga Postures)

Week	Focus	Exemplary Asanas
1	Sun salutation, breathing exercises	Downward Facing Dog, Cobra Pose, Sprinter Pose
2	Standing positions	Warrior I and II, Triangle Pose, Chair Pose
3	Forward Bends	Different variations of Forward Bends, Pigeon Pose, Butterfly Pose
4	Twists	Waist Turn, Crocodile Pose, Twisted Triangle Pose
5	Backbends	Shoulder Bridge, Locust Pose, Bow Pose
6	Sitting poses	Lotus positions, Boat Pose, Child Pose
7	Balance	Tree Pose, Warrior III, Crow Pose, Half Moon Pose
8	Combining focuses 1-7	Combinations of the previous exemplary asanas

Note. Each week of the hatha yoga intervention, comprising a total of eight weeks, a different focus was set, determining the practiced asanas (yoga postures) of that week. This focus had to be applied by all yoga teachers when teaching their respective individual yoga sessions.

Questionnaires

Measures

We used the German version of the Perceived Stress Scale (PSS-10; Schneider et al., 2020) to assess subjective stress levels within the past month, with higher scores indicating higher levels of perceived stress. Stress reactivity was measured with the German version of the Perceived Stress Reactivity Scale (PSRS; Schlotz et al., 2011), a scale commonly used to track perceived stress reactivity in longitudinal studies. Trait and State Anxiety were measured with the German version of the 20-item State-Trait-Anxiety-Inventory (STAI) – Form Y (Grimm, 2009). We converted raw values to a scale from 0 to 100 to ensure comparability to other test values, using the formula: Comparable $value_{Trait/StateAnxiety}$ = (Raw $value_{Trait/State\ Anxiety}$ – 10) × 100/ 70. The STAI – Form Y can validly distinguish anxiety from depression and has been reported as a sensitive measurement for detecting changes in state anxiety in longitudinal settings (Schneider et al., 2016). Finally, trait mindfulness levels were assessed by the short version (14 items) of the Freiburg Mindfulness Inventory (FMI; Walach et al., 2006), particularly sensitive to changes in trait mindfulness and well-applicable for mindfulness novices. We also asked participants to complete the Patient Health Questionnaire (PHQ) at baseline to characterize the sample. We also collected data regarding potential control variables listed in Table 2, looking for existing group differences. Only if significant differences between groups were found would we have included the variable(s) in question as control variables in an Analysis of Covariance (ANCOVA). No such differences were found (all *p*s > .136).

Table 2

Control Variables

Control Variable	Scale
Sleep	Pittsburgh Sleep Quality Index (PSQI)
Resilience	Resilience Scale RS-11 (RS-11)
Social Support	Berlin Social Support Scales (BSSS)
Depressiveness	Beck Depression Inventory Revision (BDI-II)
Self-Compassion	The Self-Compassion Scale (SCS)

Note. Depicted are all potential control variables analysed for preexisting differences between groups.

Data Analysis

For data analysis of questionnaires, we used RStudio (Version 1.4.1717; RStudio Team, 2021) with R (version 4.1.2; R Core Team, 2021). The most critical packages used were data.table (Version 1.14.2; Dowle & Srinivasan, 2021), ez (Version 4.4.-0.; Lawrence, 2016), schoRsch (Version 1.9; Pfister & Janczyk, 2020), and tidyverse (Wickham et al., 2019).
We analysed data from 74 participants (64 female; M_{Age} = 24.95 years; SD_{Age} = 4.48 years; range 18-40 years), out of which 34 were members of the intervention group. Participants who did not complete entire pre- or posttest questionnaires were excluded from the analysis (for reasons regarding this per-protocol approach, see 4.3).

Still, data of participants who failed to provide answers to single questionnaires was included: We treated each index independently from the others. All data was missing completely at random, as identified by Little's test (Little, 1988), all ps > .501. Missing data was replaced by first performing regression imputation fitting a statistical model based on the observed data on variables with missing values (e.g., de Waal et al., 2011; Zhang, 2016), then substituting missing values by predictions of the regression models. For all questionnaires, we excluded participants if their mean score per measurement was lower than the first quartile of all mean scores minus 1.5 times the interquartile range (IQR) or higher than the third quartile of all mean scores plus 1.5 × IQR.

We conducted mixed analyses of variance (ANOVAs) for each outcome variable with the within-participant independent variable *Measurement* (pretest/posttest) and the between-participants independent variable *Group* (intervention/control), followed up by planned comparisons (one- or two-sided *t*-tests, depending on the existence of directed hypotheses). We also report inclusion Bayes Factors (BF_{incl}) for our ANOVAs and Bayes Factors in favor of the alternative hypothesis (BF_{+0}) for our *t*-tests. The inclusion Bayes Factor can be interpreted as evidence in the data for including a specific predictor in the model (Hinne et al., 2020).

We also performed regression analyses for each significant effect of hatha yoga on the regarding outcome. Our regression models included the predictors' pretest measurement, trait mindfulness at pretest (preTM), and the interaction between both, with posttest measurement as the dependent variable. We were interested in whether including preTM in the model leads to a significant interaction, implicating a moderating role of preTM. We additionally calculated simple slopes at low ($\leq M - 1\ SD$), average, and high ($\geq M + 1\ SD$) preTM values for significant or marginally significant interactions using the Johnson-Neyman technique (Johnson & Neyman, 1936); regions of significance were calculated by identifying points on the continuous moderator preTM at which there was a significant relationship between independent and dependent variables (Hayes & Matthes, 2009; Johnson & Fay, 1950). To determine effect sizes, we used β coefficients; $\beta > 0.1$ indicates a small, > 0.3 a medium, and > 0.5 a large effect. Participants who did not complete entire pre- or posttest questionnaires were excluded from the analysis.

Suppression Experiment

The ability to suppress irrelevant distractor stimuli was assessed by an experimental task designed initially by Sawaki and Luck (2010; Experiment 4). Being one of the particularly often-cited experiments to show reliable electrophysiological evidence for proactive suppression of irrelevant singletons, it is well suited to examine between-group differences in suppression. This protocol has the additional advantage of allowing to separate electrophysiological evidence for attentional capture from proactive suppression. By incorporating both behavioral and electrophysiological markers of inhibition, the task measures the capacity to inhibit visual distractors relatively exhaustively.

Experimental Procedure, Apparatus, and Stimuli

Visual stimuli were presented on a 19″ CRT monitor (Sony Multiscan) with an aspect ratio of 4:3, a resolution of 1280 × 1024 pixels, and a refresh rate of 100 Hz. The experiment was presented via OpenSesame (Version 3.3.10; Mathôt et al., 2012). Participants sat in front of the monitor in a soundproof, dimly lit room. The distance between their eyes and the screen was kept constant at 57 cm by a chinrest. Participants responded with a conventional QWERTZ keyboard.

Participants had to indicate by keypress whether a predefined letter (which varied from block to block) was present. Uppercase letters (four in the upper, four in the lower white rectangle) appeared in each stimulus array for 200 ms, with the interstimulus interval varying between 800 and 900 ms. Figure 2 shows the target display, with an example for every experimental condition (or each step of the independent variable). For each block, a letter of a specific identity and size (large or small) was defined as the target from nine potential letters (e.g., a large letter *O*). We instructed participants to maintain fixation on the central cross and to press the “down arrow” key as soon as they detected a target. Participants were asked to refrain from pressing any key if a target was absent. Instructions stressed both speed and accuracy equally.

Stimuli were shown on a black (CIE L*a*b*, 7.8/22.7/−27.4) background. Participants had to fixate on a white (98.9/15.6/−52.9) cross at the center of the screen, which remained on the display until the end of the experimental block. Additionally, two white rectangles (18.5° wide x 3.5° tall), centered 4.5° above and below the fixation cross, were always present during blocks. The set of letters for selection per each display contained the letters *A*, *H*, *I*, *M*, *O*, *T*, *U*, *X*, and *Y*, chosen based on their symmetrical features to prevent any lateralization of event-related potentials (ERPs). In each stimulus array, two small (1.6° wide, 2.0° tall) and two large letters (2.0° wide, 2.5° tall), with randomized positions within each array, were placed within the white rectangles. The center of the letters was positioned 2° and 6° to the left and right of the vertical midline, and 4.5° above and below the horizontal midline. Letter identities and sizes varied randomly across trials, with the constraint of the number of small and large letters within each rectangle (see below). Letters could be red (56.6/70.4/51.6) or green (57.5/−67.7/49.4). Each of the nine letters in the two sizes served as a target two times, presented in randomized order. In 50% of all trials, all (or all but one) items were red; in the other half, they were all (or all but one) green, with colors randomly switching or repeating from one trial to the next and with distractor trials, with all but one red item or with all but one green items, also randomly intermixed among the color-homogenous trials.

The experiment included four different conditions: The target condition (576 trials) consisted of trials including a target stimulus; the target-similar condition (576 trials) contained trials with the same letter as the current target, but in a different size, and no target (e.g., a small letter *O* when the target would have been a large letter *O*; note that we always used capital letters in the stimulus arrays, regardless of size differences). In the distractor condition (576 trials), again, no target was shown, but a color singleton letter (with a different color than all other stimuli in the display) with an identity different from the target letter was present, and could be categorized as task-irrelevant (participants could always suppress a color-singleton letter). Finally, none of the stimuli (target, target-similar distractor, or color distractor) was present in the control condition. Participants had to complete 36 blocks of 56 trials, resulting in 2,016 trials. The experiment started with 72 practice trials, in which written feedback on incorrect or too-slow responses was given on the monitor. During data collection, no feedback was provided. The experiment took approximately 45 min to complete, including self-paced breaks after each block.

Data Recording, Processing, and Analysis

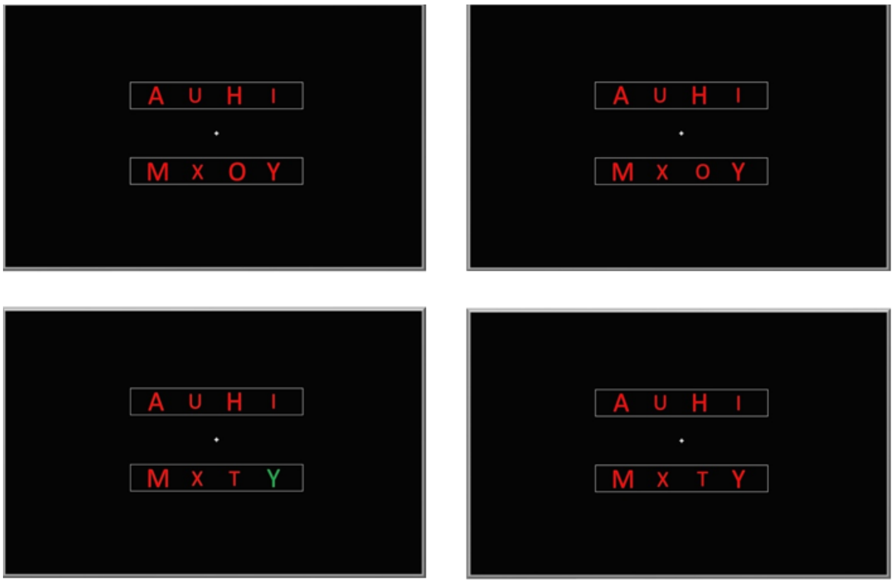
For the mixed analyses of variance (ANOVAs) conducted, we used partial eta-squared (η_p^2) as effect size measure (Richardson, 2011) and a significance level of $\alpha = 0.05$. We followed up on these omnibus tests with our planned comparisons by conducting one-sided *t*-tests, using Hedges-corrected Cohen's d (d_{unb}) as effect size and a significance level of $\alpha = 0.05$; in case of multiple comparisons, *p*-values were corrected with the Holm-Bonferroni method (Holm, 1979), if not indicated otherwise. Here, again, we report BF_{incl} (as well as BF_{+0}). If we observed heterogeneity of variances, we conducted a robust version of the Mixed ANOVA and Welch's *t*-test (Welch, 1947).

We analysed data from the 71 participants who completed the experiment twice, once during pretests and once during posttests. We also had to exclude two participants from further data analysis due to a low rate of correct answers based on the result of a generalized

Extreme Studentized Deviate (ESD) sensitive for multiple outliers (we tested for three outliers; Rosner, 1983), leaving us with the final sample of 69 participants (60 female; M_{Age} = 25.06 years; SD_{Age} = 4.54 years; range 19-40 years) for behavioral analysis of false alarm rates (proportions of responses in conditions without a target).

Figure 2

Examples of Experimental Conditions



Note. In this example, participants had to look for a large letter *O* as a target and press the down arrow when the target was present – as it is the case in the target condition (top left; 576 trials). At the top right, the target-similar distractor condition (576 trials) is shown, with a target-similar distractor letter *O* smaller than the target. At the bottom left, in the salient-distractor condition (576 trials), a salient and task-irrelevant color distractor, with a different letter identity than the target stimulus, is presented – here, a green *Y* among red letters. The control condition (bottom right; 288 trials) does not include a target, target-similar distractor, or salient color distractor.

EEG data was recorded at 512 Hz with an ActiveTwo Biosemi™ electrode system (BioSemi B.V., Amsterdam, Netherlands) from 132 electrodes (128-scalp electrodes) mounted in an equiradial ABC layout. The vertical and horizontal electrooculogram was recorded on the right eye from approximately 3 cm below the eye and the outer canthi, respectively. An additional two electrodes were placed bilaterally on the mastoids. EEG data were processed in MATLAB (Version 9.8; The MathWorks, Inc., 2020) using the toolbox EEGLAB (version 2022.1; Delorme & Makeig, 2004) with the ERPLAB extension (version 9.00; Lopez-Calderon & Luck, 2014), as well as the toolbox Fieldtrip (version 20220917; Oostenveld et al., 2011). We additionally computed and plotted EEG data in RStudio (version 1.4.1717; RStudio Team, 2021) with R (version 4.1.2; R Core Team, 2021).

For electrophysiological data, we divided our analysis into three distinct parts: 1) In a conservative, theory-based approach, we computed the *mean amplitude* of the N2pc and Pd components by calculating difference waves between contralateral and ipsilateral electrode sites (electrodes PO7 and PO8). 2) In an additional, more data-driven approach, we computed cluster-based permutation statistics on posttest minus pretest difference values per condition to identify potential attention-related effects outside the electrodes PO7 and PO8 and the respective predefined time windows. 3) Finally, we performed a spectral analysis of the data at electrode sites PO7/PO8 to test if the yoga intervention affected participants' alpha power in anticipation of each trial. Stronger alpha power could indicate an increased ability to suppress irrelevant stimuli in a preparatory, proactive manner (by suppressing irrelevant features like particular colors; Snyder & Foxe, 2010; Vissers et al., 2016). The practice of yoga also seems to increase occipital alpha activity in general, typically interpreted as reflecting a better relaxation ability (Trakroo et al., 2013). The CONSORT Chart in Figure 3 gives an overview of additional exclusion reasons during EEG preprocessing.

For the analyses performed on the ERPs, the signal was first re-sampled offline to 256 Hz, re-referenced to the average of both mastoid channels, high-pass filtered with a finite impulse response filter (FIR) at 0.1 Hz with a cut-off frequency of 0.05 Hz, a roll-off of 6 dB/octave, and a transition bandwidth of 0.1 Hz. After epoching (with epochs ranging from 100 ms before target display onset to 400 ms after), we interpolated all contaminated channels. Here, we excluded five participants from data analysis, as the amount of their to-be-interpolated electrodes exceeded 10 %. Next, the epoched EEG data was subjected to an artifact rejection procedure using the moving window peak-to-peak method (part of the ERPLAB toolbox) for a time interval from 100 ms prior to stimulus onset to 400 ms after stimulus onset. The corresponding epoched data was rejected if overall values exceeded ± 125 µV in any channel or if the EOG exceeded ± 80 µV. We also excluded participants with >25 % rejections for EEG/EOG artifacts (combined) in the pretest or the posttest measurement (five additional participants). The average amount of excluded trials per participant was 4.26 % (range: 0.32 % to 15.01 %) after participant exclusion.

For computing the mean N2pc and Pd amplitudes (1), we used the electrodes PO7 and PO8 (A10 and B7 in the ABC layout, respectively), with the time windows 115–225 ms (Pd) and

225–300 ms (N2pc) as in Sawaki and Luck (2010). Specifically, when the target was in the right visual hemifield, we subtracted the average of the right electrode (PO8) from the average of the left electrode (PO7), thereby, eliminating other ERP components due to the bilaterality of the stimuli, leaving N2pc/Pd components in the resulting difference wave (Luck, 2012). We collapsed the waveforms across the letters' colors, sizes, locations, and identities to eliminate potential sensory confounds.

For cluster-based permutation statistics (2), we computed the contralateral minus ipsilateral difference for each trial (from the target, target-similar, and distractor conditions) for all 110 channels not located on the midline, resulting in 55 difference waves per trial. We subsequently computed the posttest minus pretest difference for each participant. Then we performed three cluster-based permutation analyses (one per condition) on the respective ERP components based on an independent-samples *t*-test (one-sided for the distractor and target-similar conditions, two-sided for the target condition due to the lack of directed hypotheses regarding changes in N2pc due to the intervention when a target was present).

For the spectral analysis (3), we first calculated raw power for each participant from 1 to 21 Hz in trials with correct answers, using multitaper frequency transformation based on discrete prolate spheroidal sequences (Percival & Walden, 1993). As participants usually demonstrate a wide range of absolute power in distinct frequencies, we conducted a signal-to-noise (SNR) transformation to normalize our data and minimize inter-individual differences stemming from differences in raw power. For each frequency from 2 to 20 Hz, we divided the raw power of the frequency in question through the mean power of its upper and lower neighboring frequencies, thereby obtaining the SNR. We then calculated mean alpha (8–12 Hz) SNR and performed a repeated-measures ANOVA as well as *t*-tests as planned comparisons on the resulting data.

For the analyses of SNR, we used the same processing pipeline as for the other analyses, but with partly different parameters. Therefore, deviances from the procedure mentioned above are reported here only. We epoched the data from 100 ms before stimulus onset to 900 ms after stimulus onset and applied the moving window peak-to-peak artifact-rejection method to the time window between 200 ms and 900 ms after stimulus onset. The latter time window was then also used for our spectral analysis. This corresponded to the last 700 ms before the upcoming trial (the jittered interval before each trial was not included in the analysis to minimize potential sensory confounds), enabling us to look for changes in preparatory alpha activity within this period. Due to the large amount of blinks in these longer epochs (as participants mostly blinked when no stimulus was present in the target display), we had to exclude a significantly higher number of trials than in the ERP analyses. We only included participants with at least 200 (10% of all trials) correct trials remaining after artifact rejection. This led to the exclusion of six additional participants, leaving us with 53 participants (27 from the intervention group, 26 from the control group) for spectral analysis.

Correlational Analyses and Regression

To scrutinize the relations between the different dependent variables, we also performed correlational analyses between changes in our anxiety- and stress-related questionnaire outcomes from pretest to posttest on the one side, and electrophysiological and behavioral measures of suppression on the other side. For our correlational analyses, we initially standardized the single-participant data using z-transformation (see, e.g., Field, 2018, for details) to provide greater comparability of the variables in question. In cases where one of the assumptions of correlational analyses was violated (in this case, normality of the distribution), we used Spearman's rho as a correlation coefficient; in all other cases, we used R^2. As initially planned, we also entered changes in PSS, PSRS, STAI-ST, and STAI-TR scores, as well as group membership (and their interactions) as predictors together in a multiple regression to assess whether stress and anxiety have a mediating effect on participants' ability to suppress irrelevant stimuli (with mean Pd as a dependent variable), as hypothesized. We corrected for multiple comparisons using False Discovery Rate (FDR) correction in both regressional and correlational analyses.

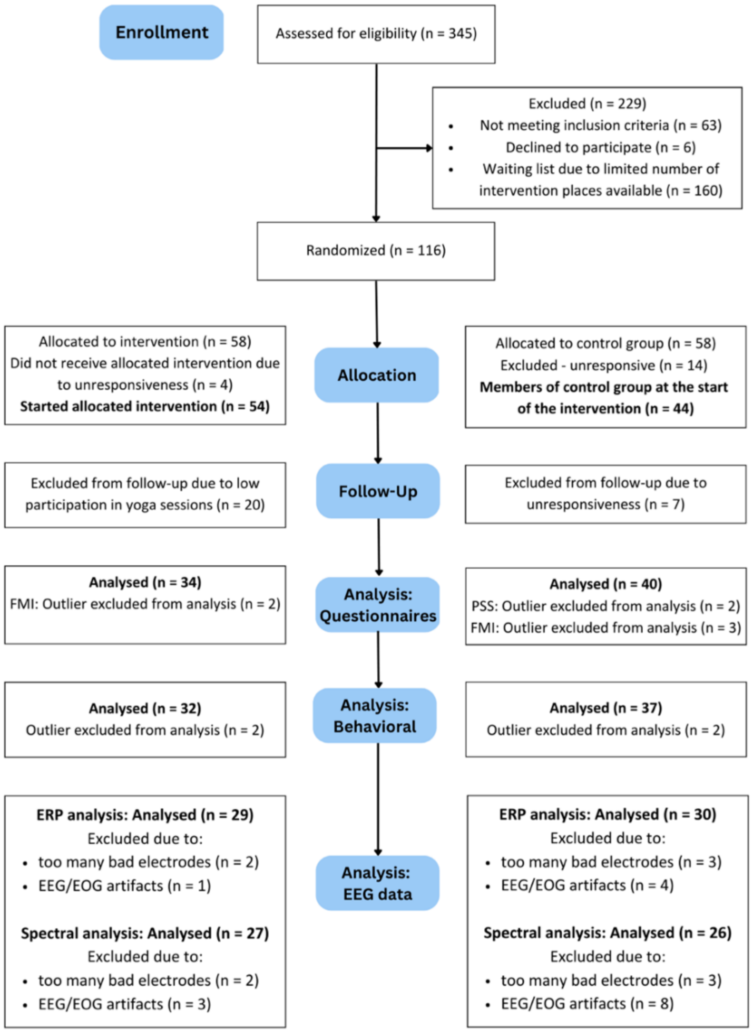
Results

Participant characteristics

Between December 2nd, 2021, and April 27th, 2022, we assessed 345 participants for eligibility in two separate cohorts. Due to the predetermined start date of the intervention and the limited number of participants that could be tested using EEG, we faced a shortage of available slots in our study. If a participant declined to participate in the study during the pretest period, and when EEG slots were still available, they were replaced by waiting list members. If not, this led to a reduction in the overall number of participants. One hundred sixteen participants were randomized into an intervention and a control group and admitted to the trial (for a detailed description of the trial profile, see the chart in Figure 3).

Figure 3

Trial Profile



Note. Reasons for exclusion after the previous analysis step are listed below the number of analysed participants for each step. Exclusions from questionnaire and behavioral analyses occurred independently; when participants were excluded from behavioral analyses, their EEG data was also not analysed. EEG: Electroencephalography; EOG: Electrooculogram. ERP: Event-related potential. FMI: Freiburg Mindfulness Inventory; PSS: Perceived Stress Scale.

Table 3

Baseline Characteristics of the Intention-to-Treat Population

	Total (n =100)	Intervention (n = 44)	Control (n = 56)	p
Age (in years)	25.12 ± 0.42	24.73 ± 0.72	25.61 ± 0.50	.316
Gender (n = 99)				.673
Women	81 (81.8%)	45 (81.8%)	36 (81.8%)	
Men	18 (18.2%)	10 (18.2%)	8 (18.2%)	
Working hours per week				.872
0	22 (22.0%)	12 (21.4%)	10 (22.7%)	
1–20	52 (52.0%)	30 (53.6%)	22 (50%)	
20–40	23 (23.0%)	13 (23.2%)	10 (22.7%)	
Over 40	3 (3.0%)	1 (1.8%)	2 (4.6%)	
Smoking (at least occasionally)				> .999
Yes	29 (29.0%)	16 (28.6%)	13 (29.6%)	
No	71 (71.0%)	40 (71.4%)	31 (70.4%)	
Alcohol use (at least occasionally)				> .999
Yes	84 (84.0%)	47 (83.9%)	37 (84.1%)	
No	16 (16.0%)	9 (16.1%)	7 (15.9%)	
Physically active (min. 1x per week)				> .999
Yes	70 (70.0%)	31 (70.4%)	39 (69.6%)	
No	30 (30.0%)	13 (29.6%)	17 (30.4%)	
Mindfulness practice (not yoga)				.991
Yes	17 (17.0%)	9 (16.1%)	8 (18.2%)	
No	83 (83.0%)	47 (83.9%)	36 (81.8%)	
Depression (PHQ-9; 0-27)	7.09 ± 0.44	7.53 ± 0.61	6.52 ± 0.62	.248
BMI	21.91 ± 0.29	21.71 ± 0.36	22.18 ± 0.48	.430
Somatic symptoms (PHQ-15; 0–30)	6.53 ± 0.45	6.73 ± 0.67	6.27 ± 0.60	.611
Stress (PHQ; 0–20)	4.43 ± 0.30	4.41 ± 0.47	4.45 ± 0.40	.943

Note. Data are presented as mean ± *SD* or *n* (%). BMI: Body-Mass-Index. PHQ: Patient Health Questionnaire. Three subscales of the PHQ are reported here: PHQ-9 assessing depression, PHQ-15 assessing somatic symptoms, and 10 specific questions of the PHQ assessing stress. *p* values are calculated from independent samples *t*-tests for continuous variables, and Chi-squared tests for categorical variables. Physical activity is defined by engaging in sports or strenuous walking at least once per week.

Out of these 116, 100 filled out the pretest baseline questionnaire (baseline characteristics are shown in Table 3); two members of the intervention group declined participation after filling out the questionnaire, which led to 98 total participants taking part in the study when the intervention started. While the awareness of the study arm might have influenced participants' pretest responses, it's noteworthy that this potential bias would inevitably be present in the posttests. Given the nature of the intervention, a double-blind procedure was unfeasible — participants were clearly aware of whether they participated in a yoga class. As such, any potential bias introduced by this awareness would be consistently present at both pretest and posttest stages. This consistency ensures that the bias should not disproportionately affect our results, even if pretest questionnaires were completed after randomization.

Questionnaires

We hypothesized that the intervention group would show a greater reduction in perceived stress, perceived stress reactivity, and anxiety. We also expected a greater increase in trait mindfulness compared to the control group from baseline to posttest. Additionally, we tested for a moderating role of trait mindfulness on perceived stress and perceived stress reactivity. Table 4 provides an overview of all questionnaire outcomes by group and measurement.

Table 4

Questionnaire Outcomes at Pre- and Posttest Measurements

Questionnaire	Measurement	Observed range	Group	*M* [95% CIs]	*SD*
Perceived Stress Scale (PSS)	Pretest	5–31	IG	17.56 [16.02, 19.10]	6.17
			CG	14.79 [13.72, 15.86]	5.90
	Posttest	4–28	IG	15.21 [13.67, 16.75]	5.80
			CG	14.84 [13.77, 15.91]	4.50
Perceived Stress Reactivity Scale (PSRS)	Pretest	5–38	IG	23.50 [22.41, 24.59]	6.78
			CG	23.68 [22.60, 24.76]	7.08
	Posttest	9–36	IG	20.94 [19.85, 22.03]	6.72
			CG	23.63 [22.55, 24.71]	7.25
Trait Anxiety (STAI-Y-TR)	Pretest	6.67–80	IG	40.83 [36.89, 44.77]	16.86
			CG	40.41 [38.24, 42.58]	16.84
	Posttest	1.67–80	IG	36.28 [32.24, 40.22]	17.48
			CG	39.26 [37.09, 41.43]	17.06
State Anxiety (STAI-Y-ST)	Pretest	5–73.33	IG	40.20 [36.21, 44.19]	16.31
			CG	39.92 [36.14, 43.70]	16.21
	Posttest	6.67–71.67	IG	37.55 [33.56, 41.54]	19.15
			CG	37.83 [34.05, 41.61]	15.99

Freiburg Mindfulness Inventory (FMI)	Pretest	27–52	IG	38.28 [37.02, 39.54]	5.21
			CG	38.33 [37.45, 39.21]	4.76
	Posttest	31–48	IG	40.34 [39.08, 41.60]	4.37
			CG	38.44 [37.56, 39.32]	3.85

Note. M = Mean*,* 95% CIs in parentheses*, SD* = Standard deviation, IG = Intervention group, CG = Wait list control group. *N* = 74, approximately equal split through the two groups. The amount of participants per group varied between n = 32 and n = 40, depending on the number of excluded outliers.

Perceived Stress and Perceived Stress Reactivity

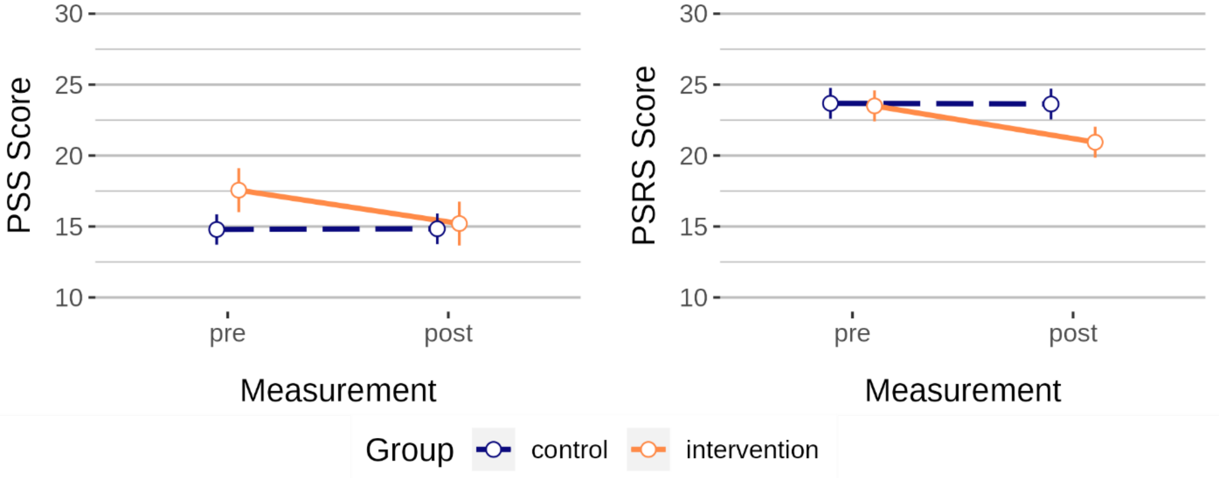
Out of the 74 participants, we had to exclude two outliers when testing for changes in perceived stress, leaving us with 72 participants (62 female; M_{Age} = 24.95 years; SD_{Age} = 4.48 years; range 18 to 40 years). No participants were excluded from the analysis of the PSRS scores. Figure 4 shows both outcomes by group and measurement.

A robust 2 × 2 mixed ANOVA on participants' Perceived Stress Score showed a trend towards a significant interaction between measurement and group, F(1, 39.71) = 3.48, p = .070, η_p^2 = 0.08, BF_{incl} = 1.63. There was a significantly greater reduction of perceived stress in the IG than in the CG, M = 2.40, t(70) = 1.87, p = .033, d_{unb} = 0.44, BF_{+0} = 2.04. We found neither a significant main effect of measurement, F(1, 39.71) = 1.51, p = .226, η_p^2 = 0.04, BF_{incl} = 0.76, nor of group, F(1, 41.51) = 2.12, p = .153, η_p^2 = 0.05, BF_{incl} = 0.58, on perceived stress.

Looking into changes in stress reactivity (PSRS scores) with another 2 × 2 mixed ANOVA, importantly, the interaction between measurement and group was significant, F(1, 72) = 5.42, p = .023, η_p^2 = 0.07, BF_{incl} = 2.34. A one-sided t-test indicated a greater reduction of perceived stress reactivity in the IG than in the CG, M = 2.51, t(70) = 2.33, p = .011, d_{unb} = 0.54, BF_{+0} = 2.34. There was also a significant main effect of measurement on perceived stress reactivity, F(1, 72) = 5.85, p = .018, η_p^2 = 0.08, BF_{incl} = 1.47, but no significant main effect of group on perceived stress reactivity, F(1, 72) = 0.88, p = .353, η_p^2 = 0.01, BF_{incl} = 0.52. To summarize, our results showed a medium-sized effect of the intervention on perceived stress, as well as perceived stress reactivity.

Figure 4

Interventional Effects on Stress and Stress Reactivity



Note. Participants' mean score (white dots) on the Perceived Stress Scale (PSS; on the left) and the Perceived Stress Reactivity Scale (PSRS; on the right), averaged for each group and measurement. Colored lines indicate the slope of the change in mean score for the intervention group (orange solid line) and the control group (dark blue dashed line) from pre- to posttest. Vertical lines show 95% CIs. pre: pretest; post: posttest.

State Anxiety and Trait Anxiety

We also tested whether the intervention had a significant (decreasing) influence on state anxiety by conducting a 2 × 2 mixed ANOVA, with the normalized STAI-Y-SA score as a dependent variable. As we detected no outliers, we analysed the data from all 74 participants, revealing no significant intervention effect, $F(1, 72) = 0.02$, $p = .885$, $\eta_p^2 < 0.01$, $BF_{incl} = 0.24$. A one-sided independent-samples t-test also showed no effects of the intervention $M = 0.56$, $t(70) = 0.15$, $p = .442$, $d_{unb} = 0.03$, $BF_{+0} = 0.22$. We also did not find a significant main effect of group, $F(1, 72) < 0.01$, $p > .999$, $\eta_p^2 < 0.01$, $BF_{incl} = 0.29$, or of measurement, $F(1, 72) = 1.52$, $p = .222$, $\eta_p^2 = 0.02$, $BF_{incl} = 0.35$.

Assessing the influence of the intervention on participants' trait anxiety, the 2 × 2 mixed ANOVA indicated no significant interaction between measurement and group, $F(1, 72) = 1.28$, $p = .262$, $\eta_p^2 = 0.02$, $BF_{incl} = 0.38$, in accordance with follow-up comparisons, $M = 3.40$, $t(70) = 1.13$, $p = .131$, $d_{unb} = 0.26$, $BF_{+0} = 0.71$. Figure 5 shows mean anxiety (both state and trait) scores per measurement and group. There were no outliers, resulting in the analysis of all 74 participants who filled out the questionnaires. The main effect of measurement on trait anxiety trended towards significance, $F(1, 72) = 3.29$, $p = .062$, $\eta_p^2 = 0.05$, $BF_{incl} = 0.78$, resulting from slightly decreasing levels of TA, especially in the intervention condition. There was no significant main effect of group, $F(1, 72) = 0.12$, $p = .730$, $\eta_p^2 < 0.01$, $BF_{incl} = 0.39$.

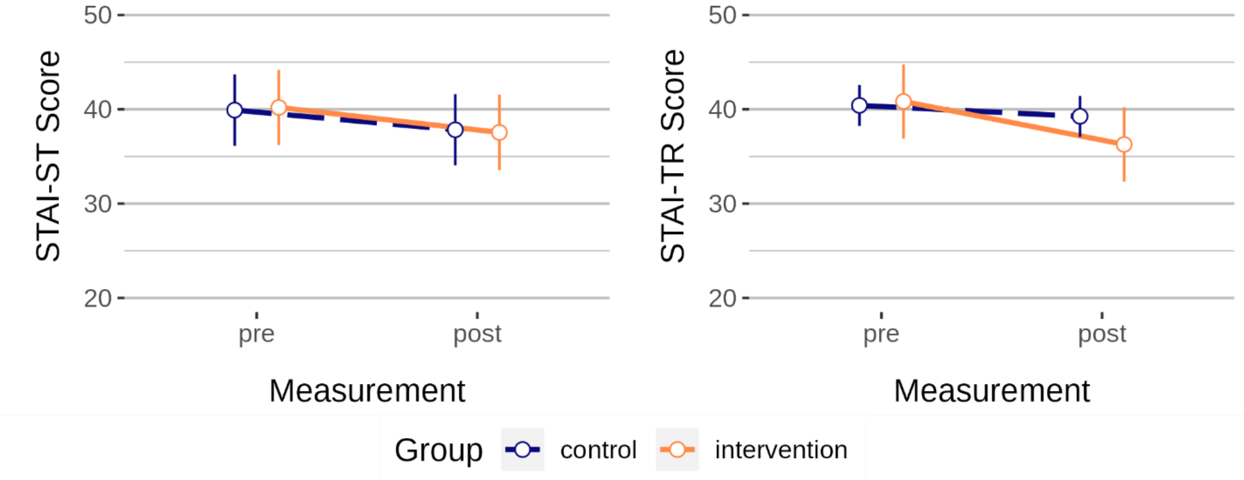
Trait Mindfulness

To answer whether there was an increase in Trait Mindfulness due to the intervention, data from 69 participants (59 female; $M_{Age} = 25.1$ years; $SD_{Age} = 4.6$ years; range 18-40 years) was analysed after excluding five outliers. The 2 × 2 mixed ANOVA revealed a marginally significant interaction between measurement and group, $F(1, 67) = 3.49$, $p = .066$, $\eta_p^2 = 0.05$, $BF_{incl} = 1.09$, with follow-up comparisons showing a significant increase of intervention-dependent trait mindfulness, $M = -1.95$, $t(70) = -1.87$, $p = .033$, $d_{unb} = -0.45$, $BF_{+0} = 2.07$.

To test if preexisting differences in Trait Mindfulness between individuals moderated intervention-dependent changes in their perceived stress levels (prePS), we performed a multiple regression analysis, with posttest perceived stress (postPS) as the dependent variable, pretest prePS as the predictor variable and pretest trait mindfulness (preTM) levels as the moderator variable. We found a trend towards a significant interaction between preTM and prePS ($\beta = 1.58$, $SD = 0.13$, $p = .064$).

Figure 5

Interventional Effects on Anxiety



Note. Participants' mean score (white dots) of State Anxiety (STAI-ST; on the left) and Trait Anxiety (STAI-TR; on the right), averaged by group and measurement. Colored lines indicate the slope of the change in mean score for the intervention group (orange solid line) and the control group (dark blue dashed line) from pre- to posttest. Vertical lines show 95% Cis. pre: pretest; post: posttest.

Following up, we tested simple slopes for the association between prePS and postPS for low (−1 *SD* below the mean), moderate (mean), and high (+1 *SD* above the mean) levels of preTM, using the Johnson-Neyman technique (Johnson & Fay, 1950). Two of the simple slope tests revealed a significant positive association between prePS and postPS: While prePS was strongly related to postPS for high levels of preTM (β = 0.51, *SD* = 0.76, $p < .001$), it was moderately associated with postPS for moderate levels of preTM (β = 0.37, *SD* = 0.58, $p < .001$). There was a small, marginally significant association between prePS and postPS for low levels of preTM (β = 0.23, *SD* = 0.70, $p = .070$). These results indicate that depending on the level of (pretest) trait mindfulness, hatha yoga acts differently on perceived stress: The more mindful participants showed more Hatha-Yoga-dependent reduction of their perceived stress.

Suppression Experiment

False Alarm Rates

A 2 × 2 × 3 mixed ANOVA, with the within-participant variables *Measurement* (pre/post) and *Condition* (target-similar/distractor/control), and the between-participants independent variable *Group* (intervention/control) on participants' false alarm rates revealed no significant three-way interaction (i.e., no evidence of an intervention effect), $F(2, 134) = 0.13$, $p = .734$, $\eta_p^2 < 0.01$, $BF_{incl} = 0.17$. Contrary to our initial expectations, the intervention did not decrease false alarm rates in the distractor condition, $M = 0.24$, $t(57) = 0.64$, $p = .263$, $BF_{+0} = 0.43$, or the target-similar condition, $M = −0.03$, $t(57) = −0.03$, $p = .514$, $BF_{+0} = 0.24$ (see also Figure 6).

Electrophysiology

Figures 7 and 8 show the waveforms at lateral occipital electrode sites for the distractor and target-similar conditions averaged across participants (left side), by group (intervention/control), and measurement (pre/post), as well as the corresponding lateralizations (contralateral minus ipsilateral electrodes; right side). The Pd is visible as a contralateral positivity at PO7/PO8 electrode sites, while the N2pc is a negative deflection of contralateral relative to ipsilateral amplitude. For the statistical confirmation that a Pd and an N2pc occurred in the first place, we first ran one-sided *t*-tests versus zero for every combination of the independent variables *Measurement* (pre/post), *Group* (intervention/control), and *Condition* (target/target-similar/distractor/control), with mean amplitude of the lateralized ERPs in the respective time windows (Pd: 115-225 ms, N2pc: 225-300 ms).

These t-tests showed significant differences for both pretest and posttest measures and for both groups in the distractor condition for the Pd (where we expected a Pd) and in the target and target-similar conditions for the N2pc (where we expected an N2pc), while not being significant in the other conditions. See also Tables A1 and A2, Appendix A, for the corresponding t-tests). As the Pd (N2pc) is always a positive (negative) deflection of contralateral relative to ipsilateral amplitude, one-sided tests ensured that only a positivity (negativity) became significant, thereby distinguishing the N2pc from a potentially occurring late Pd.

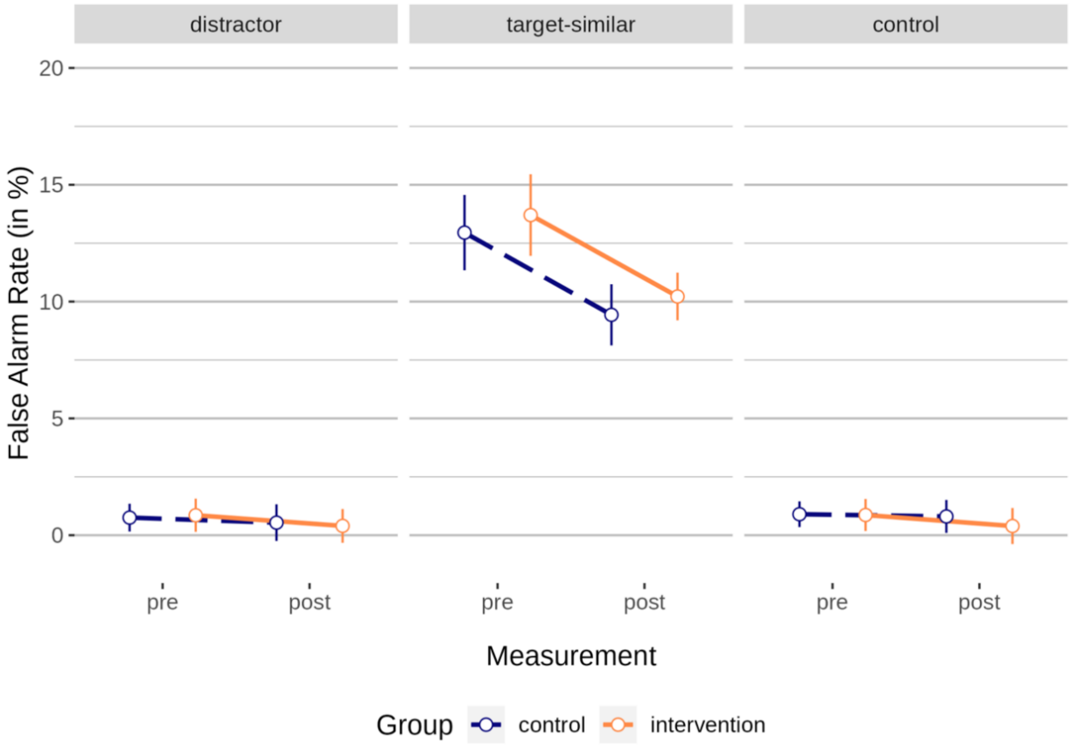
Looking at the potential effects of the intervention, we then conducted a 2 × 2 Mixed ANOVA for the distractor condition, with the independent variables *Measurement* (pre/post) and *Group* (intervention/control) for the mean amplitude differences between contra- and ipsilateral electrode sites 115-225 ms after stimulus onset as a dependent variable. The ANOVA revealed no significant main effects or interactions (all ps > .291, all $BF_{incl} < 0.18$). As planned, we tested the interaction effect with a one-sided independent-samples t-test, finding no significant group differences in mean amplitude compared to baseline, $M = 0.05$, $t(57) = 0.52$, $p = .301$, $d_{unb} = 0.13$, $BF_{+0} = 0.41$.

For the target-similar condition, we again conducted a 2 × 2 Mixed ANOVA, with the independent variables *Measurement* (pre/post) and *Group* (intervention/control), with mean contra- minus ipsilateral voltage differences within the N2pc time window. We did not find any significant main effects (all ps > .148, all $BF_{incl} < 0.64$), and no significant interaction between measurement and group, $F(1, 57) = 0.00$, $p = .956$, $\eta_p^2 < 0.01$, $BF_{incl} = 0.09$. We again tested the interaction effect with a one-sided independent-samples t-test, obtaining a nonsignificant result, $M = 0.01$, $t(57) = 0.06$, $p = .478$, $d_{unb} = 0.01$, $BF_{+0} = 0.28$, indicating that there were no differences in attentional capture by the target-similar distractors between groups compared to pretest.

Lastly, for the target condition, the 2 × 2 mixed ANOVA revealed no significant effect of the intervention (interaction between *Measurement* and *Group*) on mean N2pc amplitude, $F(1, 57) = 0.07$, $p = .788$, $\eta_p^2 < 0.01$, $BF_{incl} = 0.05$. The main effects were also not significant (all ps > .612, all $BF_{incl} < 0.23$).

Figure 6

Mean False Alarm (FA) Rates Per Condition, Measurement, and Group



Note. Orange solid lines show the FA rate (mean proportion of incorrect responses) of the intervention group; dark blue dashed lines show the FA rates of the control group. Vertical bars indicate 95% CI. Pre: pretest; post: posttest.

We also computed cluster-based statistics for each condition using an independent-samples *t*-test with participants' difference values, using mean amplitude as a dependent variable. We did so to identify potential changes in suppression and/or attentional capture due to the intervention outside the electrodes PO7 and PO8 and our previously predefined time windows. These statistics did not reveal any significant clusters in any of the conditions (all *p*s > .269), delivering corroborative evidence for the notion that mean amplitudes also did not differ at other electrode pairs than the initially selected PO7/PO8 electrodes.

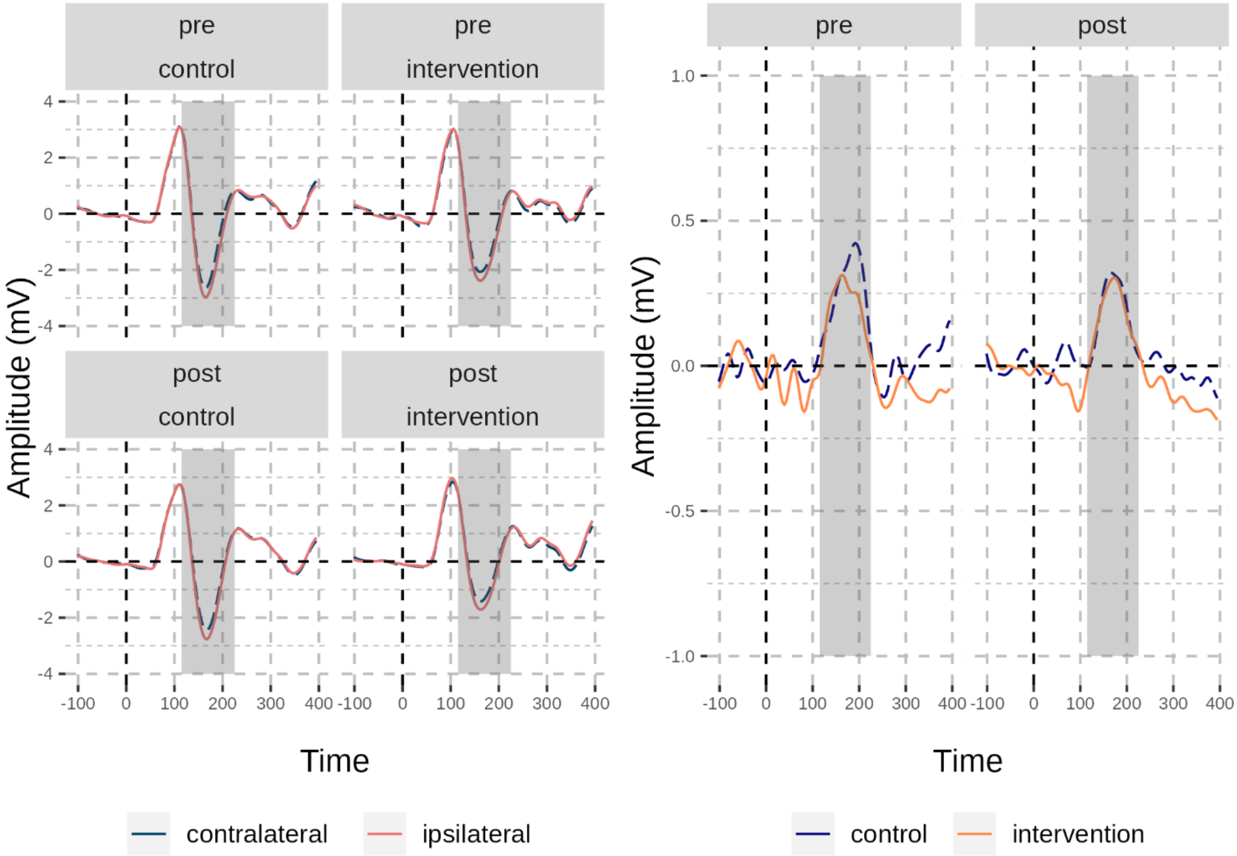
Lastly, we performed spectral analysis on the data. Figure 9 shows the Signal-to-Noise Ratio (SNR) computed in the time window 200 to 900 ms after stimulus onset at electrodes PO7 and PO8 over a frequency range from 2 to 20 Hz, averaged across participants (per group and measurement).

We first looked at changes in mean alpha SNR (8 to 12 Hz) due to the intervention and conducted a mixed ANOVA with the between-participants independent variable *Group* (intervention/control) and the within-participant independent variable *Measurement* (pre/post). The ANOVA revealed no significant interaction, $F(1, 51) = 0.72$, $p = .401$, $\eta_p^2 = 0.01$, $BF_{incl} = 0.39$. There was a significant main effect of measurement due to an increase in mean alpha SNR, $F(1, 51) = 9.76$, $p = .003$, $\eta_p^2 = 0.16$, $BF_{incl} = 11.72$. The main effect of group was not significant, $F(1, 51) = 0.77$, $p = .385$, $\eta_p^2 = 0.01$, $BF_{incl} = 0.68$.

We compared differences (post-pre) in mean alpha power between groups again by a one-sided independent-samples *t*-test, as a presumed increase in Pd amplitude would likely correlate with increased alpha power over occipital electrode sites (Mathewson et al., 2014; van Zoest et al., 2021). However, the *t*-test did not yield a significant result, $M = 0.00$, $t(57) = -0.85$, $p = .200$, $d_{unb} = -0.23$, $BF_{+0} = 0.58$, indicating that alpha power did not significantly increase as a result of the intervention (but, as shown by the main effect of measurement, as a result of practice on the task).

Figure 7

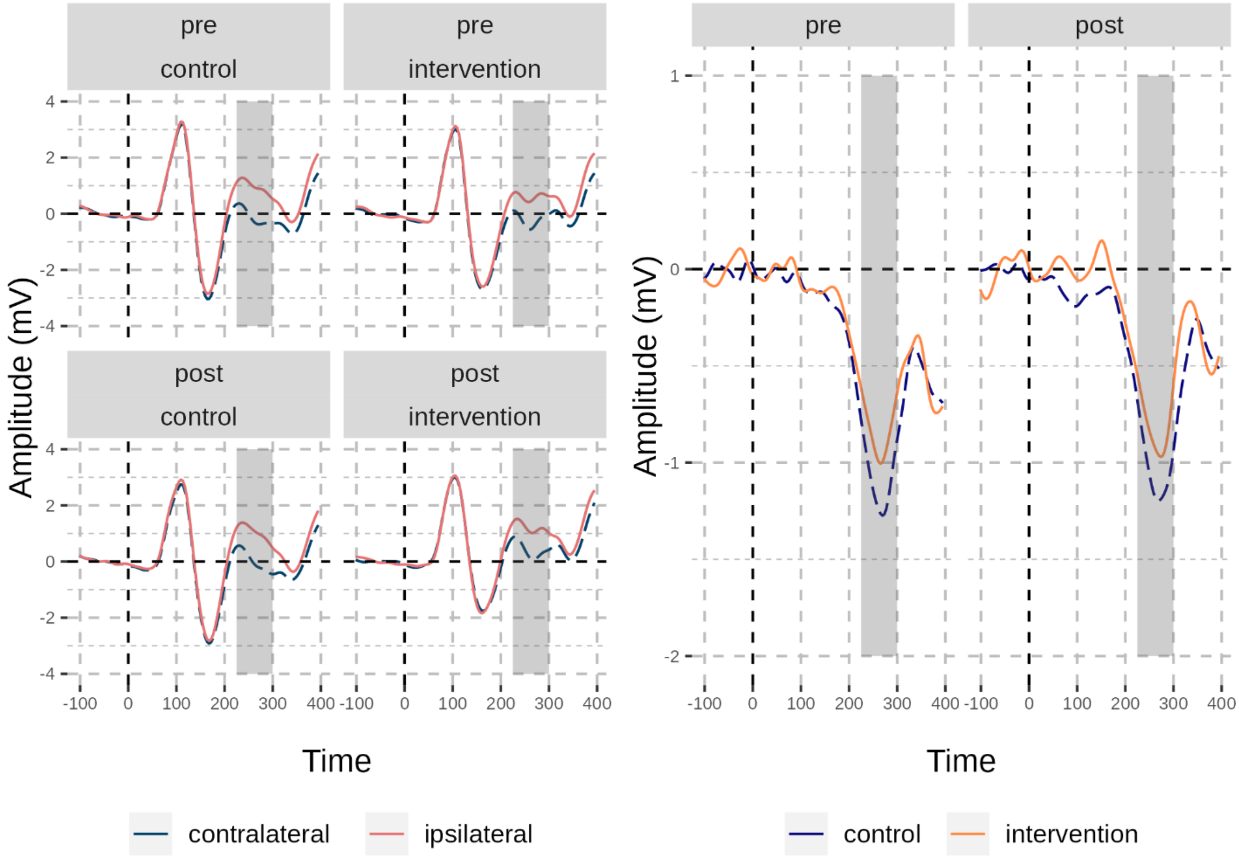
Event-Related Potentials and Difference Waves for the Distractor Condition



Note. Left: Grand average waveforms for the distractor condition at contralateral (blue dashed line) and ipsilateral (red solid line) electrode sites (PO7 and PO8) for pretest (pre) and posttest (post) measurements, showing intervention versus control group results. Right: Difference waves (contralateral minus ipsilateral) for both measurements. Orange solid lines show difference waves for the intervention group; dark blue dashed lines for the control group. Grey areas mark time windows during which we measured the Pd (analogously to Sawaki & Luck, 2010).

Figure 8

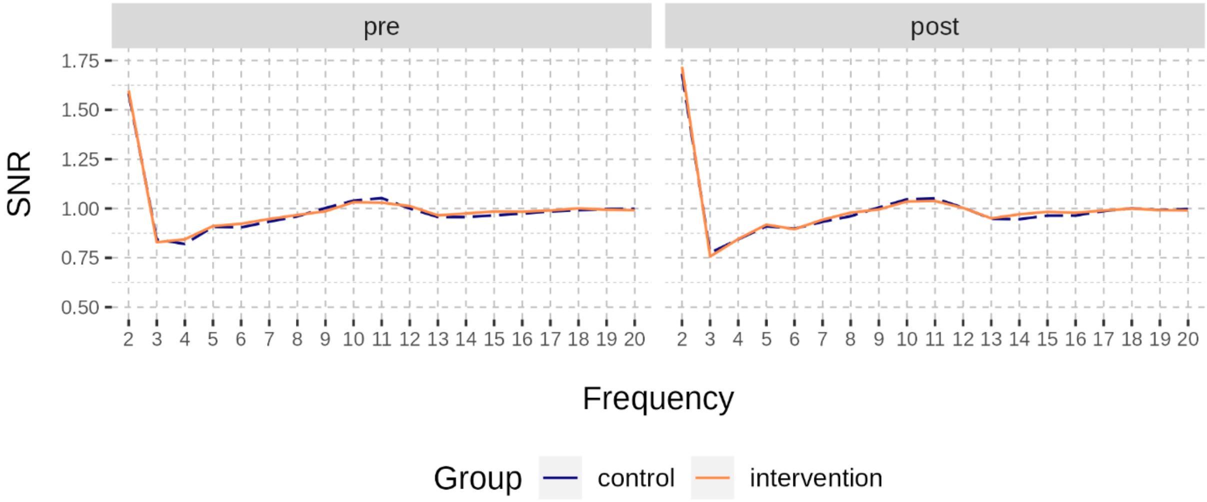
Event-Related Potentials and Difference Waves for the Target-Similar Condition



Note. Left: Grand average waveforms for the target-similar condition at contralateral (dark blue dashed line) and ipsilateral (red solid line) electrode sites (PO7 and PO8) for both measurement points, for the intervention versus control group. Right: Difference waves for pretest and posttest measures. Orange solid lines show difference waves for the intervention group; dark blue dashed lines for the control group. Grey areas mark time windows during which the N2pc was measured. pre: pretest; post: posttest.

Figure 9

Spectral Distribution



Grand average Signal-to-Noise Ratio (SNR; absolute power divided by the mean of the neighboring frequencies) for frequencies between 2 and 20 Hz computed in the time window 200 to 900 ms after stimulus onset at electrodes PO7 and PO8, for each group and measurement (pretest: left, posttest: right). Orange solid lines show the SNR of the intervention group, while dark blue dashed lines show the SNR of the control group.

Correlational Analyses and Regression

To link the possible influence of stress and anxiety on individuals' suppression ability, we calculated Pearson correlation coefficients between changes in mean Pd amplitude from pre- to posttest and stress- and anxiety-related questionnaire outcomes (differences in PSS Score, PSRS Score, STAI-ST, as well as STAI-TR score from pre-to posttest); these tests revealed no significant correlative relationship, all *ps* > .172. Additionally, to examine a hypothesized mediating role of stress on suppression, we conducted a multiple regression analysis with group (intervention/control) and PSS score difference (pre – post), PSRS score difference, STAI-ST difference, STAI-TR difference (as well as their interactions) as predictors, and mean Pd amplitude as a dependent variable. There was no significant influence of any of the predictors or their interactions, all *ps* > .195. The model did not fit significantly better than the null model, adjusted $R^2 = -0.338$, $p = .951$, implying that changes in stress and anxiety-related scores, as well as group membership did not cause changes in mean Pd amplitude.

We were also interested in possible changes in attentional capture of target-similar distractors due to stress and anxiety; there was no significant correlation between pre-to-post-difference in stress- and anxiety-related questionnaire outcomes and mean N2pc difference from pre- to posttest, all *p*s > .322. Finally, looking at the behavioral level, there were marginally significant positive Spearman correlations present for participants' score changes on the Perceived Stress Scale with changes in false alarm rate for the distractor condition, $r(57) = 0.217$, $p = .051$, as well as for the target-similar condition, r(57) = 0.194, p = .073, indicating that participants made fewer errors with decreasing stress levels. All other correlations between stress- and anxiety-related measures on the one side and false alarm rate on the other side were not significant in target-similar and distractor conditions, all *p*s > 101.

Discussion

In the current study, we set out to investigate the relationship between anxiety and stress reductions and improvements of executive functions – here, of inhibition – following hatha yoga treatment as an intervention. Past studies have shown that both – stress and anxiety, as well as executive functions – can benefit from a yoga intervention (e.g., Diamond & Lee, 2011; Gothe et al., 2013; Pascoe & Bauer, 2015; Robinson et al., 2021). Importantly, if the two effects go hand in hand, this might be due to theoretically plausible connections between the two domains. For instance, stress or anxiety could call on limited cognitive capacity, interfering with executive functioning in other tasks (Derakshan & Eysenck, 2009). This would be more so before a stress- or anxiety-relieving intervention than after such an intervention.

However, this connection was barely supported in the present study. First and foremost, we did not find an improvement in suppression as a consequence of our hatha yoga intervention. This was the case, despite using several different possible dependent variables of suppression, such as electrophysiological and behavioral markers, and a passive (waitlisted) control group for comparison. Both these measures would have increased the sensitivity of our method for any residual intervention-dependent improvement of suppression if it existed. Thus, the fact that no such improvements could be observed speaks against a connection of improved suppressive abilities with the intervention's anxiety- and stress-diminishing consequences, as the latter were observed (see below).

Positive Effects of Yoga on Stress Levels and Mindfulness

Furthermore and importantly, we found evidence for an improvement in experienced stress and stress reactivity following the yoga intervention. Both self-report measures were significantly reduced following the intervention compared to the control group. Evidence of effects of yoga interventions on self-reported stress reactivity in everyday life is very scarce, as, so far, most studies investigated stress reactivity as a biological reaction to laboratory-induced stress (e.g., Pascoe et al., 2017). Some authors argue that, even though perceived stress and stress reactivity are correlated, some kinds of yoga might be more suitable for the reduction of subjective stress levels, while other kinds may modulate stress reactivity more strongly (Park et al., 2021). These differences have yet to be explored in future studies that should explicitly report intervention characteristics and the type of stress investigated.

Interestingly, neither state nor trait anxiety levels showed a significant decrease, even though other studies have reported such decreases. It's worth noting that many studies on yoga focus on clinical populations (e.g., Broota & Sanghvi, 1994; Sharma et al., 1991, for a review, see Kirkwood et al., 2005). We were keen to explore how individuals without a DSM diagnosis would respond to the intervention. This criterion might have limited the potential for improvement, as baseline anxiety levels were inherently lower than those seen in clinical cases of anxiety disorders or related syndromes. Nonetheless, the aim of our study was not to generalize our results to clinical groups, but to encourage the general population to consider yoga as a means to alleviate stress and anxiety.

In our study, higher pretest trait mindfulness was associated with stronger intervention effects in terms of the reduction of perceived stress. Other yoga studies have also shown negative associations between perceived stress and mindfulness (e.g., Park et al., 2021). Some individuals might be more receptive and open to yoga or mindfulness interventions in general. Higher levels of pre-intervention mindfulness could, therefore, be an advantage, possibly increasing an individual's "access" to the intervention, promoting easier and faster learning of taught elements, and resulting in more substantial beneficial effects. Even though our results would, thus, provide another piece of the puzzle, future studies are needed to unravel the exact relationship between yoga and measured trait mindfulness. Maybe the connection between the effects of yoga and mindfulness is also mediated by one principle underlying both mindfulness's beneficial effects and the impact of yoga practice.

While our sample's pretest scores of perceived stress reactivity are in line with the norm values for the general (German) population (age group < 26, women: M = 24.07, SD = 7.14) (Schlotz et al., 2011), the pretest scores of perceived stress (PSS-10) were unexpectedly high and above the mean score for the general (German) population (age group 20 to 39, M = 12.74, SD = 6.67) (Klein et al., 2016). Some authors consider a PSS-10 score of 13 as a cut-off for chronically stressed individuals (e.g., Feneberg & Nater, 2022). This would mean that, contrary to our intention of investigating a healthy sample, we studied a chronically stressed group with elevated stress levels. This incidental observation offers an interesting perspective on the current study as one of the few studies on the effects of yoga on higher stress levels of otherwise healthy persons. To note, healthy populations without elevated stress levels and some clinical conditions, are well-researched regarding the impact of yoga on stress (e.g., Breedvelt et al., 2019; Pascoe et al., 2017). Our results suggest that hatha yoga also effectively reduces subjective stress among chronically stressed people.

Linking Executive Functions and Stress

In addition, in support of a general connection between executive functions and stress, we observed correlations between self-reported stress levels and false alarm rates in both target-similar and distractor conditions of the inhibition task trending both towards significance (note that this was not the case for self-reported anxiety). Thus, it might be the case that when participants are less stressed, they make fewer mistakes due to increased efficiency in their guidance of attention, reflected in an improved ability of suppression and less attentional capture by distractors being similar to the target.

Yet, in the current study, inhibition might have been too easy, thereby, diminishing performance variance across participants and, thus, decreasing the possibility for a more substantial effect of our intervention on inhibition: To note, false alarm rates were below 1% in the color distractor condition, potentially creating a ceiling effect. It is important to acknowledge that our main task (distinguishing the letter sizes of potential targets) was relatively difficult. This in turn could have fostered distractor inhibition, as humans filter out distractors more easily and efficiently if the processing demands of a task are high (Lavie, 1995; Lavie & Tsal, 1994). It might be that an easier task and, thus, more taxing distractor inhibition would provide a more sensitive measure of the impact of yoga on inhibition (Zhang et al., 2011).

It is worth considering that links between stress and anxiety on the one hand and executive functions on the other hand are not the same for each of the different discussed executive functions. Suppression as one specific executive function might not be subject to interference by higher levels of experienced stress and/or anxiety and, thus, suppression would not benefit as much from the liberation of more mental capacity through a (yoga) intervention than other executive functions. For example, if attentional control theory holds true (cf. Eysenck et al., 2007), suppression as one specific executive function might be spared from anxiety-related interference to be at the disposal of an anxious person for their unsuited emotion suppression strategies as this is what research has shown: that persons from more anxious samples rely more on suppression of unwanted feelings than persons from less anxious comparison samples (cf. Campbell-Sills et al., 2006; Dryman & Heimberg, 2018; Hofmann et al., 2009). This is also supported by the fact that the different executive functions are partly independent from one another, meaning that not all of them must be influenced by the same manipulations or independent variables. Viewed from the perspective of theories that put monitoring of control or steering values at center stage of top-down or strategic psychological processing (e.g., Anderson et al., 1997; Ansorge et al., 2021), for example, the executive function of shifting (between tasks, modalities, or stimuli) could be subject to more interference by upholding of (unsuited) anxiety- and stress-supporting strategies (or other stress- and anxiety-supporting processes) and, thus, also benefit more from a stress- or anxiety-relieving intervention such as hatha yoga (cf. Gothe et al., 2016). We will look at this possibility in a follow-up article in which we will analyze shifting performance in the same groups and study design that was reported in the present research.

Another more trivial possibility is that our procedure was simply underpowered. In fact, the dropout rate was higher than expected, leaving us with fewer full data sets than originally aimed for. However, looking at the pattern of results in the suppression measure, with its slightly declining suppression effects across time, and the results of Bayesian analysis, we do not expect that a higher sample size would dramatically change our conclusion that suppression was barely affected by our intervention. Reflecting further on the power issue, however, the current study was definitely not suffering from low internal validity – that is, too short an intervention, coarse mismatches between intended and taught lesson content, or too little practice of the participants involved. We used a relatively substantial period of two months of regular yoga training, including only participants who continuously participated in the intervention, and ensured that yoga lessons' content aligned with the intended yoga intervention program using short questionnaires about the practice or content following each single yoga lesson.

Generalizability and Reliability of Results

Our analysis approach, prioritizing treatment effects as received rather than as initially assigned, might be perceived as a deviation from the conventional benefits of randomization (Tripepi et al., 2020). However, this decision was underpinned by several methodological considerations. The focus of our study was not on efficacy and generalization to the whole population (see also the related point of restricting data collection in terms of age and the exclusion of potential participants with psychiatric conditions), but rather on evaluating the effectiveness of our yoga intervention. In our opinion, this objective is best served by analysing outcomes of participants adhering to our intervention protocol. By imposing rigorous exclusion criteria and adherence thresholds, we wanted to ensure that our participants were genuinely reflective of the intervention’s impact.

By comparison, while intention-to-treat analyses might fully preserve randomization and lead to considerably less self-selection bias (Andrade, 2022), they would have greatly distorted the results of our study, especially given the high amount of dropouts from whom very few showed up for posttests. Concentrating on actual, observed outcomes and sidestepping the uncertainties introduced by a large amount of imputed data, thus, allowing for a more accurate reflection of the intervention's impact in our opinion.

This strategy underscores our commitment to presenting results that represent real-world implications. Moreover, the nature of our intervention – a non-pharmacological, behavioral intervention with multiple known health benefits – diverges from clinical context where a conservative approach like ITT in accepting new treatments as effective is necessary. Such safeguards are essential in pharmaceutical trials but should be questioned in the realm of lifestyle interventions without adverse side effects. We, therefore, advocate for a nuanced view of analysis strategies in research, with context-appropriate methodology to yield the most accurate findings.

Conclusion

In conclusion, we observed significant improvements in self-reported stress, stress reactivity, and mindfulness levels in a hatha yoga intervention group relative to a passive (waitlisted) control group that were not accompanied by a proportional improvement of performance in a suppression task, showing that this particular executive function was neither responsible for the self-reported improvements nor affected by them.

Appendix A

Table A1

t Tests Versus Zero of Mean Pd Amplitude per Condition, Measurement, and Group

Condition	Measurement	Group	*M*	*SD*	*t*	*df*	*p*
target	pre	CG	−0.20	0.36	−3.06	29	> .999
target	post	CG	−0.26	0.38	−3.75	29	> .999
target	pre	IG	−0.30	0.43	−3.76	28	> .999
target	post	IG	−0.29	0.40	−3.91	28	> .999
target-similar	pre	CG	−0.27	0.33	−4.51	29	> .999
target-similar	post	CG	−0.24	0.33	−3.89	29	> .999
target-similar	pre	IG	−0.23	0.36	−3.45	28	> .999
target-similar	post	IG	−0.12	0.33	−1.88	28	.965
distractor	pre	CG	0.26	0.29	4.94	29	< .001
distractor	post	CG	0.18	0.29	3.32	29	.001
distractor	pre	IG	0.19	0.34	3.01	28	.003
distractor	post	IG	0.16	0.38	2.31	28	.014
control	pre	CG	0.24	2.20	0.61	29	.466
control	post	CG	0.03	2.17	0.09	29	.274
control	pre	IG	0.68	2.89	1.26	28	.109
control	post	IG	0.46	2.22	1.13	28	.135

Note. M = mean, *SD* = standard deviation, IG = intervention group, CG = wait list control group, *df* = degrees of freedom. Time window: 115-225 ms after target onset. Here, we did not correct for multiple comparisons for obtaining p values.

Table A2

t Tests Versus Zero of Mean N2pc Amplitude per Condition, Measurement, and Group

Condition	Measurement	Group	M	SD	t	df	p
target	pre	CG	−1.66	0.88	−10.29	29	<.001
target	post	CG	−1.48	0.77	−10.52	29	<.001
target	pre	IG	−1.54	0.85	−9.68	28	<.001
target	post	IG	−1.4	0.78	−9.72	28	<.001
target-similar	pre	CG	−1.09	0.68	−8.86	29	<.001
target-similar	post	CG	−1.05	0.77	−7.47	29	<.001
target-similar	pre	IG	−0.88	0.58	−8.23	28	<.001
target-similar	post	IG	−0.83	0.52	−8.64	28	<.001
distractor	pre	CG	−0.04	0.38	−0.57	29	>.999
distractor	post	CG	0.01	0.5	0.13	29	.549
distractor	pre	IG	−0.1	0.4	−1.33	28	.098
distractor	post	IG	−0.07	0.45	−0.85	28	.202
control	pre	CG	0.38	2.24	0.93	29	.359
control	post	CG	0.48	2.68	1.31	29	.198
control	pre	IG	1.55	3.11	2.68	28	.821
control	post	IG	1.31	2.19	3.22	28	.833

Note. M = mean, *SD* = standard deviation, IG = intervention group, CG = wait list control group, *df* = degrees of freedom. Time window: 225-300 ms after target onset. Here, we did not correct for multiple comparisons for obtaining p values.

3

Hatha Yoga Increases Executive Control and Task Switching Efficiency: A Randomized Controlled Trial

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Results of this manuscript were presented in a talk at the European Conference of Visual Perception (ECVP) 2023 in Paphos, Cyprus.

Abstract

Understanding conditions optimal for attention switching is of utmost importance. Switching attention between tasks or within tasks is part of the implementation and maintenance of executive control processes and plays an indispensable role in our daily lives: It allows us to perform on distinct tasks and with variable objects, enabling them to adapt to and respond in dynamically changing environments. Here, we tested if yoga could benefit switching of attention between distinct objects of one's focus (e.g., through practicing switching attention between one's own body, mind, feelings, and different postures) in particular and executive control in general. We therefore conducted a randomized controlled trial with 98 participants and a waitlisted control group. In the intervention group, healthy yoga novices practiced hatha yoga three times a week, for eight weeks. At the electrophysiological level, frequency-tagging indicated no interventional effect on participants' ability to switch between the auditory and visual modalities. However, increases in task-related frontocentral theta activity, resulting from the intervention, indicated an ability to increasingly deploy executive resources to the prioritized task when needed. At the behavioral level, our intervention resulted in the more efficient holding of target representations in working memory, indicated by decreased mixing costs. Again, however direct effects on switching were missing. We, thus, conclude that hatha yoga has a positive influence on executive control functions but likely not directly on (or via) the switching function.

Keywords: executive control, mixing costs, task switching, theta, yoga
Clinical trial registration number: NCT05232422 (clinicaltrials.gov)

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Introduction

Executive control refers to the human ability to guide thoughts and action processes through goals and intentions (Miyake & Friedman, 2012). It is, thus, essential for human performance and wellbeing. Executive control encompasses several interrelated higher-order cognitive processes serving goal-directed behavior (Diamond, 2013; Miyake & Friedman, 2012), adaptation to complex situations (Burgess & Simons, 2005), and the control of behavior (Miller & Cohen, 2001; Miyake et al., 2000). Cognitive flexibility, referring to the ability to adapt human thinking and behavior to changing task demands, rules, or priorities (Diamond, 2013), is one of three core functions summarized under the umbrella term executive control (also called executive functions).

The shifting function, a core facet of cognitive flexibility, is important for regulating and directing attention appropriately – that is, for abandoning responses or processing of features and objects that are currently irrelevant, and for initiating goal-congruent processing or action (Friedman & Miyake, 2004; Miyake et al., 2000). Shifting is implied by focusing attention successively on different features, locations or objects, both within or between tasks. This occurs most powerfully through using different top-down control representations or mental sets in turn (e.g., changes between task-control representations for visual search of different target colors or for monitoring of distinct actions). The shifting function, thus, enables humans to perform effectively on multiple tasks and to adapt to changing rules or information in a timely manner (Kiesel et al., 2010).

Importantly, certain physical and mental exercises should benefit executive functions (Diamond & Lee, 2011). Among them is yoga, a holistic approach, encompassing a number of practices of Indian origin that is clearly and explicitly directed at the physical and mental realm simultaneously (Feuerstein, 2012). Here, we looked at hatha yoga because of its popularity, increasing the potential impact of our findings. Hatha yoga emphasizes combining physical and mental exercises, potentially setting it apart from other, more puristic mental (e.g., meditation) or physical (e.g., running) activities. Hatha yoga includes different forms of stretching, changing postures, as well as mindful breathing and imagination (Shapiro et al., 1998). Past research investigating yoga's effect on executive functioning has mainly focused on inhibition (e.g., Luu & Hall, 2017; Oken et al., 2004, 2006; Sandroff et al., 2015; Szaszkó et al., 2023; Telles et al., 2013), working memory (Bowden et al., 2012; Danilewitz et al., 2021; Kyizom et al., 2010; Telles et al., 2012), or both (Gothe et al., 2013; for a review on Yoga's effects on executive functions, see Luu & Hall, 2016). In the current study, we, thus, looked at the impact of a yoga intervention on the shifting function, aiming to close a knowledge gap in yoga's effects on the distinct executive functions. Previous evidence suggests that yoga may influence the shifting function both acutely (Gothe et al., 2013, 2016; Luu & Hall, 2017) and for extended times (Telles et al., 2013; Vhavle et al., 2019; but cf. Fritz & O'Connor, 2022; Oken et al., 2006). However, very few randomized controlled trials have been conducted regarding this question, with most research using clinical or otherwise potentially compromised samples (like sedentary older adults). Our study is one of the first to examine such potential changes in a healthy sample, thereby providing an opportunity to test the hypothesis under more conservative conditions, with less room for improvement from a better pre-intervention level of executive functioning.

Possible reasons for the beneficial effects of yoga on the shifting function include improvements in executive functioning in general through the attentive nature of yoga, where one is encouraged to focus on one's own body, thoughts, feelings, and, in general, the present moment (Schmalzl et al., 2015), as well as a direct training of the shifting function in particular through the shifts of attention during yoga (e.g., from one posture to another or from one object to another) promoting cognitive flexibility relatively directly (Bransford et al., 1999). In addition, the potential stress- and anxiety relieving effect of yoga, achieved through parasympathetic activation (Zaccaro et al., 2018), may also liberate resources for executive control that would otherwise be bound (e.g., by rumination; cf. Derakshan & Eysenck, 2009; Liston et al., 2009; McRae & Gross, 2020).

To examine whether yoga has an effect on the shifting function, in two experiments, we looked at distinct scenarios. To note, our study is the first to distinguish between different types of shifting: shifting between distinct feature-directed control representations (Experiment 1) and between modalities (Experiment 2). In this way, we can test for convergent evidence of shifting improvements across Experiments 1 and 2 and, thus, control for the more specific side conditions of each specific test.

In Experiment 1, we wanted to know if yoga improves participants' ability to switch between representations of searched-for target colors in a visual search task. In Experiment 1, we looked at two types of behavioral costs: that of participants' switches between two distinct task sets for different target colors in subsequent trials (switching costs; Monsell, 2003) and that of sequentially performing multiple tasks versus performing a single task (mixing costs;

e.g., Rubin & Meiran, 2005). In contrast, in Experiment 2, we investigated whether the intervention influenced shifting between auditory and visual modalities (while ignoring the currently unattended modality). For this, we used frequency tagging through steady-state potentials (Norcia et al., 2015; Picton et al., 2003; Vialatte et al., 2010), where we used distinct frequencies for both auditory and visual presentation modalities so that the currently prioritized modality input resulted in higher spectral power than the nonattended one. This enabled us to study the distribution of attention between distinct modalities, as well as their respective changes through the intervention (Saupe et al., 2009; Talsma et al., 2006). Additionally, we looked at a single oscillatory frequency bands known to be critical for optimal task switching: Theta (4-7 Hz) oscillations. Increased frontoparietal connectivity and spectral power in the theta range, particularly in midfrontal regions, has been repeatedly linked to enhanced cognitive flexibility and executive functioning (Cavanagh et al., 2012; Gevins et al., 1997). These oscillations also reflect diverse memory-related processes vital for task switching: the reactivation of task set memories (Gladwin & de Jong, 2005), successful manipulation of working memory content (Itthipuripat et al., 2013; Karayanidis et al., 2009), and facilitated encoding, retrieval, and transfer between memory systems (Klimesch et al., 1994, 2001; Rizzuto et al., 2006; Sauseng et al., 2002). Such (working) memory processes are integral to task switching because maintaining different relevant task-control representations in memory is essential to swiftly switch between them if the conditions require this. In line with this reasoning, increased theta activity and connectivity are associated with task switching (Cooper et al., 2015; Sauseng et al., 2006) and theta activity, originating in medial cingulate cortex. is a key to maintaining task-control representations (Cohen et al., 2008; Cooper et al., 2017). Neurofeedback studies even suggest a causal role of theta in switching performance (Enriquez-Geppert et al., 2014).

If yoga improves switching performance, in Experiment 1, we expected that the intervention decreased switching costs and mixing costs compared to the control group (H1). In Experiment 2, following the intervention phase, we expected higher (vs. lower) spectral power differences in the tagging frequency - or its second harmonic - of the attended (vs. unattended) modality in the intervention group versus the control group, relative to the pretest baseline differences (H2a). Looking at the period directly after a modality switch, we also expected changes in power at the respective tagging frequency or their second harmonic (H2b). Additionally, if the yoga intervention increased task switching or altered executive control processes in general (i.e., even in case that H2 could not be confirmed), we expected increased clustered theta activity in response to a switch (H3).

Method

Participants

Initial recruitment (from November 2021 until April 2022) consisted of 116 participants, 98 of which (NIntervention = 54; 83 female; MAge = 25.03 years; SDAge = 4.18 years; range 18-40 years) completed baseline questionnaires and both pretests, thus, still being part of the study once the intervention started. Our intended sample size was 102 in order to achieve 80% power with d = 0.5 and an alpha error probability of .05, not only for our EEG data (which typically result in very high power) and experiments, but also the questionnaires used. Figure 1 shows the trial profile of the study in form of a CONSORT chart. We recruited participants via the University of Vienna's Laboratory Administration for Behavioral Sciences (LABS) platform and the Vienna Cognitive Science Hub's Study Participant Platform (SPP), and via advertisement through flyers and social media.

Next, we screened potential participants with a shortened version of the Diagnostic Interview for Mental Disorders (Mini-DIPS; Margraf, 1994). If subjects showed possible current or past psychiatric or psychological disorders, they were excluded from the study. We did this for several reasons: First, focusing on a non-clinical, general, and healthy sample helps to enhance the generalizability and external validity of our findings. Studies on the impact of yoga on specific populations are abundant (Bilderbeck et al., 2013 for prison inmates; Gothe et al., 2014; 2016 for older adults; Oken et al., 2004, for patients with multiple sclerosis), and we aimed to contribute insights relevant to the general population, even if this meant we measured the impact more conservatively (i.e., in a group benefitting less because they were already good at task shifting and executive control). Second, assessing cognitive abilities in individuals with psychiatric or psychological disorders can be challenging due to the potential confounding effects of their conditions. Individuals with such disorders may also have different baseline cognitive abilities, making it difficult to attribute any observed changes solely to the intervention.

Participants that had practiced yoga more than twice a month for the last 12 months, those that consumed psychopharmaceuticals regularly, as well as those with alcohol or drug abuse were also excluded. In addition, only participants between 18 and 40 years of age were admitted. Participants were also excluded if they had below level C1 German proficiency, uncorrected impaired vision or hearing, or had suffered a skull fracture or concussion within the past 6 weeks. For legal reasons at the time of the study, lack of proof of COVID-19 recovery or vaccination also led to exclusion from the study.

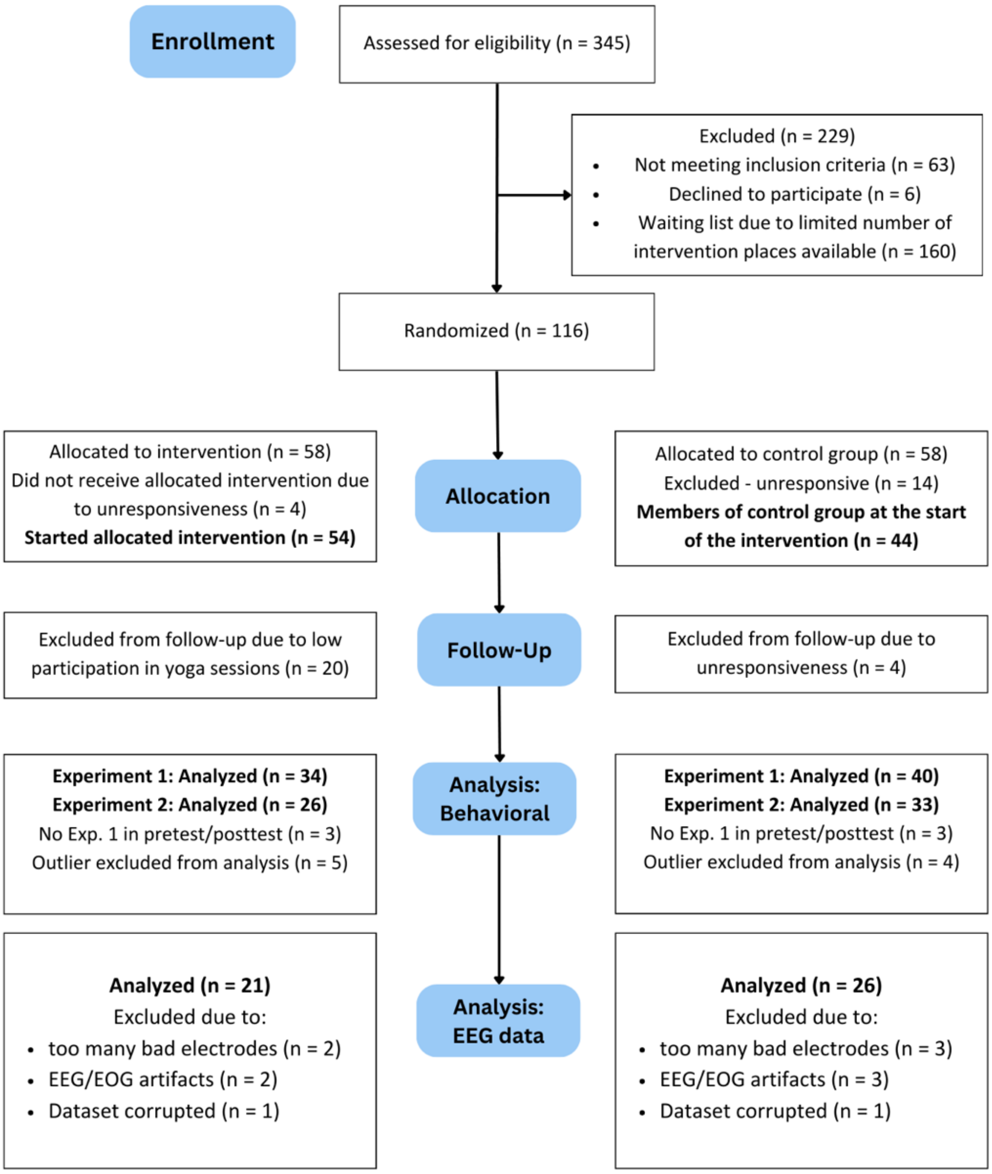
The starting date of our intervention was pre-set, and pretesting laboratory capacity was limited. Therefore, whenever a participant opted out during the pretesting phase, substitutes from the waiting list were invited to participate in the experimental group instead. However, sometimes no fitting testing slots were available anymore. Thus, already from the outset, the total number of participants was lower than intended.

To compare against the intervention, we used a control group not taking part in the intervention. This comparison is maximally sensitive to any beneficial effect the yoga intervention might have because the waiting list group did not receive any treatment at all before posttests were administered. However, using this approach also meant that double-blinding was not possible. It was clear to participants if they were participating in a yoga intervention or not (the waitlist control group). The same was true of the yoga teachers. They were aware that they were teaching yoga classes. However, participants and yoga teachers were naïve with respect to the hypotheses of the current study, and yoga teachers were not involved in the analyses of the data. In addition, a pre-post comparison of participants' performance in different cognitive tasks meant that participants were instructed to perform as well as they could at each measurement time point. Thus, forging of the hypothesized intervention-dependent performance difference between pre- and posttest was unlikely and would have required sophisticated knowledge and strategies on the side of the participants (e.g., participants' holding back during pretest measurement and giving it their best at posttest measurement in the intervention group based on their expectations of what we would have hypothesized).

During the first pretest session, participants were briefed on the procedure and risks of the study and gave their written informed consent. After this session, participants were assigned to a group using block randomization (block size: 4; custom Python script written and executed by the first author). All participants were debriefed in the second posttest session. Participation in pretests / posttests was compensated with a payment of 30 EUR each, with a bonus payment of 10 EUR (20 EUR) for participation in an average of four (five) classes per week. There were no adverse experiences associated with the intervention or the waitlist reported by any of the participants throughout the duration of the intervention; one participant had to abort Experiment 1, as she did not feel well during practice trials.

Figure 1

Trial Profile



Note. Reasons for exclusion after the previous analysis step are listed below the number of analyzed participants for each step. When participants were excluded from behavioral analyses, their EEG data was also not analysed. EEG: Electroencephalography; EOG: Electrooculogram.

Study Design and Intervention

The present experiments were part of a larger study with a parallel design investigating the effect of a hatha yoga intervention on stress, anxiety, and the executive function of suppression. Data collection began in January 2022 and ended in August 2022. In the course of this study, we used questionnaires, behavioral, electrophysiological, and biological markers. Detailed results on these measures, as well as experimental and electrophysiological results on the inhibition function can be found in Szaszkó et al. (2023). Because the present study mainly focuses on hatha yoga's effect on the shifting function, the results concerning hormonal stress markers and their relations to stress, anxiety, and cognitive functioning will be published in a following manuscript.

After preselection, participants were pseudo-randomly assigned to an intervention- and a waitlisted control group, to ensure equal group sizes. The intervention group was split into two cohorts. During two pretest sessions, participants gave their informed consent, were scanned for colorblindness using an Ishihara test, filled out questionnaires, were trained on the collection of saliva samples, and, in the laboratory of the University of Vienna, completed a suppression task and two switching tasks. The days after pretests, participants submitted their saliva samples. Participants in the intervention group were required to attend at least three 60-min yoga classes per week, for a total of 8 weeks. Subjects were excluded if they failed to participate at least twice for 3 consecutive weeks. This led to an average participation of 2.55 sessions per week (SD = 0.55).

Classes were taught privately by four professional yoga instructors at the "FREIRAUM" studio in Vienna. Table 1 shows the focus of each week's classes. Online pre-registration was required to track attendance, which was then double-checked by the yoga teachers at the beginning of class. Following the 8-week intervention, participants took part in two posttest sessions, which consisted of the same suppression and switching tasks, as well as questionnaires participants had previously completed during pretests, collection of saliva samples, and a debriefing. Participants in the control group underwent the same process as those in the intervention group, except for the yoga intervention. Once posttests were completed, they were, however, given the opportunity to participate in yoga classes free of charge for a duration of 8 weeks.

Table 1

Focus of Yoga Sessions per Week and Exemplary Asanas (Yoga Postures)

Week	Focus	Exemplary Asanas
1	Sun salutation, breathing exercises	Downward Facing Dog, Cobra Pose, Sprinter Pose
2	Standing positions	Warrior I and II, Triangle Pose, Chair Pose
3	Forward Bends	Different variations of Forward Bends, Pigeon Pose, Butterfly Pose
4	Twists	Waist Turn, Crocodile Pose, twisted Triangle Pose
5	Backbends	Shoulder Bridge, Locust Pose, Bow Pose
6	Sitting poses	Lotus positions, Boat Pose, Child Pose
7	Balance	Tree Pose, Warrior III, Crow Pose, Half Moon Pose
8	Combining focuses 1-7	Combinations of the previous exemplary asanas

Note. Taken from Szaszkó et al., 2023. In each week of the hatha yoga intervention, comprising a total of eight weeks, a different focus was set, which determined the practiced *asanas* (yoga postures) of that week. This focus had to be applied by all yoga teachers when teaching their respective individual yoga sessions.

We used a per-protocol (PP) approach to analyze the data. This may have had some impact on the generalizability of our findings, disabling us from benefitting from some of the conventional benefits of randomization (Tripepi et al., 2020). However, because our focus lay less on generalizability to the whole population and more on investigating the efficacy of our yoga intervention in a healthy sample, the approach is acceptable (Green et al., 2019). By imposing strict exclusion criteria and including only those participants that rigorously adhered to the intervention schedule we believe we were able to gather information truly representative of the intervention's impact. In this sense, our study is what Green et al. (2019) considered a mechanistic study. Besides, compared to intention-to-treat analyses, the PP approach is more vulnerable to self-selection bias (Andrade, 2022), but it does not require data imputation. By only considering the actually observed data of participants that complied with the instructions of the experimental tasks and the requirements of the intervention protocol, the PP approach navigates around the pitfalls of large numbers of imputed data, thus, reflecting more accurately the interventions' impact.

Experiment 1: Switching Attention Between Colors

Apparatus, Stimuli, and Procedure

In Experiment 1, participants had to search for a color-defined target ring and report the orientation of a letter T within the target. The experiment consisted of two blocked conditions: a single-color condition and a dual-color condition. In the single-color condition, the target was always of the same color defined at the beginning of the block (red, a* = 65, b* = 56, or green, a* = −47, b* = 48, between blocks). In the dual-color condition, in each trial, the target could unpredictably take on one of two colors (red or green, within blocks), with both instructed as target-defining colors at the start of the block.

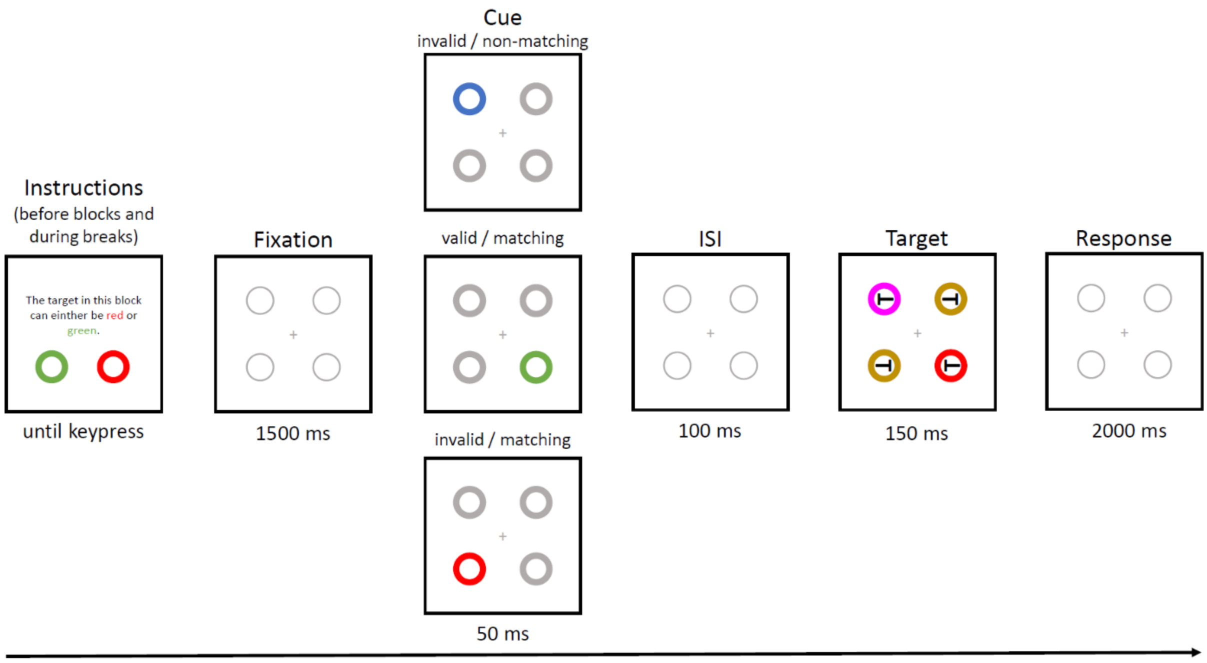
The experimental task was presented on a 24.5" G2590PX AOC Gaming LCD monitor (with 54.4 cm x 30.3 cm visible), with a refresh rate of 100 Hz. Responses were logged using a QWERTZ- keyboard. Viewing distance was held constant at 57 cm using a chin-forehead-rest. OpenSesame (Version 3.3.10; Mathôt et al., 2012) was used to present the task.

The experiment started with an instruction screen, in which participants were instructed about the target color(s) of the block. In each trial, participants first saw a grey fixation cross (0.6° x 0.6°) presented for 1 s against a black background (L* = = 8, a* = 23, b* = −27), and, next, a cueing display for 50 ms, containing four gray (L* = 70, a* = −4, b* = 1) rings (outline width: 0.1°; radius: 1.2°) with a 2.7° eccentricity. The rings were presented on the corners of an imagined square centered on the screen. One of the rings in the display was a color singleton. It took on either the target color (in single-color blocks) or one of the target colors (in dual-color blocks), which all constituted instances of top-down matching cues (as they matched a task set), or the cue took on another color, blue (a* = 25, b* = −85), constituting a nonmatching cue. Matching and nonmatching cues were equally likely, and participants did not know in advance which cue was presented. For each trial, one cue appeared at the location of the target (valid trials) or at a location away from the target (invalid trial). Across trials, cue and target positions were uncorrelated. Therefore, the cues were not predictive of the target locations. After an interval of 100 ms following the cueing display, the target display was presented for 150 ms. The target display consisted of four rings. All of them were colored, one of them in the target color. All colors used were equally bright ($L^* = 70$). Two rings were yellow ($a^* = -5$, $b^* = 49$), and one ring was either magenta ($a^* = 75$, $b^* = -69$) or cyan ($a^* = -29$, $b^* = -13$), with equal probability. Figure 2 illustrates an exemplary trial. All circles in the target display contained a horizontally tilted T, two of them oriented to the left, the other two to the right, with different orientations pseudo-randomly distributed across all four possible stimulus locations. Participants reported the target T by pressing Key "y" to a counter-clockwise and key "m" to a clockwise tilted T. In two-color blocks, the target color changed with .5 probability from trial n to n + 1, yielding equal numbers of trial-by trial target-color changes and repetitions.

Participants were instructed to respond as fast and accurate as possible. Feedback was given on screen for 500 ms after wrong responses (the message "wrong" was displayed) and after response times exceeding 1,200 ms ("respond faster" was displayed). The experiment consisted of four blocks containing 240 trials and 24 practice trials each. Blocked conditions (single- vs. dual-color) were either A-B-A-B or B-A-B-A, balanced across participants.

Figure 2

Exemplary Trial of Experiment 1



Note. Taken from Büsel et al. (2019). Blocks began with an instruction display showing possible target colors, which, in single-color blocks, were red or green (in different blocks, one block with red, one with green color), and in dual-color trials (depicted here) were red *and* green, but only one of the colors was realized unforeseeably per each trial. After a fixation display, a cueing display followed, with as singleton-color cue in a unique color either matching (same color as one of the potential target colors) or not matching (color different from all potential target colors) the top-down set. Cues could also be valid (same position as target) or invalid (position different from that of the target). After a fixed interstimulus interval, the target display with four black "T"s was presented. "T"s were tilted to the left or right with equal probability, and surrounded by colored rings, one of which was the target color. Participants had to indicate the direction of the tilt (here, left) inside the ring with the target color by keypress.

Data Analysis

Behavioral data (of both experiments) was analyzed using RStudio (Version 1.4.1717; RStudio Team, 2021) with R (version 4.1.2; R Core Team, 2021), based on the packages 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). We excluded participants using a generalized Extreme Studentized Deviate (ESD) sensitive for multiple outliers (Rosner, 1983) with an alpha level of .05. In Experiment 1, we analyzed participants' response times (RTs) and accuracy rates (ARs).

For RT analysis, individual trials in which participants' RTs exceeded ± 2.5 SDs from their individual mean RTs were removed. This was done to ensure that mean performance was representative for each condition and not distorted by extreme outliers. Where indicated, we corrected for multiple comparisons using the Holm-Bonferroni method (Holm, 1979)

To measure switching costs (for both RTs and ARs), we used a two-color search task and compared performance between trial-by-trial target-color switches (e.g., between a green target in Trial x and a red target in Trial x + 1) versus trial-by-trial target-color repetitions. (2) To measure mixing costs, we compared performance (again for both RTs and ARs) between trials where participants searched for two potential target colors as compared to trials where participants searched for one target color, with trial-by-trial target color repetitions only.

The effects of the intervention were calculated by subtracting posttest from pretest values and by comparison between groups using independent-samples t-tests (one-sided only in case of directional hypotheses).

Experiment 2: Switching Attention Between Colors

Apparatus, Stimuli, and Procedure

Picking up upon a general problem concerning task-switching experiments, here, we encouraged switching. Typically, switching between tasks slows responses and decreases accuracy. These switching costs imply that, for the participants, there is not much incentive to willingly switch a task. This is even the case with cued switches (so-called "residual switch costs", e.g., Monsell, 2003). In the current Experiment 2, however, we ensured participants' willingness to switch tasks by providing a relatively substantial performance benefit for the switches.

We used a two-back memory comparison task in which participants perceived a stream of stimuli in two modalities, and, depending on which modality was currently relevant, compared the current input from one modality to that of a stimulus two positions back in time in the same modality. In this situation, participants perceived a switch cue (present in both, the visual and auditory modality) indicating that they should switch from vision to audition or vice versa (depending on which of the two tasks was currently carried out). In this n-back task, participants are likely to willingly switch between tasks and happily drop the ongoing task because a task switch means that the modality-specific information currently held in working memory can be dropped with immediate effect. To note, this should mitigate switching costs, but, in Experiment 2, we focussed on electrophysiological outcomes anyway. Therefore, unlike in Experiment 1, we do not report switching (and mixing) costs here.

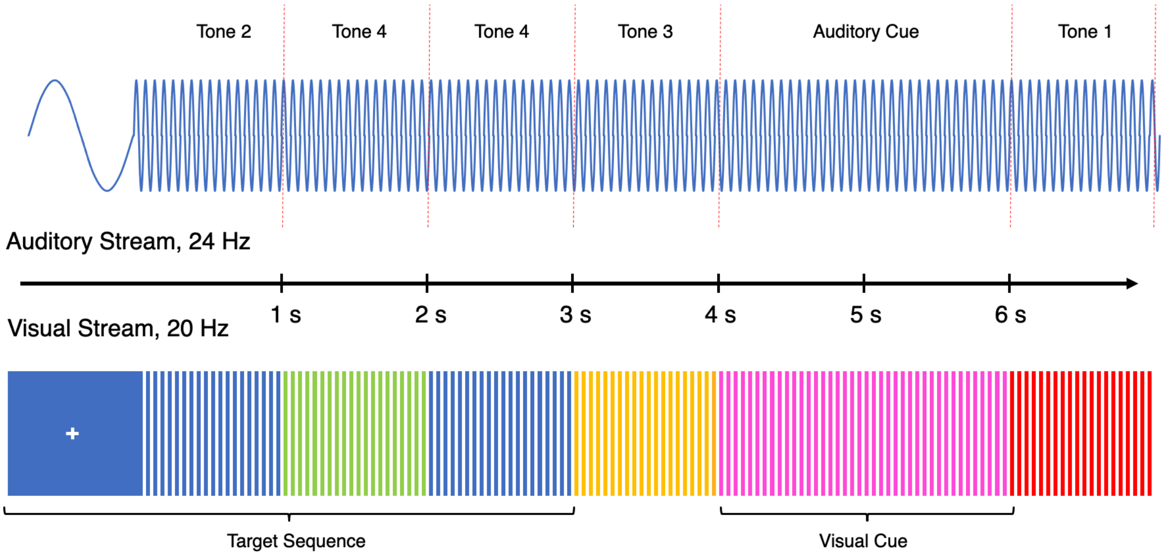
Participants completed the experimental task on a 19” CRT monitor (Sony Multiscan). The monitor had a resolution of 1,280 × 1,024 pixels and an aspect ratio of 4:3. The refresh rate was 100 Hz. PsychoPy 3 (Peirce & MacAskill, 2018) was used to present the task. The distance between participants’ eyes and the screen was 57 cm and kept constant by a chinrest. A conventional QWERTZ-keyboard was used for collection of participants’ responses. The experiment took place a soundproof, dimly lit room. Participants had to complete a two-back task, in which they were concurrently presented with stimuli at a consistent rate in the visual (20 Hz) as well as in the auditory (24 Hz) domain, using modality-unique tagging frequencies. Figure 3 illustrates a part of an exemplary block. Stimuli in the visual domain consisted of four differently colored equiluminant (CIE L*a*b*, L* = 60) rectangles (orange: a* = 61, b* = 71, blue: a* = 12, b* = −71, red: a* = 80, b* = 69, green: a* = −54, b* = 55) at screen center on a black (L* = 3.3, a* = 0.1, b* = −6.5) background and changed color once per second, while flickering at 20 Hz. We used a black background to increase contrast and, thereby, salience of the visual stimuli. The visual target was a pattern of a blue rectangle followed by another blue rectangle, with one differently colored stimulus in-between (i.e., a two-back task). In the auditory domain, a total of six pure tones (at frequencies of 311 Hz, 440 Hz, 622 Hz, 880 Hz, 1244 Hz, 1760 Hz, with a sinusoidal waveform) served as stimuli. Analogous to the visual task, the auditory target was a pattern of a 1,760 Hz tone followed by another 1,760 Hz, with one different tone in-between. Participants were informed about the identity of the target patterns before the experiment had started. Auditory and visual targets could not appear at the same time. The number of targets followed a Gaussian distribution, ranging from three to eight targets per block and modality. If a stimulus had the characteristic N in Trial X, it could not assume the same characteristic N in the following Trial X + 1 (i.e., if a visual stimulus was blue in Trial X, it could not be blue again in Trial X + 1). Sound volume was adjusted to individually comfortable levels. Subjects were required to respond to a target pattern in both the visual and auditory condition by pressing the “down arrow” key as fast and accurate as possible.

The experiment itself did not consist of distinct trials, but of 15 blocks of 180 s of auditory and visual stimuli presented continuously and concomitantly, with self-paced breaks in between blocks. By doing so, we refrained from the traditional combination of switch- versus repeat trials (including repetition cues), using our experiment in a more ecologically valid framework with concurrent information presented for a varying amount of time, with high temporal ambiguity regarding possible switches. This meant that direct comparisons of switching and repetition performance are difficult to interpret. Remember, however, that our focus was on the evaluation of the (electrophysiological) outcomes of switches to either one or to the other modality, as well as the related interventional effects. At the beginning of the experiment, participants completed a 3-min practice block, which they could repeat if necessary. Before and after the experimental blocks, participants also completed two 1-min baseline blocks where only stimuli in one modality were presented. These four blocks (two auditory, two visual) were used to calculate a baseline for the respective steady-state potentials and to demonstrate that these potentials were present (and present only in the according condition).

In the experimental blocks, participants had to attend to only one of the two modalities at the same time, resulting in the two conditions, here called attend-to-auditory, and attend-to-visual. To achieve this, participants were cued at the beginning of each block as well as at random times during blocks by a bimodal stimulus signaling a switch in modality. For this, the rectangle changed its color to pink ($L^* = = 60$, $a^* = 80$, $b^* = 13$) or turquoise ($L^* = = 60$, $a^* = -28$, $b^* = -13$). Which color signaled a switch to which modality was counterbalanced across participants. The task cue was shown for 2 s, with every other color shown for 1 s. In the auditory domain, concurrent with the visual cue, one of two distinct tones could be heard, depending on the to-be-attended-to modality (cues were always presented in both modalities). How often certain auditory and visual stimuli appeared as well as the number of switches to both domains (40 for each domain) was counterbalanced across blocks. The auditory task-switching cue was presented for 2 s, synchronized with the visual task-switching cue.

Figure 3

Schematic Illustration of Part of an Exemplary Block in Experiment 2



Note. Depicted is the bimodal n-back task in Experiment 2, during which participants had to detect a certain pattern (a repetition of the color blue/the highest tone with one stimulus in-between) in the respective to-be-attended-to modality. The blue sine wave in the auditory domain represents sequential stimulation with six distinct tones of equal durations (1 s each) but of distinct high frequencies (Tones 1 to 4 + one other frequency that was used for the cue) that each were presented 24 times per second. Red dotted vertical lines indicate a change between subsequent tones occurring every second (with the exception of the cue that lasted for 2 s). The auditory cue consisted of a single pure tone that lasted for 2 s and indicated a switch of the to-be-attended-to modality. In the line below, the rectangle with the fixation cross and the colored lines to the right of it represent stimulation by six consecutively presented and differently colored rectangles in the visual domain at the center of the screen, each presented 20 times per second, with colors switching every second (again with the exception of the cue). Colors switched every second and in synchrony with the auditory stimuli. An exception to this rule is the visual cue (one of two colors, depending on the to-be-attended-to modality), which lasted for 2 s. The first set of blue stimuli, followed by a second set at position n−1 represents the target sequence in the visual modality to which participants were asked to respond. The set of pink stimuli represents the visual cue which, together with the synchronously presented auditory cue signaled that the other modality was now to be attended to.

Data Recording, Processing, and Analysis

Behavior. We conducted a 2 × 2 × 2 mixed analysis of variance (ANOVA), with Measurement (pre/post), Condition (visual/auditory), and Group (intervention/control) on participants' false alarm rates (defined as number of false alarms divided by the total of all stimuli that could have provoked a false alarm). We used partial eta squared (eta2) as the effect size measure as well as a significance level of alpha (α) of .05 and planned to follow-up with post-hoc t tests in case of a significant interventional effect. We did not report RT and AR analysis because the experiment was not designed to measure classical switch costs (i.e., overt responses were not that frequent and given only to the second of two similar stimuli following a switch cue, i.e., at least 3 s after a switch cue).

Electroencephalography Recording and Preprocessing. EEG data was recorded using an ActiveTwo Biosemi™ electrode system (BioSemi B.V., Amsterdam, Netherlands), at 512 Hz. From 132 electrodes in total, 128 were scalp electrodes, mounted in an equiradial ABC layout. Out of the remaining electrodes, two measured the horizontal and vertical electro-oculogram on the right side and two, located bilaterally on the mastoids, were offline reference electrodes.

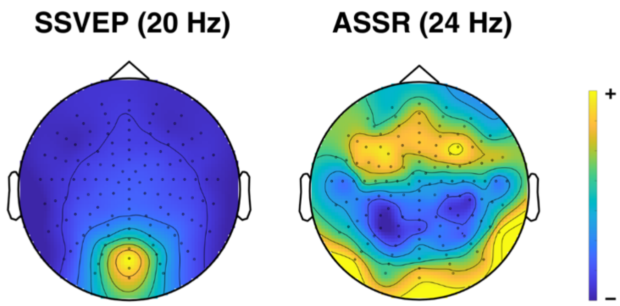
EEG data was analyzed using MATLAB (The MathWorks Inc., 2022) and preprocessed with EEGLab (version 2022.1; Delorme & Makeig, 2004) using custom code. Two datasets had to be excluded due to corruption. First, data were resampled to a sampling rate of 256 Hz, after which they were low-pass (1 Hz) and high-pass (40 Hz) filtered. We then separated data according to condition (visual baseline, auditory baseline, attend-to-visual, attend-to-auditory) and rejected faulty channels manually. Five participants were excluded, as more than 15% of their channels had to be rejected in any of the conditions. Next, we created epochs: For analysis of the spectral power of steady-state visual evoked potentials/auditory steady-state responses (SSVEP/ASSR), independently of switching — we selected the first 10 s after each switch and divided the data into 2-s epochs. This was necessary to provide comparability of data in both modalities as the length of each attend-to-modality-X section was pseudorandomized. For time-frequency analysis, which we used to investigate the time course of spectral changes in the data, especially around the time of switches of the to-be-attended-to modality, we selected epochs of 3 s length, with epochs starting 1 s before and ending 2 s after the time-locking stimulus (here, the cue indicating a modality switch). Epochs containing artefacts other than eye blinks were manually rejected by trained personnel. After exclusions, if more than 25% of epochs in any of the four conditions at pretest or posttest had to be excluded, the participant was excluded from further data analysis entirely (five participants). From the data of the analyzed participants, an average of 4.13% of epochs was rejected. An independent component analysis (ICA) was run on the remaining data to identify components reflecting eye blinks and other artefacts, which were manually rejected. Only then did we interpolate rejected channels to not cause rank deficiency problems in ICA due to additional dimensions of previously interpolated channels with a near-zero eigenvalue.

Spectral Analysis. After preprocessing, we conducted a spectral analysis using the FieldTrip toolbox (Oostenveld et al., 2011), to investigate whether there were changes in steady-state responses due to the intervention. For this, raw power was calculated from 1 to 42 Hz, in 1-Hz steps, for each participant at each timepoint, by applying a Fourier transform using multitaper frequency transformation based on discrete prolate spheroidal sequences (Percival & Walden, 1993). To identify steady-state potentials significantly different from noise (Meigen & Bach, 1999), to increase their visibility (Derzsi, 2021), and due to the wide range that participants' absolute power in distinct frequencies usually takes, we transformed participants' raw power values into signal-to-noise ratio (SNR). We did this by dividing the raw power values for each frequency band, timepoint, and channel for each participant by the average raw power of the neighboring frequencies (−2 Hz, −1 Hz, +1 Hz, +2 Hz). Further, we subtracted a value of one from the resulting SNR, so that it can be seen as a signal measure relative to the noise level (here, the denominator of the SNR).

For both attend-to-visual and attend-to-auditory conditions, we averaged over those channels where the respective SNR of the steady-state responses was the highest, collapsed over pre- and posttests (four occipital channels for SSVEP, fifteen frontocentral channels for ASSR).

Figure 4

Topographical Map of Spectral Activity for Steady-State Responses



Note. Topographical distributions of the steady-state visual evoked potential (SSVEP), the auditory steady-state response (ASSR), averaged across pre- and posttests, groups, and conditions. Yellow areas indicate the highest levels of activity, dark blue areas indicate the lowest levels.

We then conducted repeated-measures ANOVAs to 1) show that there were steady-state responses present at the stimulation frequencies in the experiment, and 2) test whether the intervention had any effect on the SNR of these steady-state responses (H2a). For 1), we focused on the baseline conditions where only an SSVEP (but not an ASSR) should be present in the visual baseline condition, and only an ASSR (but not an SSVEP) in the auditory baseline condition, and computed three repeated-measures ANOVAs with Measurement, Condition and Group as independent variables, and with spectral SNR at posterior-occipital electrodes at 20 Hz and 40 Hz (sensitive to the frequency of the visual stimulus), and at frontocentral electrodes at 24 Hz (sensitive to the auditory stimulus) as dependent variables. We expected to find significant main effects of condition (indicating the sole presence of the appropriate steady-state potential), and no threefold interactions. For 2), we conducted three additional 2 × 2 × 2 mixed ANOVAs for data from the experimental blocks, with Measurement, Condition and Group as independent variables, and the dependent variables SNR at 20 Hz and 40 Hz at posterior-occipital electrodes, and SNR at 24 Hz at frontocentral electrodes. If the yoga intervention had a significant effect on participants' SSVEP or ASSR (H2a), we expected to find a threefold interaction. In further exploratory analyses, we also looked at the spectral changes in theta and alpha range (shown in Appendix A).

Time-Frequency Analysis. To test H2b and H3, using the FieldTrip toolbox again, we conducted a time-frequency analysis with a time window of 1 s before, until 2 s after stimulus onset. For this, we used multitaper method convolution with Hanning tapers. The time from 1 s until 0.25 s, before the onset of the cue signalizing a change in to-be-attended-to modality (requiring participants to change their focus of attention from the visual to the auditory modality or vice versa), was used as a baseline, against which we normalized the rest of the data in the epoch by subtracting the mean of the baseline from each data point and then dividing each resulting value by the baseline. By this, we obtained the relative change in power in the current modality compared to the previously attended-to modality. This resulted in a participant × channel × frequency × timepoint matrix, averaged over distinct trials. We then subtracted pretest from posttest normalized power values for each participant, channel and timepoint, and, using cluster-based permutation tests with 1,000 permutations and an alpha level of .05, tested whether there were significant clusters in the data reflecting differences between the intervention and the control group.

For the analysis of SSVEP (20 Hz, 40 Hz) and ASSR frequencies (24 Hz) (H2b), we averaged over the channels where these steady-state responses were present (see spectral analyses above). Regarding theta's role in aiding task switching (H3), we were interested in 1) whether there were significant clusters showing changed theta activity in the data in response to a switching cue, 2) which distinct frequencies within these frequency bands were particularly affected by these changes, and 3) their exact time course, potentially revealing more about the neural changes that took place due to the intervention aiding task execution or switching. We ran a permutation test for theta (4-7 Hz) activity, including all 128 channels in our analysis, and treating them, just as all timepoints and frequencies, as independent data points. When we found a significant difference, indicative of an effect of the intervention, we followed up calculating contrasts (paired t tests) by testing for significant clusters of pre-to-posttest differences in relative changes of power for each group separately, restricted to the timeframe where the interaction was significant.

Results

Participant characteristics

Three hundred and forty-five participants were assessed for eligibility between December 2nd, 2021, and April 27th, 2022. For the exact allocation of places on the waiting list, see Szaszkó et al. (2023). One hundred and sixteen participants were admitted to the trial, out of which 98 participants were part of the study at the start of the intervention. For baseline characteristics, see Table 2.

Table 2

Baseline Characteristics of the Intention-to-Treat Population (from Szaszkó et al., 2023)

	Total (n =100)	Intervention (n = 44)	Control (n = 56)	p
Age (in years)	25.12 ± 0.42	24.73 ± 0.72	25.61 ± 0.50	.316
Gender (n = 99)				.673
Women	81 (81.8%)	45 (81.8%)	36 (81.8%)	
Men	18 (18.2%)	10 (18.2%)	8 (18.2%)	
Working hours per week				.872
0	22 (22.0%)	12 (21.4%)	10 (22.7%)	
1–20	52 (52.0%)	30 (53.6%)	22 (50%)	
20–40	23 (23.0%)	13 (23.2%)	10 (22.7%)	
Over 40	3 (3.0%)	1 (1.8%)	2 (4.6%)	
Smoking (at least occasionally)				> .999
Yes	29 (29.0%)	16 (28.6%)	13 (29.6%)	
No	71 (71.0%)	40 (71.4%)	31 (70.4%)	
Alcohol use (at least occasionally)				> .999
Yes	84 (84.0%)	47 (83.9%)	37 (84.1%)	
No	16 (16.0%)	9 (16.1%)	7 (15.9%)	
Physically active (min. 1x per week)				> .999
Yes	70 (70.0%)	31 (70.4%)	39 (69.6%)	
No	30 (30.0%)	13 (29.6%)	17 (30.4%)	
Mindfulness practice (not yoga)				.991
Yes	17 (17.0%)	9 (16.1%)	8 (18.2%)	
No	83 (83.0%)	47 (83.9%)	36 (81.8%)	
Depression (PHQ-9; 0-27)	7.09 ± 0.44	7.53 ± 0.61	6.52 ± 0.62	.248
BMI	21.91 ± 0.29	21.71 ± 0.36	22.18 ± 0.48	.430
Somatic symptoms (PHQ-15; 0–30)	6.53 ± 0.45	6.73 ± 0.67	6.27 ± 0.60	.611
Stress (PHQ; 0–20)	4.43 ± 0.30	4.41 ± 0.47	4.45 ± 0.40	.943

Note. Data are presented as mean ± SD or n (%). BMI: Body-Mass-Index. PHQ: Patient Health Questionnaire. Three subscales of the PHQ are reported here: PHQ-9 assessing depression, PHQ-15 assessing somatic symptoms, and 10 specific questions of the PHQ assessing stress. p values are calculated from independent samples t-tests for continuous variables, and Chi-squared tests for categorical variables.

Experiment 1: Switching Attention Between Colors

Seventy-four participants completed the first experiment during both pretests and posttest. We did not have to exclude any of these participants, so that data of all 74 participants could be analyzed (64 female; NIntervention = 34, MAge = 24.95 years; SDAge 4.48 years; range 18-40 years).

Switching Costs

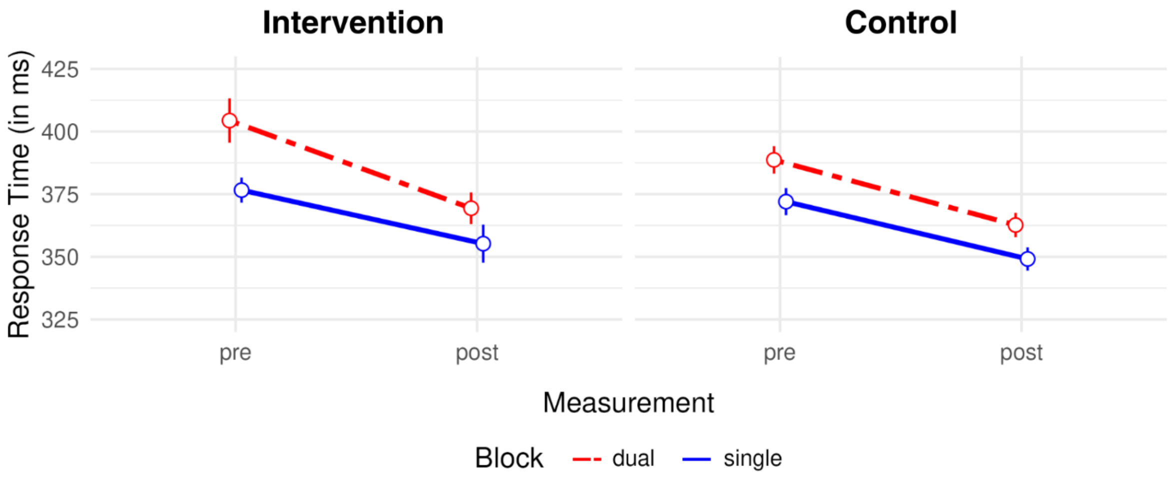
Switching costs were present in RTs (in both pre- and posttests), $M = 8$ ms, $t(73) = 5.61$, $p < .001$, $d = 0.65$; but the intervention had no effect on RT switching costs, $M = 1.49$, $t(73) = 0.40$, $p = .346$, $d = 0.09$. For hit rates, we did not find switching costs, $M = 0.05\%$, $t(73) = 0.26$, $p = .399$, $d = 0.03$. The intervention also had no effect on switching costs in hit rates, $M = -1.10\%$, $t(72) = -1.62$, $p = .945$, $d = -0.38$.

Mixing Costs

As expected, in dual-color blocks, RTs were 18 ms longer than in single-color blocks, $t(73) = 8.59$, $p < .001$, $d = 1.00$, reflecting mixing costs. Importantly, mixing costs decreased 10 ms more in the intervention group than in the control group compared to pretest baseline, $t(72) = 1.75$, $p = .042$, $d = 0.41$. Figure 4 shows mixing costs for RTs. We also found mixing costs in hit rates, $M = 1.46$ %, $t(73) = 4.04$, $p < .001$, $d = 0.47$. Unlike in RTs, the intervention did not affect mixing costs in ARs, $M = 0.38\%$, $t(72) = 0.25$, $p = .403$, $d = 0.06$.

Figure 4

Mixing Costs in Response Times



Note. Dual-color (red dashed line) versus single-color (blue solid line) trial-by-trial target color repetitions as a function of pre- and posttest measurements and groups (intervention vs. control). The difference in response times between dual- and single-color blocks per measurement and group equals the mixing costs. Vertical bars indicate 95% CIs.

Experiment 2: Task Switching Between Modalities

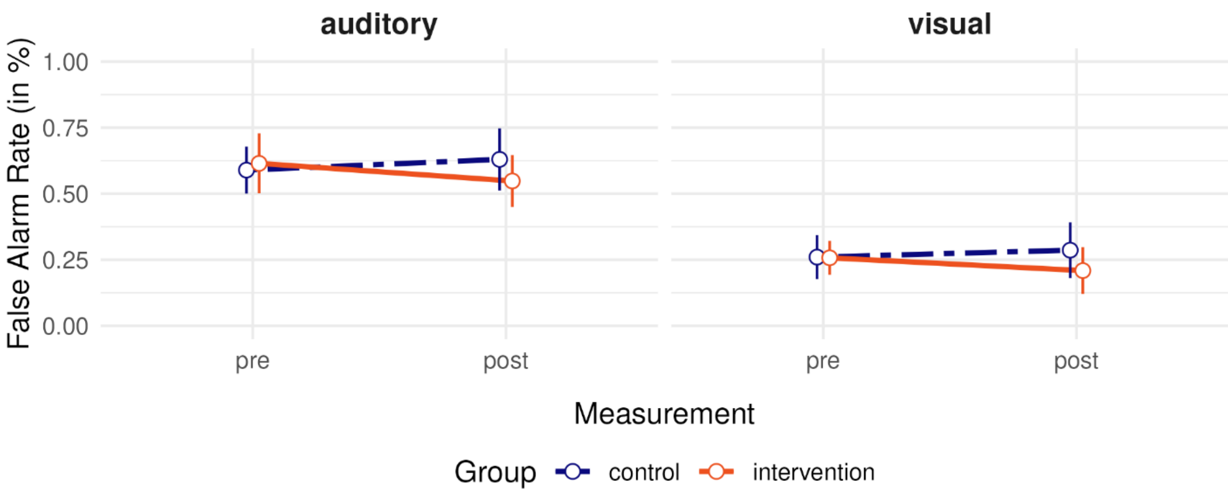
Behavioral Results

Sixty-eight participants completed the experiment both during pretests and posttests (with every participant who completed Experiment 1 completing Experiment 2 as well, ensuring a highly overlapping sample). If a participant missed out on too many targets, or if a participant had too many false alarms (as this mostly resulted from not knowing about the correct to-attend-to modality), we excluded them from the experiment. This resulted in nine exclusions altogether, leaving 59 participants (51 female, NIntervention = 26, MAge = 25.01 years; SDAge = 4.57 years; range 19-40 years) for behavioral data analysis.

The mixed ANOVA resulted in a significant main effect of Modality, $F(1, 57) = 63.32$, $p < .001$, etap2 = .53, showing significantly more false alarms in case of attend-to-auditory trials, but no significant interaction between group and measurement, $F(1, 57) = 2.13$, $p = .150$, etap2 = .04 (indicating no modality-independent changes in false-alarm rates), as well as no significant interaction between group, measurement, and modality (indicating no modality-specific changes in false alarm rates), $F(1, 57) = 0.10$, $p = .750$, etap2 < .01. All other interactions and main effects were not significant, all ps > .694. Figure 5 shows false alarm rates for both modalities, groups, and timepoints.

Figure 5

False Alarm Rates in Experiment 2



Note. False alarm rates shown split by to-be-attended-to modality for both measurement time points (pretest and posttest), as well as for both groups: Orange solid lines for the intervention group, and purple dashed lines for the control group. Vertical bars indicate 95% CIs.

Electrophysiology

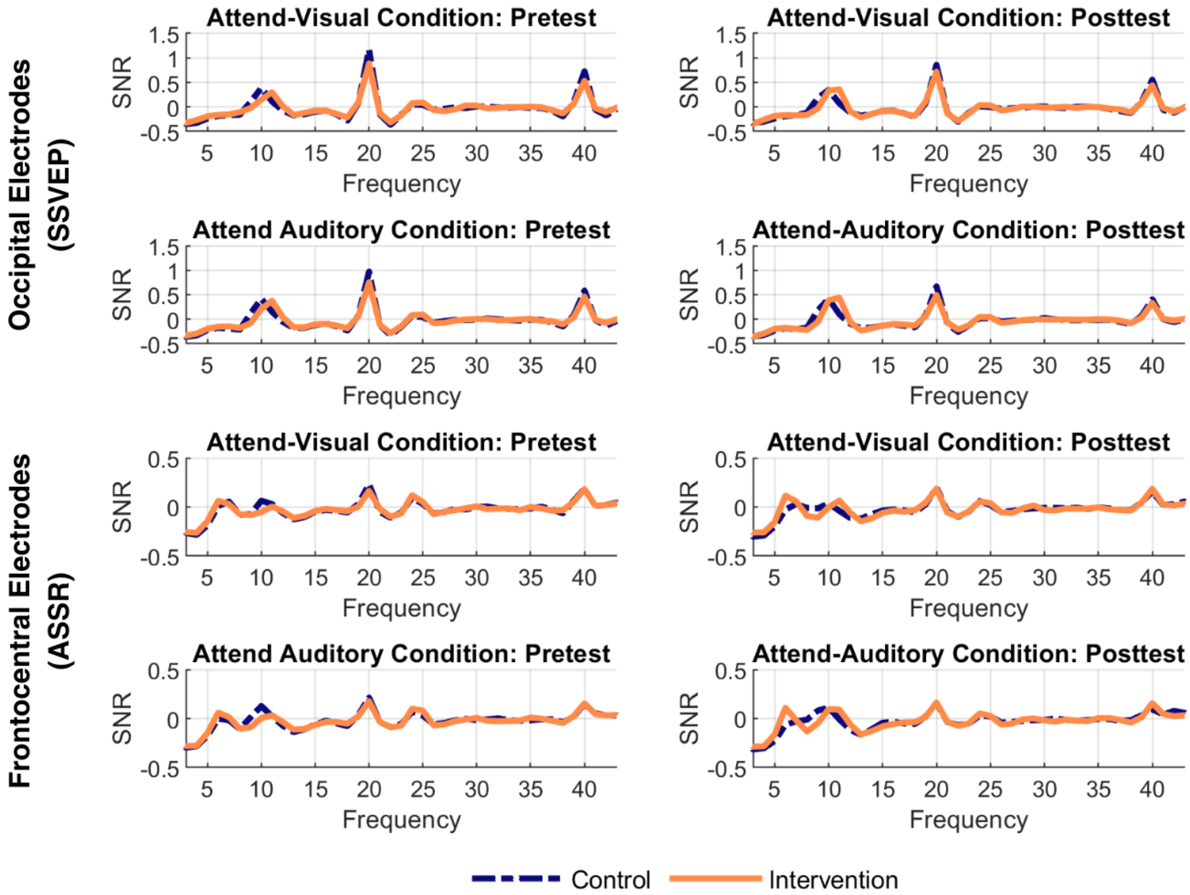
For the analysis of electrophysiological data, all participants omitted from the behavioral analysis were excluded (for details, see CONSORT chart in Figure 1). Additionally, we had to exclude five participants due to their high numbers of to-be-interpolated channels, as well as five participants due to their high percentages of to-be-deleted epochs. Two datasets could not be used for analysis because they were corrupted, leaving us with the final sample of 47 participants (38 female, NIntervention = 21, MAge = 24.64 years; SDAge = 4.39 years; range 19-40 years) for data analysis.

Spectral Analysis of Steady-State Responses. We wanted to know if SSVEP and ASSR changed in magnitude between attend-to-auditory and attend-to-visual conditions due to the intervention. After testing for the presence of the steady-state potentials in the first place (as a "sanity check", all ps < .001), we tested if the intervention had any effect on them. This was not the case, as reflected in the lacking threefold interaction for SSVEP frequencies, 20 Hz: F(1, 45)

= 0.47, p = .273, etap2 = .03; 40 Hz: F(1, 45) = 0.07, p = .637,   < .01, and the ASSR frequency, 24 Hz: F(1, 45) = 0.99, p = .325, etap2 = .02. Also, no significant interactions between measurement and group indicative of modality-unspecific steady-state potential changes due to the intervention were found, all ps >.479. Figure 6 shows the signal-to-noise ratio (SNR) of the first 10 s after each modality switch for all four conditions.

Figure 6

Spectral Distribution with Steady-State Responses



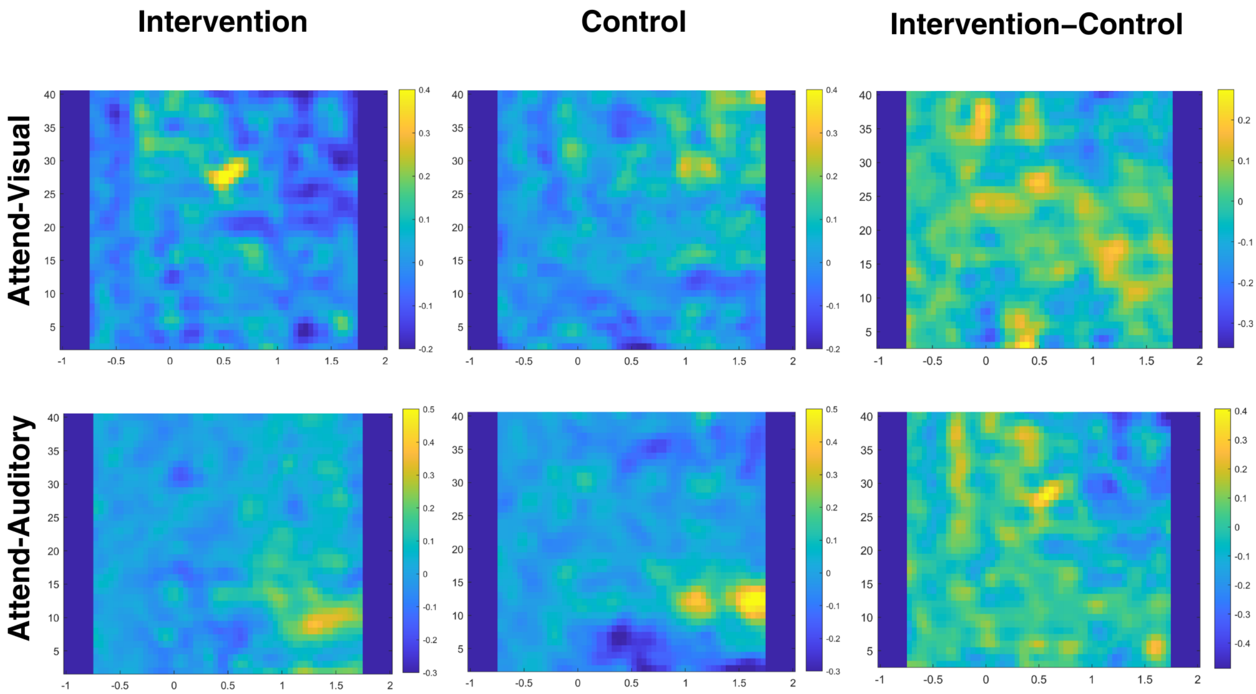
Note. Grand average Signal-to-Noise Ratio (SNR; raw power divided by the mean of the neighboring frequencies minus 1) for frequencies between 3 and 45 Hz, for each group and measurement (pretests: left, posttest: right), calculated for both attend-to-auditory and attend-to-visual conditions, once from occipital electrodes (where the steady-state visual evoked potential was present; top part of the figure) and once for frontocentral electrodes (where the auditory steady-state response was present; bottom part of the figure). Orange solid lines show the SNR of the intervention group, while purple dashed lines show the SNR of the control group.

For visual frequencies, there was a significant main effect of measurement, reflecting a decrease of SNRs from pre- to posttest at 20 Hz, $F(1, 45) = 17.21$, $p < .001$, etap2 = .28, and at 40 Hz: $F(1, 45) = 9.59$, $p = .003$, etap2 = .18. However, there was no such decrease of ASSRs at 24 Hz, $F(1, 45) = 3.03$, $p = .089$, etap2 = .01. The main effects of condition were significant at 20 Hz SSVEP, $F(1, 45) = 34.72$, $p < .001$, etap2 = .44, and 40 Hz SSVEP, $F(1, 45) = 30.88$, $p < .001$, etap2 = .41, and for 24 Hz ASSR, $F(1, 45) = 6.64$, $p = .013$, etap2 = .13. These results reflect higher SNRs for 20 Hz and 40 Hz SSVEPs in the attend-to-visual than in the attend-to-auditory condition, and higher ASSRs in the attend-to-auditory than in the attend-to-visual condition. This is plausible because there should be a change in complementary steady-state activity once the stimulus in question is attended to. All other interactions and main effects were not significant at any of the target frequencies (all ps > .194).

Time-Frequency Analysis. Figure 7 shows time-frequency plots for both conditions and groups. We found a significant negative cluster ($p = .017$) at 40 Hz between 1,150 ms and 1,400 ms after switching to the visual modality, reflecting decreased 40 Hz SSVEP (compared to the attend-to-auditory baseline) in the intervention group relative to the control group and pretests. To evaluate the nature of this effect, we conducted two additional cluster-based permutation tests on the pre-to-post-test differences, separately for each group, limited to the timeframe of the significant interaction cluster: While the control group showed a significant increase between 1,250 and 1,400 ms ($p = .010$), there were no significant clusters in the intervention group, potentially indicating reduced reactivity to the entraining stimulus. No significant clusters at 20 Hz or 24 Hz were found (all ps > .103).

Figure 7

Time-Frequency Difference Plots for All Conditions and Groups

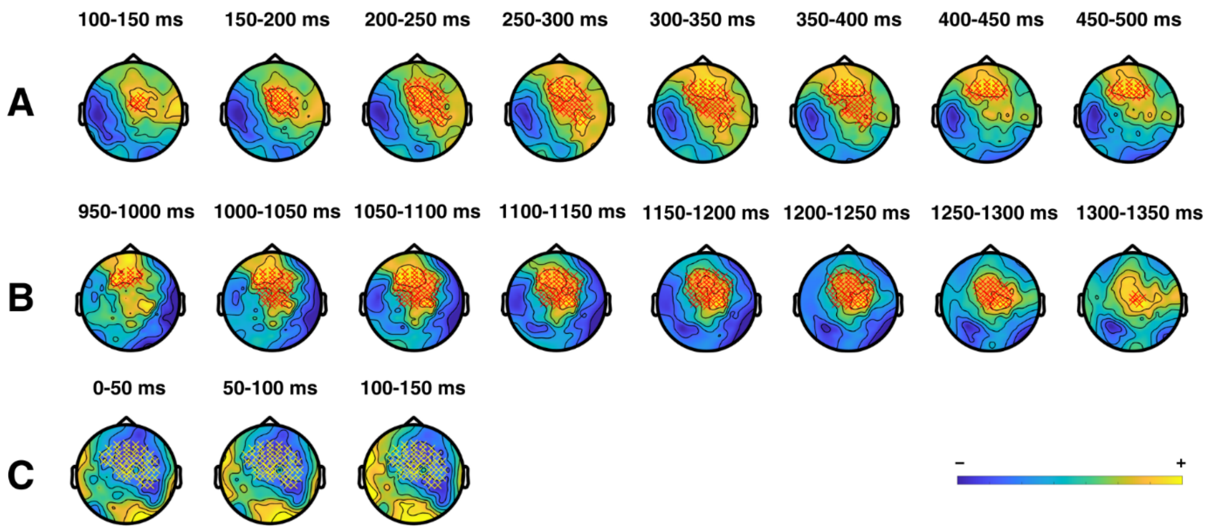


Note. Time-frequency plots of differences between posttest and pretest values for attend-to-visual and attend-to-auditory conditions for control and intervention groups, as well as differences between groups for both modalities (the rightmost column). The cue indicating a modality switch is the time-locking stimulus. The x-axis represents time (from 1 s before cue to 2 s after the cue), and the y-axis represents frequency (from 2 to 45 Hz). Brighter colors indicate higher relative change in power at a given frequency and timepoint compared to baseline (the previously attended condition).

In our analyses regarding switch-related changes in theta (H3), we found two positive clusters in the data, indicating an increase of a relative change in theta power in the attend-to-auditory trials compared to the respective preceding attend-to-visual trials as baseline. Figure 8 shows the time course and topography of all significant interaction clusters. The time course of these changes was from 150 to 500 ms ($p = .035$), and from 1,000 to 1,300 ms ($p = .026$) after switching from attend-to-visual to attend-to-auditory. Interestingly, these changes were mainly present in the upper theta band (6-7 Hz): In the first cluster (150-500 ms), they started in the upper band before spreading over to the entire theta band for a short time, to be followed by a recurse to 6-7 Hz only. The second cluster consisted entirely of changes in 6-7 Hz. We calculated post-hoc tests for these clusters by performing cluster-based permutation tests for each group individually, comparing pre-to-post-test differences, and restricting for the timeframe where the interaction was present. For the time range of the first interaction cluster, we only found significantly decreased theta activity in the control group between 150 and 500 ms after switching, $p < .001$, indicating decreased theta activity in the control group, but no changes in the intervention group. For the second significant interaction cluster, we found a concurrent positive cluster only in the intervention group (between 1,000 and 1,250 ms), $p = .004$, reflecting relative power increase after switching modalities compared to the control group.

Figure 8

Significant Clusters of Theta Activity



Note. Depicted are significant clusters of electrodes, timepoints, and frequencies, indicating a change in theta power after a switch in modality. Clusters A and B (shown for 7 Hz) show greater theta power in the intervention group relative to the control group after a switch to the attend-to-auditory condition relative to a switch to the attend-to-visual condition. Cluster C (shown for 5 Hz) shows lower theta power in the intervention group compared to the control group after switching to the visual domain relative to switching to the auditory domain.

In attend-to-visual trials, we found a significant negative cluster ($p = .037$), indicating a stronger relative decrease in theta power in the intervention group in the first 100 ms after switching, but at different frequencies, namely 4 and 5 Hz. Post-hoc-tests showed significant clusters in opposing directions for both groups: A relative theta decrease for the intervention group (0-100 ms, p = .019), as well as a relative theta increase for the control group (0-50 ms after switching, p = .027). This could be related to the increase in posterior alpha under attend-to-auditory conditions indicating suppression of the visual modality (Clements et al., 2022; 2023; Pfurtscheller et al., 1996) that we found in an exploratory analysis looking at increases in spectral power in distinct frequency bands reported in Appendix A. However, it is important to keep in mind that the latter analysis was entirely post-hoc in nature.

Discussion

Decreased Mixing Costs as a Potential Marker of Improved Switching Efficiency

Our first hypothesis could not be confirmed. In Experiment 1, the intervention led to a significant decrease of mixing, but not switching costs: Participants did counter the increased demands when keeping two target colors rather than one target color in mind better when they had participated in the intervention. Because mixing costs are indicative of the use of distinct task sets (Monsell, 2003) but switching ability between distinct task sets was not improved through the intervention, we think effects on mixing costs were unrelated to task switching, despite being a general aid for switching performance (Kiesel et al., 2010; Mayr & Kliegl, 2000). For example, participants in the intervention group might have found it easier to retrieve different color-specific task sets from working memory, but, as switching depends on the implementation rather than just the retrieval of task sets, improved memory in the form of reduced mixing costs might not always support switching performance (cf. Koch et al., 2005). To note, increased frontoparietal theta connectivity has been associated with reduced mixing costs (McKewen et al., 2020; 2021), linking improved executive functioning and this behavioral measure across Experiments 1 and 2, see below. To summarize, our result speaks against a direct effect of the intervention on switching. It speaks instead for improved executive control that is relatively independent of switching.

Does this result rule out a direct effect of practicing switches during hatha yoga on switching performance in general? Not necessarily. Benefits from practicing task switching for other executive functions have been observed in the past (Karbach & Kray, 2009), also resulting in improvements in other executive functions. However, it is also possible that other facets of yoga practice account for the effect on mixing costs. For example, yoga requires focusing, for maintaining specific poses, regulating breathing, and monitoring thoughts. Focused attention (characterized by reduced mind-wandering and directed attention towards present experiences, fundamental in mindfulness and yoga) may also profit from yoga practice (Luu & Hall, 2016). In turn, practicing mindfulness within yoga may cultivate a mental state where attention is anchored in the current moment, bolstering executive control functions reflected in reduced mixing costs.

Hatha Yoga Does Not Impact Steady-State Potentials, But Increases Frontocentral Theta

Looking at steady-state potentials in Experiment 2, if the intervention had an effect on the switching function, we would have expected that to-be-attended modalities would have exhibited higher power values in response to it. This was not the case. We did not find a change in the spectra of these potentials due to the intervention, neither in the visual (20 Hz SSVEP and its 40 Hz harmonic), nor in the auditory modality (24 Hz ASSR). These results, thus, speak against the validity of H2 and a positive effect of yoga on task switching in healthy participants, too.

However, when focusing on changes in spectral activity over time, following modality switches, 40 Hz activity increased in the control group while it did not change in the intervention group, starting at 1,150 ms after a switch to the visual modality was announced. SSVEP decreases have been observed after an 8-week mindfulness meditation course (Schöne et al., 2018), with the authors attributing this decrease to increased efficiency in the use of attentional resources. As the SSVEP's amplitude also reflects the amount of resources used for perceiving and processing the stimulus, such a change in sensory and attentional regulation may be advantageous for long-term task performance by saving cognitive resources, as well as through more efficient processing (Andersen et al., 2011). In other words, it is possible that only the participants in the control group felt the need to pay more top-down attention to the visual targets following a task shift and that the less effortful processing in the intervention group was just as appropriate, as was suggested by similar task performance in both groups. Thus, there was no decisive evidence for a change in the switching function, but a hint for increased efficiency in stimulus perception.

A related, and particularly interesting finding in Experiment 2 concerns the significant effects of the intervention in frontocentral theta, particularly when participants switched from attend-to-visual to attend-to-auditory conditions (H3). These effects were present at two distinct timepoints: 150-500 ms (a relative decrease in the control group) and 1,000-1,300 ms (a relative increase in the intervention group) after onset of the bimodal cue associated with switching between to-be-attended-to modalities. Theta oscillations in the frontocentral region have been repeatedly linked to improvements in task switching, as well as to related executive control processes: Midfrontal theta activity in response to stimuli is assumed to reflect adjustment to increasing demands in response to novelty, as well as conflict, through endogenous and exogenous action monitoring processes, both indicated by theta power increments (e.g., Cavanagh et al., 2012; Cavanagh & Frank, 2014; Enriquez-Geppert et al., 2014). Particularly, during response conflict, a situation where executive control is especially needed, a specific pattern of 6 Hz theta activity over medial frontal cortex is present (Cohen, 2014; Nigbur et al., 2012). Verbeke et al. (2021) combined computational modeling, EEG, and behavioral paradigms to test the role of theta during task switches. They found that the midfrontal cortex, utilizing theta oscillations, likely tracks current task rules. Verbeke et al. noted that midfrontal theta correlated with prediction error levels, determining the required level of executive control. These errors peak during a switch of the task rules, suggesting a corresponding peak in theta activity. The group differences in theta activity we found directly after a switch in modality are therefore likely to be indicative of an improved utilization of cognitive and attentional resources to resolve this conflicting situation. The increase of frontocentral theta SNR that we found in our spectral analysis also speaks for this improved deployment of executive resources.

In addition, the decrease in theta activity in the control group, during the first 500 ms following a switch, plausibly indicated a decrease in attentional control due to stimulus-driven attentional processes (Corbetta & Shulman, 2002), a pattern that was not present in the intervention group, possibly due to facilitated executive control (Cavanagh & Frank, 2014). The distinct patterns and periods of increased theta activity post-switching point to two different cognitive processes at play, with the subsequent increase after 1 s (the second significant cluster) possibly indicating sustained attentional processes (which rely heavily on frontomedial theta oscillations in general) maintaining proactive cognitive control due to the intervention (Clayton et al., 2015; Cooper et al., 2015; Cunillera et al., 2012).

To note, activity in the lower theta band (4-5 Hz) significantly decreased in the first 100 ms following a switch to the visual modality in the intervention group, while it significantly increased in the control group. The alpha effect reported in the supplementary analyses might give a clue to the understanding of the opposing theta effects under attend-to-auditory versus attend-to-visual conditions following the intervention. To note again, these analyses were entirely post-hoc and data-driven, and, therefore, our interpretation should be considered under this perspective. However, taking it earnest, it could mean that enhanced posterior alpha in the attend-to-auditory condition and following the intervention reflected inhibition of visual processing altogether (cf. Clements et al., 2022, 2023; Pomper & Chait, 2017; Pomper et al., 2015). If posterior alpha reflected suppression of the visual modality and frontal theta the corresponding cognitive control signal (Cavanagh & Frank, 2014; Cooper et al., 2019), then a switch to attend-to-visual conditions would liberate frontal areas from initiating suppression of the visual modality. This interpretation aligns relatively well with the observed general advantage for attend-to-visual compared to attend-to-auditory conditions in behavioral performance differences, reported above, that would suggest visual dominance and, thus, an asymmetrically increased necessity for modality inhibition in attend-to-auditory compared to attend-to-visual conditions. Thus, it appears as if more active inhibition of the prioritized but currently irrelevant visual input was necessary under attend-to-auditory conditions than of the currently irrelevant auditory modality under attend-to-visual conditions. Such inhibition, in turn, can aid optimal task performance (van Zoest et al., 2021; Zanto & Gazzaley, 2009) because task shifting needs to be coordinated with and subserved by the two other executive functions, working memory holding different task-control representations, and suppression shielding against currently irrelevant information and keeping the impact of paused task representations in check.

On the behavioral level, better performance in attend-to-visual compared to attend-to auditory conditions could explain why frontocentral theta pre-to-posttest increase was only present after switching to the attend-to-auditory condition in the intervention group (compared to the control group): Because the auditory task provoked significantly more false alarms, participants had to employ more resources to maintain executive control to solve the auditory task in an optimal manner – which was increasingly possible due to the intervention (Duncan, 2010). Our data also showed a trend towards decreased false alarm rates for both modalities, in the intervention compared to the control group, but with relatively high interindividual variability. Together with the relatively small effect size and the compromised statistical power, due to the high number of excluded participants, a true modality-independent behavioral effect of the intervention might have went undetected. The investigation of this link between increased frontocentral theta, improved shifting ability, and decreased false alarm rates, could be a fruitful line of future research, possibly taking into account better response inhibition of participants due to yoga as well.

Limitations, Challenges, and Future Directions

By using both behavioral and neural indices of participants' switching abilities, we were able to provide an objective answer to the question of whether hatha yoga increased participants' ability to switch their attention more efficiently between tasks and modalities. The likely answer is "no", with our results speaking for improved executive control processes instead that are independent from switching. However, there were some limitations to the study that need to be acknowledged in order to provide a complete picture.

The physical nature of yoga, involving various postures that require strength, flexibility, and balance, might be partly responsible for the above-mentioned behavioral and electrophysiological changes: Physical activity has been repeatedly linked to improved executive functioning (Hillman et al., 2003; 2006; 2008). Thus, it is possible that physical activity overshadowed some of the direct improvements in executive functioning through yoga, such as improved switching, and led to the currently found effects. We think that at least in yoga practice, physical and cognitive abilities are practiced jointly and are not improved in a mutually independent manner. However, this could only be demonstrated with an active control group, the lack of which is, thus, a limitation of the present study. To examine the role of physical activity, future studies could employ an active control group with equivalent levels of physical practice but without the same degree of systematic practice in, for example, switching of attention as required in yoga practices, ensuring a clearer distinction between the effects of any physical activity in general and hatha yoga in particular (cf. Deng et al., 2022; Sharma et al., 2014).

Another limitation of our study can be seen in the high number of dropouts and exclusions. Through the combination of a palette of diverse methods, we were still able to draw meaningful conclusions from our study. In addition, it was crucial for us to be rigorous in our cutoff criteria (e.g., exclusion of participants who did not participate often enough in the intervention, or who, according to behavioral measures, did not understand the task or were not motivated enough to complete it in compliance with the instructions), and, thus, sacrificed nominal statistical power while increasing the internal validity of our measures. Despite the comparatively high dropout rate, statistical power for most of the analyses reported above should have been high enough due to robust repeated-measures designs to detect at least medium effect sizes in the current designs (as sample size calculations were based on the “weakest links” regarding statistical power, namely the questionnaires reported in Szaszkó et al., 2023, with only two measurements per person).

Finally, an important factor that limits the generalizability of our findings was our predominantly female (over 80%), as well as relatively young sample, which consisted mostly of students, with less than a quarter working more than 20 hrs. Also, some level of self-selection bias, despite our admission restrictions, could have had an influence on the results, with people longing for a change in daily habits or health improvement, signing up for the study. We therefore suspected a relatively high average level of cognitive performance that probably limited any potential effects that the intervention may have had in our study in comparison to tests with a more varied sample. At the same time, this rationale implies that the current intervention effects were measured under conservative conditions and, thus, that the intervention must have been relatively powerful to exert any effect at all. Be that as it may, the insights derived from our study offer a foundation upon which further investigations linking yoga with executive function can be built. We hope our findings encourage researchers to delve deeper into understanding these relationships, especially with the intention of improving people’s mental and physical health.

Conclusion

We found that an 8-week hatha yoga intervention did not have any direct effect on participants’ switching performance, measured by both behavioral switching costs and changes in oscillatory activity. However, the intervention increased participants’ frontocentral theta activity, with frontocentral theta also increasing directly after switching modalities; in line with these results, it also decreased the behavioral costs of keeping multiple target features in working memory. We attribute these findings to increased executive control and switching efficiency, ultimately benefitting switching performance, despite not being directly related to it.

Declarations

No third-party funding was received from any organization for the work presented in this manuscript. We have no conflicts of interest to disclose. Ethical approval for the study was granted by the Ethics Committee of the University of Vienna, with the approval number 00753, and the study was conducted in alignment with the ethical principles set forth in the 1964 Declaration of Helsinki and its subsequent modifications. Consent was explicitly obtained from each participant included in the study, and they all consented to have their anonymized or pseudonymized data published by signing a formal written agreement. Data and the code used for all analyses can be acquired from the corresponding author upon a reasonable request.

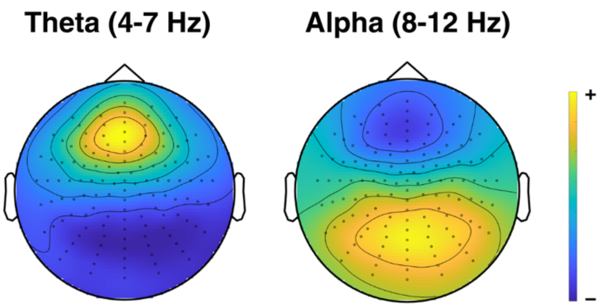
Appendix A

Spectral Analysis of Alpha and Theta

We were also interested in how posterior alpha as well as frontocentral theta activity has changed due to the intervention. For the selection of the appropriate region, we again averaged over both timepoints and groups, and looked at the spectral distribution of frequencies between 8 and 12 Hz for both attend-auditory and attend-visual conditions for the alpha band, and between 4 to 7 Hz for the theta band. The electrodes with the highest alpha and theta power overlapped across conditions, and we subsequently selected these (alpha: 44 electrodes; theta: 10 electrodes) to measure changes in posterior alpha activity and frontocentral theta activity. Figure A1 shows the topographical distribution of the theta- and alpha-band in our participants, averaged over pre- and posttests.

Figure A1

Topographical Map of Spectral Activity for Theta and Alpha



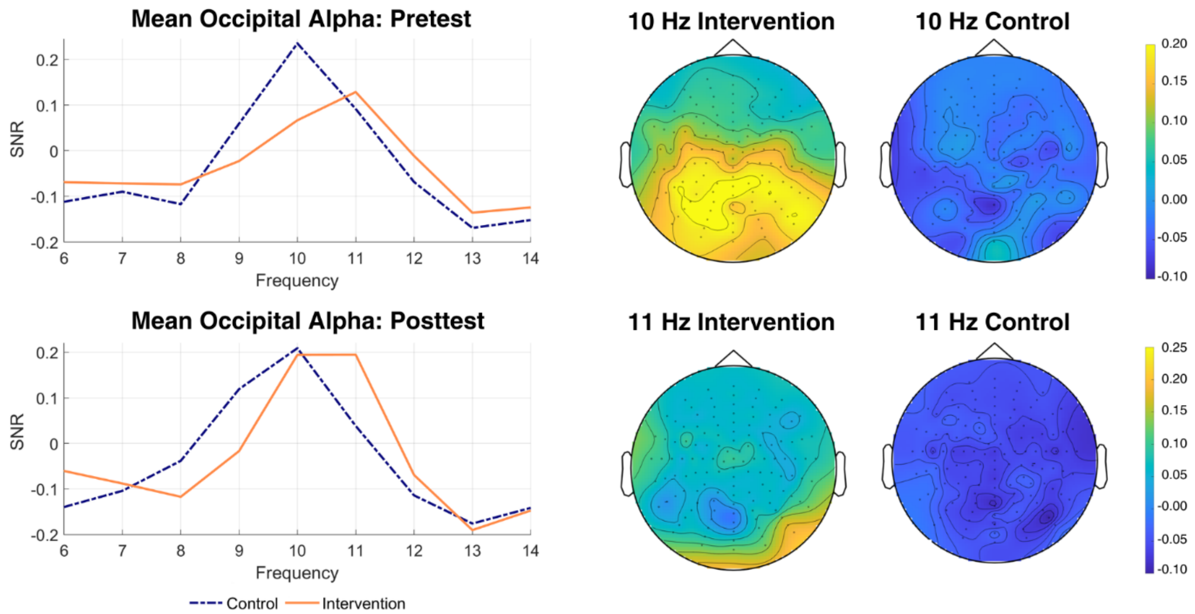
Note. Topographical distributions of theta- and alpha band activity, averaged across pre- and posttest, groups, and conditions. Yellow areas indicate the highest levels of activity, dark blue areas indicate the lowest levels.

For posterior alpha activity, a 2 × 2 × 2 mixed ANOVA, with Measurement (pre/post), Condition (visual/auditory), and Group (intervention/control) on participants' mean Signal-to-Noise Ratio (SNR) averaged over 8 to 12 Hz showed an interaction between group and measurement, indicating a significant influence of our yoga intervention, $F(1, 45) = 5.39$, $p = .025$, etap2 = .11. Follow-up t tests on posttest minus pretest SNR differences showed that the difference stemmed from alpha increases in the intervention group, M = 0.02, t(45) = 3.21, p = .004, d = 0.29, while there was no significant change in the control group, M = 0.00, t(45) = 0.09, p = .932, d = 0.02.

There was also a significant main effect of condition, F(1, 45) = 13.70, p = .001, etap2 = .23, with lower SNRs in attend-to-visual, M = 0.073, SD = 0.020, than in attend-to-auditory conditions, M = 0.084, SD = 0.026. This is particularly interesting, because if posterior alpha reflects increased inhibition of unwanted stimuli rather than improved processing or concomitant relaxation ability, we would expect it to be higher when suppressing unwanted visual rather than auditory input. Therefore, the corresponding results might reflect active suppression of processing in the visual modality in attend-to-auditory conditions. However, this reflected a general effect not tied to the intervention. All other interactions were not significant, all ps > .118.

Figure A2

Changes in Mean Posterior Alpha

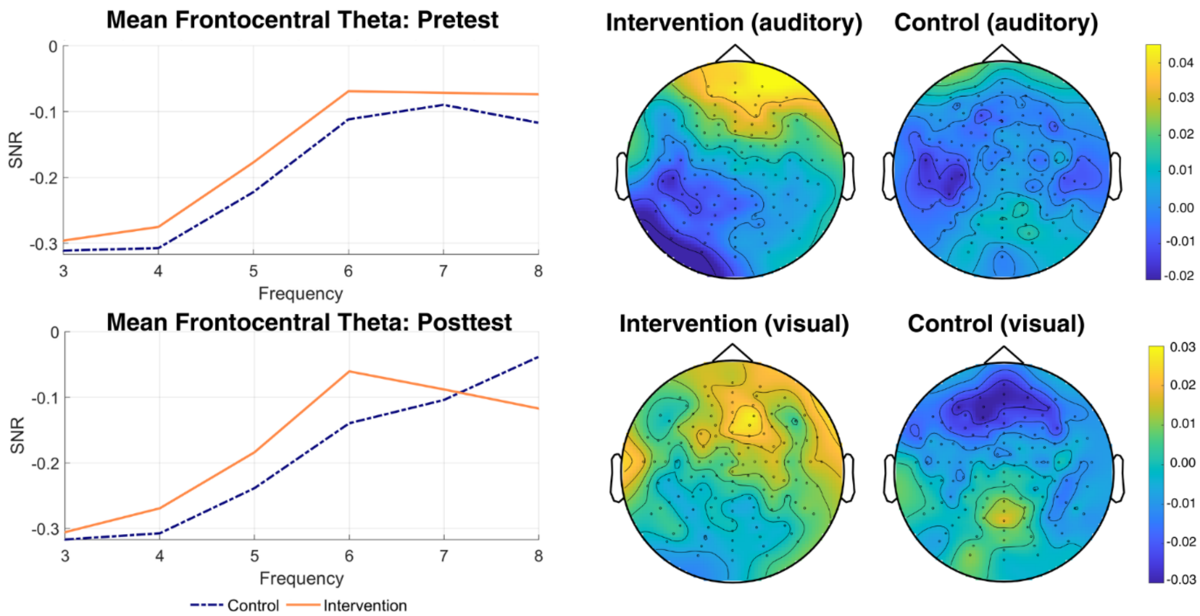


Note. Spectral distributions for mean posterior alpha (on the left), as well as the topography of changes at 10 Hz and 11 Hz from pretest to posttest by group for the frequencies exhibiting the largest changes. Spectral distributions are shown for both pretest (top) and posttest (bottom), for the intervention (orange solid line), as well as the control group (purple dashed line). The topographical map indicates the locus of changes in the respective alpha rhythm.

For the theta-band, we conducted another 2 × 2 × 2 mixed ANOVA with the same factors on participants' mean SNR averaged over 4 to 7 Hz. Here, we also found an effect of the intervention, reflected in an interaction between group and measurement, $F(1, 45) = 1.98$, $p = .018$, etap2 = .12. A follow-up t test between groups on posttest minus pretest SNR differences again confirmed the finding from the ANOVA, $M = 0.04$, $t(45) = 2.44$, $p = .018$, $d = 0.71$. This intervention effect was, again, condition-independent, reflected in a nonsignificant threefold interaction, $F(1, 45) = 0.06$, $p = .812$, etap2 < .01. Again, there was a significant main effect of condition, reflecting higher SNR in the attend-to-visual, $M = -0.078$, $SD = 0.045$, than in the attend-to-auditory condition, $M = -0.103$, $SD = 0.055$. All other main effects and interactions were not significant (all ps > .135).

Figure A3

Changes in Mean Frontocentral Theta



Note. Spectral distributions for mean frontocentral theta (left) for pretest (top) and posttest (bottom) for intervention (orange solid line) as well as control (purple dashed line) groups, and the topography of changes from pretest to posttest averaged over the theta band (4-7 Hz), split by group and condition (auditory vs. visual).

4

Hatha Yoga Reduces Subjective Momentary Stress, But Does Not Impact Diurnal Profiles of Salivary Cortisol and Alpha-Amylase: A Randomized Controlled Trial

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*Bence Szaszkó and Hannah Tschenett contributed equally to this manuscript. The manuscript is submitted only as a part of the dissertation of Bence Szaszkó, but not of Hannah Tschenett.

Abstract

Does the practice of yoga impact how stressed we are (and feel)? Various studies have reported that yoga may decrease self-reported stress levels, as well as those of stress biomarkers; however, evidence for these claims remains inconclusive, with results even more ambiguous for yoga styles with a focus on physical postures. In a randomized controlled trial with 98 participants, we therefore intended to answer the question if an eight-week hatha yoga intervention (3×/week or more, 60 min), compared to a waitlisted control group, decreased levels of diurnal salivary cortisol, salivary alpha-amylase, and subjective momentary stress. To ensure concomitant assessment of self-reported and biological measures in an ecologically valid setting, and to capture the diurnal profile of cortisol and alpha-amylase, we utilized an ecological momentary assessment approach, asking participants to report their momentary stress levels on a visual analogue scale five times a day together with self-collecting salivary biomarkers. While subjective momentary stress decreased significantly due to the intervention, we did not observe a change in diurnal salivary cortisol or alpha-amylase levels. Our results give room for several possible explanations: Participants may have learned to better cope with stress as a consequence of the intervention, but this may have left diurnal levels of stress biomarkers unaffected or, at least, diurnal sCort and sAA levels did not reflect this change. Alternatively, participants may have reported reductions in stress to indicate positive effects of the intervention, potentially influenced by a favorable disposition towards yoga, thus reflecting a self-reporting bias. Our findings contribute to a better understanding of the effects of distinct yoga interventions, showing their potential to serve as low-risk stress mitigation tools.

Keywords: alpha-amylase, cortisol, ecological momentary assessment, stress, yoga

Clinical trial registration number: NCT05232422 (clinicaltrials.gov)

Author contributions: B.S.: Conceptualization, Methodology, Resources, Software, Formal Analysis, Investigation, Writing (Original Draft; Review & Editing), Visualization, Project Administration; H.T.: Conceptualization, Methodology, Resources, Software, Formal Analysis, Investigation, Writing (Original Draft; Review & Editing), Visualization, Project Administration; U.M.N.: Conceptualization, Methodology, Resources, Writing – Review & Editing, Project administration; U.A.: Conceptualization, Methodology, Resources, Writing – Original Draft, Writing – Review & Editing, Supervision, Project Administration.

Introduction

Stress is a ubiquitous experience in our everyday lives. While the stress response of our bodily stress systems (hypothalamic-pituitary-adrenal [HPA] axis, the autonomic nervous system [ANS], and the immune system) is adaptive to maintain or re-establish homeostasis when facing threats or challenges, sustained strain can lead to excessive or ongoing arousal and pose allostatic load on the human organism (McEwen, 1998). This is known as chronic stress, which can contribute to a range of mental and physical health disorders, including anxiety, depression, trauma-related disorders, and cardiac disease (Schneiderman et al., 2005). Salivary cortisol (sCort) and salivary alpha-amylase (sAA) are two well-researched biological correlates of the HPA axis and ANS activity, respectively (Kirschbaum & Hellhammer, 2007; Nater & Rohleder, 2009). Both sCort and sAA levels seem to be altered in individuals experiencing chronic stress (Nater et al., 2007, 2008; O'Brien et al., 2013) and in various stress-related disorders (e.g. anxiety-related disorders, Correll et al., 2005).

The pathological consequences of such alterations highlight the need for effective stress management strategies that can not only mitigate stress-related symptoms but can also prevent the development of these pathologies (and potentially even adverse immediate effects of an overactive HPA axis) in the first place. One such strategy is yoga, an ancient Indian practice (Büssing et al., 2012), which, in recent decades, has been increasingly used as a mind-body intervention in the Western world, with stress management being one of the primary motives for its practice (Cagas et al., 2022). Yoga consists of the practice of various bodily postures (asanas), breath regulation (pranayama), and meditative aspects, embedded in an ethical framework based on self-discipline and moral observances (Gard et al., 2014). Yoga can to lead to various improved mental and physical health outcomes (Büssing et al., 2012; O'Shea et al., 2022) and improve the relaxation response. It is open how exactly this happens, but possibly by activating the parasympathetic nervous system via deep breathing (Zaccaro et al., 2018) and by reducing emotional reactivity to thoughts and feelings, which, in turn, has the potential to decrease subjective and biological stress levels, as well as levels of anxiety (Folkman et al., 1986; McRae & Gross, 2020). Hatha yoga, our form of intervention, is a yoga style commonly practiced in the Western world and is focussed on physical aspects, including stretching exercises, postures, and mindful breathing (Shapiro et al., 1998).

Past studies have found that yoga may decrease self-reported stress levels (Erogul et al., 2014; Hartfiel et al., 2012; Szaszkó et al., 2023; cf. also Gothe et al., 2016; for reviews, see Li &

Goldsmith, 2012; Sharma, 2014) and impact stress biomarkers (Michalsen et al., 2005; Robinson et al., 2021; West et al., 2004; for reviews see Dalpati et al., 2022; Pascoe & Bauer, 2015; Pascoe et al., 2017; Ross & Thomas, 2010). Importantly, most studies investigating the effects of yoga on stress did not examine the daily fluctuations inherent to stress levels, a point that was crucial to consider when designing our intervention. Looking at the results of past studies, they generallypoint towards a decrease of sCort and a decrease of sympathetic nervous system (SNS) activity (with the SNS being one of the two counterparts of the ANS), while there is currently insufficient evidence for a potential decrease in sAA. However, evidence for decreasing stress markers through yoga interventions is limited and results are ambiguous, particularly when looking at more physically active forms of yoga, such as hatha yoga. This scarcity, alongside its popularity in the Western world, primarily motivated our choice of hatha yoga for the intervention. Sieverdes et al. (2014) found no reductions in sCort or sAA levels, either in the awakening response or throughout the day, among school children practicing hatha yoga. However, the sample size (14 participants in the Hatha-Yoga group and another 14 in the active control group) used for this study might have been too small to yield a significant benefit. Gothe et al. (2016) also did not observe differences in sCort and self-reported stress levels after a hatha yoga intervention in elderly adults when measured before a lab-induced stress induction. However, they observed significant decreases in stress reactivity, measured by less prominent changes in sCort levels in the intervention vs. the control group as a result of the stress induction. To note, stress reactivity refers to how an individual responds to stress, including physiological, emotional, and behavioral reactions. The physiological stress response is, however, only adaptive when it is aligned with the threat and when the corresponding systems return to baseline after the cessation of the stressor (Kiecolt-Glaser et al., 2020). Exaggerated response magnitudes and/or durations can lead to numerous health-related risks described above.. Both studies targeted specific populations, and several other studies (e.g., Banerjee et al., 2007; Telles et al., 2010) focused on clinical populations, resulting in limited insight of the beneficial effects of hatha yoga on the stress response in the general population.

Therefore, we carried out a randomized controlled trial to explore the impact of an eight-week hatha yoga intervention on the stress levels of healthy adults without any history of psychiatric or neurological disorders. Eight weeks were taken as past studies have shown that this intervention duration is sufficient for the observation of significant cognitive improvements (Gothe et al., 2017). To maximize the reliability of our stress measurse, we used an ecological momentary assessment (EMA) approach (Trull & Ebner-Priemer, 2013). EMA can be optimally aligned with the repeated measurements of the stress biomarkers; it also enables an investigation of participants' everyday lives, thereby, minimizing recall bias and allowing the consideration of daily fluctuations in subjective stress through multiple daily assessments (Stone & Shiffman, 2002). Both EMA and the assessment of biological markers are important for validating outcomes of self-report questionnaires and allow for a multi-dimensional assessment of the effects of hatha yoga on the multi-facet construct stress. We, thus, assessed both subjective momentary stress and stress-related biomarkers using EMA. The simultaneous assessment of momentary stress and saliva sampling ensures a more accurate and temporally proximate correlation between self-reported stress and biomarkers. While studies investigating yoga interventions with EMA are still limited, they have been proposed as crucial for gaining a deeper understanding of how yoga influences stress (e.g., Park et al., 2021). We hypothesized that our intervention decreased levels of subjective momentary stress (main hypothesis 1; H1). Our study found a significant decrease in subjective stress reactivity and in subjective stress levels using a more traditional, static approach, as we have previously reported elsewhere (Szaszkó et al., 2023). We additionally hypothesized that the intervention decreased levels of both sCort (main hypothesis 2, H2) and sAA (main hypothesis 3, H3) in our sample.

Material and Methods

Participants

Via social media and the recruiting systems of the University of Vienna, we recruited potential participants without significant yoga experience (with experience defined as practicing yoga more than twice a month in the past year) and any current or past psychological or psychiatric disorders. We screened for such disorders using a shortened online version of the Diagnostic Interview for Mental Disorders (Mini-DIPS; Margraf, 1994). Potential participants were also excluded if they were older than 40 years (to prevent confounds by cognitive decline (Salthouse, 2009), as the study sought to answer cognition-related hypotheses reported in Szaszkó et al. 2023, 2024), if their German level was not sufficient to take part in the intervention (below C1), in case of uncorrected visual/hearing impairments, a skull fraction or concussion within the last six weeks (also due to potential impacts on cognition confounding the experimental results), as well as a lacking COVID-19 recovery or vaccination (as the study took place during the pandemic). Participants were screened for inclusion and exclusion criteria via an online questionnaire using the survey platform Unipark (Questback GmbH).

A sample size of 72 was determined using G*power (version 3.1, Erdfelder et al., 1996) to reach 80% power with an effect size of d = 0.6 for the salivary biomarkers. This effect size was based on previous studies of yoga and sCort (for a systematic review and meta-analysis, see Pascoe et al., 2017), as well as findings by Brysbaert (2019), who state that the power of a study increases significantly by having multiple observations per participant and condition. For sAA, there is a lack of studies reporting effects through yoga that can be taken as a reference. Note that the required sample size for other study outcomes, reported in Szaszkó et al. (2023), was higher, namely 102 participants. We were able to recruit 116 subjects, starting with recruitment in November 2021 and finishing in April 2022 (for two separate cohorts); 98 of them (54 intervention, 44 control; 83 female; MAge = 25.03 years; SDAge = 4.18 years; range 18-40 years) were still part of the study when the intervention began (for details see supplement S1). The study was preregistered on the Open Science Framework (https://osf.io/cdx96), approved by the ethics board of the University of Vienna (reference number 00753), and was conducted in accordance with the Declaration of Helsinki. All participants provided written consent and were informed about the study at the first in-person meeting.

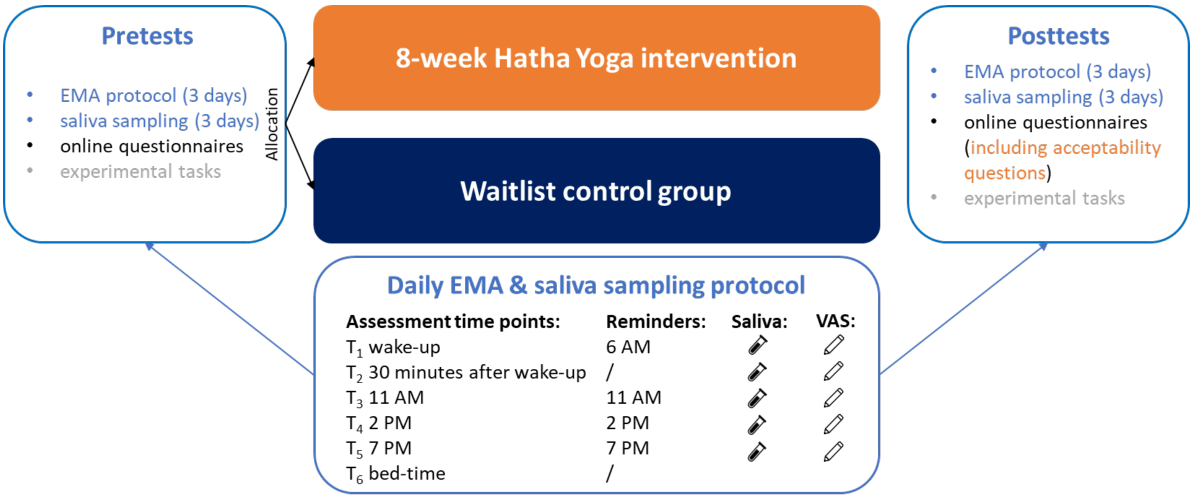
Study Design and Procedure

As the results presented are part of a larger interventional study, here, our primary focus lies on the presentation of the biomarker and EMA results. Figure 1 depicts an overview of the study procedure including the relevant details discussed in this paper. Methods and results on our other outcomes, as well as a detailed description of the intervention can be read in Szaszkó et al. (2023) and Szaszkó et al. (2024a).

Between January 2022 and August 2022, every participant completed pretest and posttest sessions at the University of Vienna. Pretest and posttest sessions included experimental procedures (not relevant for this paper; described in Szaszkó et al., 2023), the completion of online questionnaires via Unipark, as well as an EMA including saliva sampling. We used a parallel design with two cohorts (cohort 1: n = 52, cohort 2: n = 64). Participants (N = 116) were randomized to either the intervention or the waitlisted control group using block randomization (29 blocks, block size 4, allocation ratio 50:50) after the first pretest session. Research team members completed enrollment and randomization (through custom Python scripts). Neither participants nor research team members were blinded for the group allocation. Participants were financially compensated (30 EUR per measurement plus 20 EUR bonus if the average participation in the intervention per week was ≥ 4 sessions), and the intervention was free of cost for all participants.

Figure 1

Overview of Study Procedure



Note. Details on experimental tasks can be found in Szaszkó et al. (2023) and Szaszkó et al. (2024a). Daily ecological momentary assessment (EMA) and saliva sampling protocol apply to the three consecutive assessment days during the pretest and posttest phase. VAS = assessment of momentary subjective stress using a visual analogue scale. Icons provided by www.flaticon.com.

In the first pretest (and posttest) sessions, participants were instructed on the completion of the EMA schedule as well as on the collection and storage of saliva samples. We used a fixed-occasion design to adequately assess diurnal salivary cortisol (as an index of the HPA axis; Hellhammer et al., 2009) and sAA (as an index of the ANS; Nater & Rohleder, 2009) as well as momentary stress, while aiming at achieving high compliance. Participants were required to collect saliva samples five times a day (at wake-up time, 30 min after waking up, at 11 AM, 2 PM, and 7 PM) and complete an EMA at the five saliva sampling time points as well as before going to bed (evening assessment). To minimize within-participant variance and thus increase the power of our design, this was done for three consecutive days each for pretests and posttests. Participants were sent a reminder to their mobile devices 10 min before the scheduled assessment time points (11 AM, 2 PM, 7 PM). The initial daily measurement (at wake-up time) was preceded by a 6 AM reminder, while the second measurement (30 min after waking up) did not prompt a reminder, as its timing varied based on the respective participant’s wake-up time. While momentary stress experiences and control variables were collected analogously to the saliva sampling, the evening assessment was used to collect data about daily experiences (e.g., wake-up time, stress events) and control variables (e.g., medication intake) for the respective day. Participants were initially instructed to complete the bedtime assessment shortly before going to sleep and were reminded together with the 7 PM assessment. Self-report data were collected using a paper-pencil format. All considered control variables are outlined in Section 2.4. All EMA items are available as online supplement (S2). EMA data, including self-reports and saliva samples, were returned to the research team at the first posttest. EMA data were digitalized by a research team member and checked by one of the authors.

Intervention

The intervention group (IG) took part in an eight-week hatha yoga course led by four certified yoga instructors ($M_{\text{Job Experience}}$ = 4.00 years; $SD_{\text{Job Experience}}$ = 1.15 years; range 3-5 years of job experience), while members of the waitlisted control group (CG) had the opportunity to take part in the same intervention after the conclusion of posttests for both groups. The intervention was based on instruction guidelines for each week, including a weekly focus and exemplary asanas for the sessions (for details see Szaszkó et al., 2023) designed by the yoga instructors in cooperation with the research team after multiple briefing sessions. The Essential Properties of Yoga Questionnaire (EPYQ) with a Cronbach’s α of .70-.90 (Grössl et al., 2015) was filled out by the instructors to characterize the intervention. Results showed that our hatha yoga intervention moderately-to-largely focussed on breathwork, body awareness, and acceptance/compassion, while meditation/mindfulness and physicality were moderately targeted in the intervention (for details see Szaszkó et al., 2023). Members of the IG were required to participate in at least three (maximum: five) sessions a week (analyzed participants: $M_{\text{Participation}}$ = 2.55 sessions/week, SD = 0.55 sessions/week). They were excluded from the study if they did not participate at least twice for three consecutive weeks. Each session commenced with a warm-up lasting between 5 to 10 min, followed by 40 to 50 min dedicated to practicing asanas, and concluded with a 5 to 10-min *savasana*, a relaxation phase where participants lie flat on their backs (60 min total).

Measurements

To measure subjective momentary stress, we used a visual analogue scale (VAS). At each EMA measurement time point except the evening assessment, participants indicated their momentary subjective stress level from 0 (“not at all”) to 100 (“very”).

We used the SaliCap system (IBL, Hamburg, Germany) to collect saliva samples measuring participants' sCort and sAA levels. Using the passive drool method, we asked participants to collect saliva in their mouth for 2 min and then use a straw to salivate into a polypropylene tube. Samples were kept frozen at –20 °C up until data analysis once they were delivered to the research team. Saliva samples were analyzed at the biochemical laboratory of the Faculty of Psychology, University of Vienna. The salivary cortisol concentration was determined in nmol/l using luminescence immunosorbent assay (IBL-Tecan, Hamburg, Germany). sAA activity was determined in U/ml using an enzymatic photometric test with reagents from DiaSys (Diagnostics Systems, Holzheim, Germany) following the procedure outlined in Skoluda et al. (2020). Both intra- and inter-assay coefficients of variation for sCort and sAA were below 10%. Data were analysed for each participant and measurement time point individually, resulting in 30 data points per participant for sCort and sAA each. We excluded all values from statistical analysis which were below the measurement threshold (sCort: < 0.33 nmol/l, sAA: < 3 U/ml).

In addition to baseline sociodemographic and medical data, we used the German versions of the Patient Health Questionnaire (PHQ-D; Löwe et al., 2002), Perceived Stress Scale (PSS-10; Klein et al., 2016), and the Perceived Stress Reactivity Scale (PSRS; Schlotz et al., 2011) to characterize the sample regarding their mental health state and ongoing stress experience. The PHQ-D is a widely used screening instrument for mental health disorders including 47 to 78 items (varying according to skipping rules). According to the manual, answers represent the presence of different syndromes. Additionally, sum scores for depression (PHQ-9), somatic symptoms (PHQ-15), and experienced stress (PHQ-Stress) can be calculated. The reliability of the sum scores was good to very good (PHQ-9: 0-27, Cronbach's α = .84; PHQ-15: 0-30, Cronbach's α = .80; PHQ-Stress: 0-20, Cronbach's α = .71). The PSS-10 was used to assess ongoing stress within the last month, comprising 10 items answered on a 5-point Likert scale ranging from 0 (never) to 4 (very often). The reliability of the sum score was very good (0-40, Cronbach's α = .83). PSRS was used to describe the domain-specific habitual stress reactivity (prolonged reactivity, reactivity to work overload, reactivity to social conflicts, reactivity to social failure, reactivity to social evaluation) using 23 items answered on a scale with three answer options. The sum score of the five domains and the total value showed very good reliability (0-46, Cronbach's α = .88).

Furthermore, we descriptively analyzed four adapted items form the PSS-4 (Vallejo et al., 2018) which were assessed analogously to the saliva sampling, as well as frequency and number of stress events assessed in the EMA evening assessment to characterize the daily stress experience in everyday life (for details see supplement S2). To characterize the acceptability of the intervention, we descriptively analyzed ten self-developed items by the research team administered in the online post questionnaire. Eight of the items were dichotomous (yes/no), one was answered on a 5-point Likert scale (1 = do not agree, 5 = fully agree), and one was answered on a visual analogue scale ranging from 0 (not at all) to 100 (very). The acceptability questions are available as online supplement (S3).

Statistical Analyses

Descriptive statistics were calculated using IBM SPSS (Version 28.0.1.1) and MS Excel (Microsoft Office Professional Plus 2016). We used RStudio (Version 1.4.1717; RStudio Team, 2020) with R (version 4.2.3; R Core Team, 2023) for our statistical analyses and data plotting. For this, we relied on the R package emmeans (Version 1.10.0; Lenth, 2024). To test the effect of the intervention on sCort (H1) and sAA (H2) levels, as well as on subjective stress (H3), we used linear mixed effect models (level 1: measurements, level 2: participants) with restricted likelihood estimation, using the R package lme4 (Bates et al., 2015). To test whether the intervention modulated biological and self-reported stress levels, we ran two-level hierarchical models for all outcome variables (sCort, sAA, momentary stress) separately. We selected a three-phase approach (Schlotz, 2019; Woltman et al., 2012), with the unconstrained (null) model, the model including all control variables, and, finally, the model including all predictors of interest, as well as all control variables. We have calculated estimated marginal means of the respective values of sCort, sAA, and VAS by *Group* to test for differences between intervention and control groups at baseline, and by *Group* and *Measurement* to calculate and quantify the intervention effect, using Cohen's *d* (Cohen, 1988) for this purpose (calculated by dividing the *SE* of the contrast by the estimated marginal mean of the contrast).

We applied a base-10 logarithmic transformation for normalizing the dependent variables of sCort and sAA after adding a constant of 10 (log(x+10)). We included the following predictors in our model: *Measurement* (pre / post), *Group* (intervention / control), and the interaction of these two predictors, *Measurement* × *Group* (the intervention effect). At level 1, we included the following control variables: intake of medication, intake of food or drinks, physical activity, and smoking (all during the last hour; 0: no; 1: yes), menstrual phase (0:

follicular; 1: luteal). These variables were centered within clusters, following recommendations for centering categorical covariates in multilevel models (Yaremych et al., 2023). In addition, we included timepoint as a categorical covariate (wake-up, +30 min, 11 AM, 2 PM, 7 PM). At level 2, we included age, body-mass index (BMI), current medication potentially affecting sCort and/or sAA levels (0: no; 1: yes), smoking (0: no; 1: yes), usage of hormonal contraception (0: no; 1: yes), and sex (0: female; 1: male), centered at the grand mean (Enders & Tofighi, 2007). The latter two control variables were dropped by the model due to rank deficiency. The significance level for all analyses was set at $\alpha = .05$.

Results

Participant Characteristics

Three hundred forty-five participants were assessed for eligibility in two separate cohorts between December 2nd, 2021, and April 27th, 2022, leading to 116 participants randomized into one of the two groups (with 100 filling out the pretest baseline questionnaire). With two participants declining participation before the start of the intervention, 98 total participants took part in the study at intervention start. Out of these 98, we could collect data from 74 participants (for dropout reasons, see the CONSORT chart in our supplementary materials S1). One participant was excluded for consuming illicit substances repeatedly during the study period. Thus, in all models specified for the analysis of biological stress markers and momentary stress, we used data of 73 participants (63 female; $M_{\text{Age}} = 24.97$ years; $SD_{\text{Age}} = 4.51$ years; range 18-40 years), out of which 34 were members of the intervention group. Details about missing values due to missing saliva samples, values being below the measurement threshold, and missing data entries, as well as the number of valid measurements per group are described in supplement S3. The final sample size and analyzed values are sufficient to detect medium and large effects (we used the power calculator for multi-level studies on https://kleimanlab.org/resources/power-curves/, January 2024).

Participant characteristics of the intention-to-treat sample are described in Szaszkó et al. (2023). Relevant participant characteristics of the analyzed sample are described in Table 1. The acceptability of the intervention as rated by participants in the intervention group is described in supplement S4.

Table 1

Selected Baseline Characteristics of Analyzed Sample

	Total			Intervention			Control		
	M	*SD*	Range	*M*	*SD*	Range	*M*	*SD*	Range
Gender									
Male	10	(14%)		4	(12%)		6	(15%)	
Female	63	(86%)		30	(88%)		33	(75%)	
Age	24.9	4.2	18 - 40	24.7	3.9	18 - 40	25	4.5	19 - 40
Education									
High School	28	(38%)		11	(32%)		17	(44%)	
Bachelor	35	(48%)		20	(59%)		15	(38%)	
Master	6	(8%)		3	(9%)		3	(8%)	
Working Hours per Week									
Not working	18	(25%)		9	(26%)		9	(23%)	
1-10 hours	19	(26%)		10	(29%)		9	(23%)	
11-20 hours	16	(22%)		7	(21%)		9	(23%)	
21-30 hours	11	(15%)		5	(15%)		6	(15%)	
31-40 hours	3	(4%)		2	(6%)		1	(3%)	
More than 40 hours	2	(3%)		1	(3%)		1	(3%)	
Perceived Stress Reactivity Scale (PSRS)	23.5	7	5 - 38	23.5	6.8	9 - 37	23.5	7.3	5 - 38
Prolonged reactivity	3.1	2	0 - 8	3	1.8	0 - 7	3.2	2.2	0 - 8
Reactivity to failure	4.7	1.7	1 - 8	4.6	1.7	1 - 8	4.8	1.8	1 - 8
Reactivity to social conflicts	6.4	2.2	1 - 10	6.5	2.5	1 - 10	6.2	2	1 - 10
Reactivity to work overload	4.2	2.2	1 - 9	4.2	2	1 - 9	4.1	2.3	1 - 9
Reactivity to social evaluation	5.1	2.2	0 - 10	5.2	2.2	1 - 10	5.1	2.2	0 - 8
Perceived Stress Scale (PSS-10)	16.5	6.4	5 - 31	17.6	6.2	7 - 30	15.6	6.6	5 - 31
Somatic symptoms (PHQ-15)	7	4.1	2 - 20	7.5	4.8	2 - 20	6.6	3.4	2 - 17
Depression (PHQ-9)	6.4	4	0 - 20	6.9	4.6	1 - 20	6	3.3	0 - 15
Stress (PHQ Stress)	4.4	3.1	1 - 17	4.3	3.1	1 - 13	4.5	3.1	1 - 17

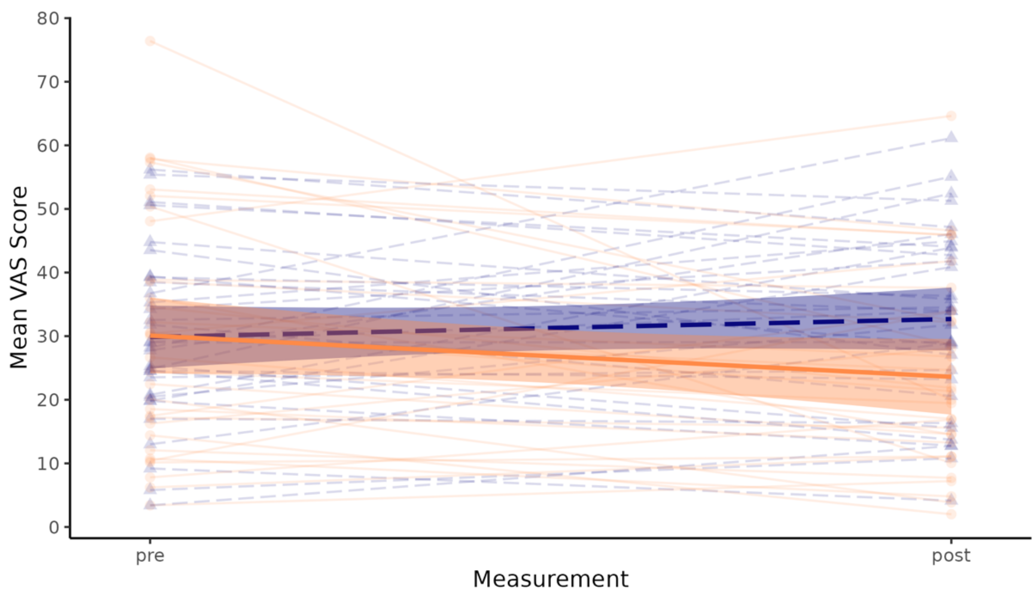
Note. $N = 73$, thereof $n = 34$ in the intervention group.

Subjective Momentary Stress

In the baseline phase, no significant differences between groups in momentary stress, $t(40.7) = -1.59$, $p = .992$, were apparent. The intra-class correlation (ICC) of the null model for subjective momentary stress was ICC = .374, indicating a high degree of clustering and, thereby, supporting a multi-level modeling approach. The assessment of subjective momentary stress by our visual analogue scale revealed a significant effect of the intervention ($\beta = -11.06$, $p = .040$, $d = -2.12$). Figure 2 shows changes in VAS scores during the intervention period, while Table 2 depicts respective predictors and control variables of the final model. The model with the predictor terms and their interaction, with random slopes for each participant and for each measurement, explained significantly more variance (ΔR^2_{cond} = 15.1%, ΔR^2_{marg} = 3.1%) than the null model, $\chi^2(19) = 195.28$, $p < .001$, and the model including only control variables, ΔR^2_{cond} = 12.4%, ΔR^2_{marg} = 1.8%; $\chi^2(5) = 178.34$, $p < .001$, while also showing a better fit compared to a model with random slopes only for each participant, ΔR^2_{cond} = 9.2%, ΔR^2_{marg} = −0.3%; $\chi^2(2) = 143.73$, $p < .001$. Estimated marginal means and standard errors for both measurement time points and groups are shown in Table 3.

Figure 2

Changes in Visual Analogue Scale (VAS) Scores During the Intervention Period



Note. Depicted are mean VAS scores (intervention group, IG: orange dots; control group, CG: dark blue triangles) as well as the slope of their predicted changes from pre- to posttest (IG: orange solid lines; CG: dark blue dashed lines) by linear regression. Colored areas around regression slopes indicate the standard error of each group.

Table 2

Hierarchical Linear Modeling with Subjective Momentary Stress as Outcome

	Subjective Momentary Stress (VAS)			
Variable	*β*	SE	*t*	*p*
Intercept	29.35	4.15	7.07	< .001*
Measurement	4.14	3.78	1.09	.281
Group	1.59	5.62	0.28	.779
Measurement * Group	−11.06	5.21	−2.12	.040*
Timepoint +30 min.	−0.22	1.47	−0.15	.883
Timepoint 11 AM	1.38	1.56	0.89	.374
Timepoint 2 PM	3.31	1.64	2.02	.044*
Timepoint 7 PM	−0.82	1.65	−0.50	.618
Age	0.27	0.48	0.56	.580
BMI	−0.08	0.79	−0.10	.924
Medication intake (L2)	1.08	7.48	0.14	.886
Smoking (L2)	0.93	5.31	0.18	.862
Food intake	−2.21	1.26	−1.76	.079
Drink intake	0.50	1.64	0.31	.761
Medication intake (L1)	1.23	4.80	0.26	.799
Smoking (L1)	−1.43	3.09	−0.46	.644
Physical Activity	−2.26	1.95	−1.16	.248
Menstruation cycle	1.68	2.86	0.59	.557

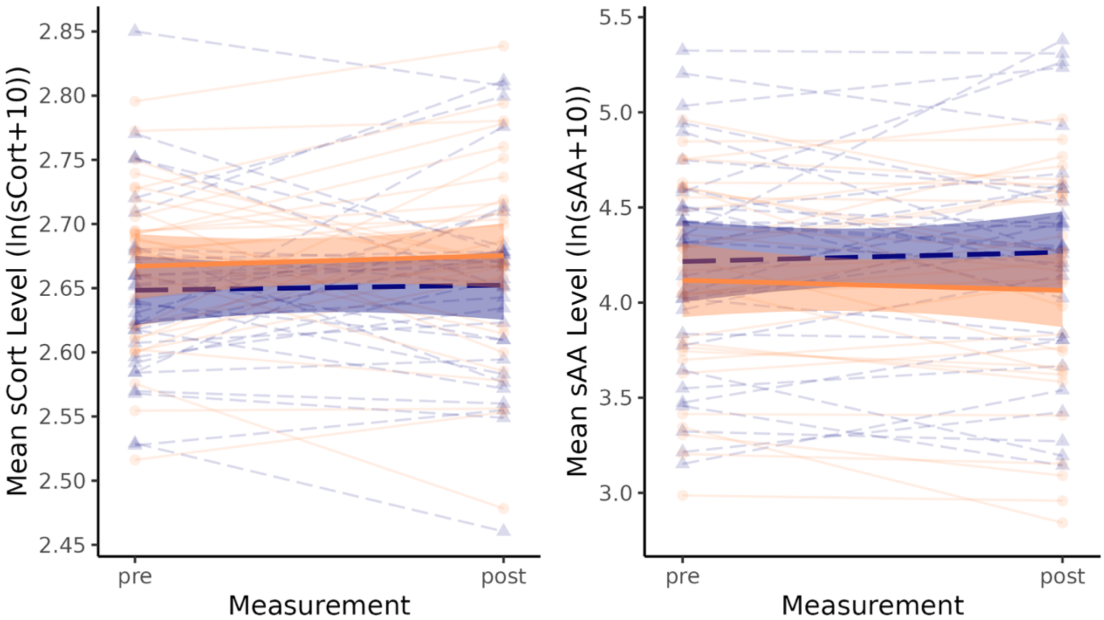
Note. Significant variables are marked with an asterisk. SE = standard error; BMI = Body mass index; L1 = Level 1 control variable; L2 = Level 2 control variable. Timepoint values are related to the first measurement of the day; other categorical control variables are coded with no = 0, yes = 1. Values for food, drink, and medication intake (L1), as well as smoking (L1) and physical activity refer to the last hour before measurement.

Salivary Cortisol and Alpha-Amylase

In the baseline phase, data showed no significant differences in sCort, $t(58.9) = -0.47$, $p = .967$, and sAA, $t(38.6) = 0.93$, $p = .790$, between groups. The ICCs of the null model for sCort and sAA were ICC = .038 and ICC = .435, respectively. Table 4 shows all predictors and control variables included in the final model, with their respective parameters, and corresponding inference statistics. Figure 3 shows changes in sCort and sAA levels during the intervention period; estimated marginal means and *SE*s for both measurement time points and groups are shown in Table 3.

Figure 3

Changes in sCort and sAA Levels During the Intervention Period



Note. Depicted are mean scores of sCort (A) and sAA (B) (intervention group, IG: orange dots; control group, CG: dark blue triangles) as well as the slope of their predicted changes from pre- to posttest (IG: orange solid lines; CG: dark blue dashed lines) by linear regression. Colored areas around regression slopes indicate the SE of each group.

The intervention did not have a significant effect on participants' sCort ($\beta = -0.02$, $p = .407$, $d = -0.82$) and sAA levels ($\beta = -0.06$, $p = .536$, $d = -0.62$). For sCort, hierarchical model comparisons revealed that the model including the predictor terms and their interaction, with random slopes for each participant, explained significantly more variance (ΔR^2_{cond} = 49.1%, ΔR^2_{marg} = 47.4%) than the null model, $\chi^2(17)$ = 816.8, p < .001, but not significantly more than the model including only control variables, ΔR^2_{cond} = 0.1%, ΔR^2_{marg} = −0.1%; $\chi^2(17)$ = 0.71, p = .871. For sAA, the interaction model including a random slope for measurement in addition to that of participants was superior to the null model, ΔR^2_{cond} = 15.9%, ΔR^2_{marg} = 15.8%; $\chi^2(19)$ = 313.19, p < .001, the model without control variables, ΔR^2_{cond} = 2%, ΔR^2_{marg} = 1.4%; $\chi^2(5)$ = 18.41, p = .002, as well as a similar model without the random effect of measurement, ΔR^2_{cond} = 1.9%, ΔR^2_{marg} = 0.2%; $\chi^2(2)$ = 14.99, p < .001. The timepoint of the salivary assessment significantly modulated both the levels of sCort and sAA (results in the table are compared to the first assessment after waking up). Smoking during the last hour, as well as luteal compared to follicular menstrual cycle were associated with significantly elevated sCort levels, while no differences in sAA levels were found for any of the control variables.

Table 3

Estimated Marginal Means and SEs for Both Measurements and Groups.

		Pretest		Posttest	
Variable	Group	Mean	SE	Mean	SE
Salivary Cortisol	Intervention	2.67	0.22	2.66	0.22
	Control	2.65	0.23	2.66	0.22
Salivary Alpha-Amylase	Intervention	3.98	0.17	3.98	0.18
	Control	4.14	0.18	4.21	0.18
Subjective Momentary	Intervention	32.46	5.18	25.53	4.89
Stress	Control	30.87	5.38	35.01	5.03

Table 4

Hierarchical Linear Modeling with Salivary Cortisol and Alpha-Amylase as Outcome.

	Salivary Cortisol				Salivary Alpha-Amylase			
Variable	*β*	SE	*t*	*p*	*β*	SE	*t*	*p*
Intercept	2.80	0.02	138.01	< .001*	4.23	0.13	33.35	<.001*
Measurement	0.01	0.02	0.63	.529	0.07	0.07	1.00	.326
Group	0.01	0.02	0.47	.641	−0.16	0.17	−0.93	.358
Measurement * Group	−0.02	0.02	−0.83	.407	−0.06	0.10	−0.62	.536
Timepoint +30 min.	0.13	0.02	8.21	< .001*	−0.46	0.05	−8.90	<.001*
Timepoint 11 AM	−0.20	0.02	−12.23	< .001*	0.01	0.05	0.17	.867
Timepoint 2 PM	−0.26	0.02	−14.60	< .001*	0.29	0.05	5.31	<.001*
Timepoint 7 PM	−0.37	0.02	−20.82	< .001*	0.37	0.06	6.77	<.001*
Age	0.00	0.00	1.29	.204	0.02	0.02	1.04	.304
BMI	0.00	0.00	−1.11	.273	−0.01	0.03	−0.22	.826
Medication intake (L2)	−0.01	0.03	−0.43	.667	−0.29	0.27	−1.07	.293
Smoking (L2)	0.00	0.02	−0.33	.743	−0.11	0.19	−0.54	.590
Food intake	0.03	0.01	1.94	.053	0.05	0.04	1.20	.232
Drink intake	0.00	0.02	0.24	.808	−0.04	0.05	−0.78	.437
Medication intake (L1)	0.02	0.05	0.32	.746	0.03	0.16	0.17	.866
Smoking (L1)	0.08	0.03	2.50	.013*	0.03	0.10	0.27	.791
Physical Activity	0.01	0.02	0.46	.644	−0.01	0.07	−0.09	.931
Menstruation cycle	0.03	0.02	2.18	.029*	−0.01	0.07	−0.11	.917

Note. Significant variables are marked with an asterisk. SE = standard error; BMI = Body mass index; L1 = Level 1 control variable; L2 = Level 2 control variable. Timepoint values are related to the first measurement of the day; other categorical control variables are coded with no = 0, yes = 1, except for Measurement (pretest = 0, posttest = 1) and group (control = 0, intervention = 1). Values for food, drink, and medication intake (L1), as well as smoking (L1) and physical activity refer to the last hour before measurement.

Discussion

The aim of this randomized controlled trial, which incorporated an ecological momentary assessment approach, was to examine the impact of an eight-week hatha yoga intervention on salivary cortisol, salivary alpha-amylase, and momentary subjective stress in everyday life. Our findings indicate that the intervention effectively alleviated subjective daily stress, aligning with hypothesis 1. However, it did not yield significant changes in salivary cortisol or salivary alpha-amylase levels, contradicting hypotheses 2 and 3.

Effects of Hatha Yoga on subjective momentary stress in everyday life

The effects of our hatha yoga intervention on momentary stress in everyday life are difficult to compare to other studies, as very few studies investigated yoga using an ecological momentary intervention approach so far. For example, one study found a comparable reduction in stress in a 12-week Iyengar Yoga intervention in obese women (Schäfer, 2022). Similar EMA studies investigating other mind-body interventions, such as mindfulness-based interventions, report mixed effects regarding subjective momentary stress in everyday life, with some studies finding significant reductions (e.g., Chin et al., 2019) and others not (e.g., Aguilar-Raab et al., 2021). This might be due to differences in the intervention components, intervention intensity, or intervention length, which may also apply to yoga interventions. To support our results and to find out more about the specifics of daily stress levels in everyday life, EMA studies investigating yoga interventions are needed. Looking at our large effect sizes and concurrent significant reductions in perceived stress and stress reactivity (for details see Szaszkó et al., 2023), our results strongly suggest the effectiveness of our hatha yoga intervention in reducing subjective stress experiences overall, including momentary stress in everyday life.

Effects of Hatha Yoga on Salivary Cortisol and Alpha-Amylase

Contrary to our hypotheses, we did not observe any reductions in salivary cortisol or salivary alpha-amylase levels due to the intervention. The literature on the effects of yoga on salivary cortisol levels is currently mixed. A meta-analysis by Pascoe et al. (2017) indicated significant changes in waking, afternoon, and evening cortisol due to yoga interventions. However, these effects were mainly observed in clinical samples, particularly among women with breast cancer, in which cortisol levels deviated from non-ill controls, potentially due to dysregulated stress systems often present in chronicillnesses, or, in case of cancer, even driving them (Dai et al., 2020; Liu et al., 2022). In contrast, a study investigating hatha yoga in students did not report any significant effects (Sieverdes et al., 2014). Similar findings were reported in a review on Yoga's effects on stress measures and mood (Pascoe & Bauer, 2015). One study within this review using Iyengar Yoga, which can be counted as a form of hatha yoga, found no effects on daytime sCort in healthy adults, although significant effects on subjective stress were noted (Bowden et al., 2012). Another study in cancer survivors reported significant effects on sCort (Banasik et al., 2011). These results suggest that hatha yoga might be more effective in modulating changes in sCort in clinical populations as opposed to healthy individuals, which would explain the lack of significant results in our study.

Regarding salivary alpha-amylase, results are very limited so far. Yoga has been shown to affect SNS activity, mainly measured by heart rate, heart rate variability, and blood pressure, also when compared to active control groups conducting physical exercise (Pascoe & Bauer, 2015; Pascoe et al., 2017). Similar to sCort, also among these studies, data mainly come from clinical samples, suggesting that SNS activity might be more affected by yoga interventions when baseline levels are elevated. Furthermore, it is unclear whether the results regarding cardiac SNS outcomes are comparable for sAA. One study found a trend but no significant change in sAA in a hatha yoga intervention with students (Sieverdes et al., 2014). It is possible that cardiac outcomes are more strongly influenced by yoga interventions than sAA, as seen in the study by Sieverdes and colleagues (2014). Future studies should, therefore, assess multiple SNS outcomes to answer this question.

Besides the above-mentioned limited efficacy of the intervention on stress-related biomarkers due to their comparatively normal levels in our healthy sample, the discrepancy between psychological and physiological results may be explained by increased psychological coping (Lazarus & Folkman, 1984). Under the assumption that biomarkers measure the initial stress response, the initial stress response might not be altered by the intervention, but subsequently a better coping with the initially felt stress might lead to less negative affect in challenging situations compared to controls (Froeliger et al., 2012). Decreased self-reported stress reactivity and increased mindfulness both reported in our study (Szaszkó et al., 2023) also speak for this interpretation (for the role of latter in decreasing stress, see Park et al., 2021). The practice of yoga is also meant to teach humans acceptance and nonreactivity, both of which could contribute to increased psychological well-being without changes in the underlying physiology (Tellhed et al., 2019). However, it is also possible that demand characteristics in the absence of an active control group (Grossman, 2008), as well as the positive social effects of being a member of a group focusing toward one common goal led to the aforementioned changes in subjective momentary stress. From this perspective, it is possible that the participants in the IG did not respond truthfully but instead reported less subjectively felt stress, despite not such changes.

Strengths, Limitations, and Future Directions

This study is the first to investigate a hatha yoga intervention using ecological momentary assessment to measure both subjective and biological stress markers, allowing for a multi-dimensional evaluation of the intervention's effects. This approach not only improves ecological validity and contextual richness of the data but also enhances the statistical power of the results by having multiple assessment time points per participant. EMA, together with a multi-dimensional assessment of stress, as applied in the current study, may also be used in future studies to understand the mechanisms underlying yoga's effects on stress. More studies examining daily fluctuations of dynamic variables and long-term changes are needed. To understand stress reactivity in everyday life, EMA studies should examine moments of acute stress in daily life, combining biological and subjective stress outcome assessments. Future studies should assess the impact of hatha yoga on stress in chronically stressed populations because they may profit more from the intervention than less stressed samples.

A significant merit of this study lies in the concurrent assessment of HPA axis and ANS activity, two critical components implicated in chronic stress and its associated disorders. For a holistic understanding, future research should integrate the evaluation of immune system responses, thus including all major stress-related systems and their interplay. Subsequent studies could therefore benefit from incorporating inflammatory biomarkers that are said to vary with levels of stress (Rohleder, 2019), to achieve an integration of related mechanisms in a comprehensive framework. Besides its strengths, our study also had important limitations. To begin with, we did not experimentally manipulate participants' stress levels using an external stressor. As outlined above, one study by Gothe et al. (2016) found differences in participants' HPA axis reactivity as a result of a hatha yoga intervention, without noticing similar changes in waking sCort or perceived stress levels. Further, the present study did not have an active control group, limiting the informative value of the effects, as placebo effects might interfere with the intervention effects. An active control group utilizing another comparable physical activity should be utilized in future research to isolate the effects that are solely attributable to the practice of yoga. Additionally, comparing various yoga styles could provide insights into the effectiveness of different yoga components: Other forms of yoga may be more effective in changing HPA axis activity, especially in healthy individuals. As yoga has been shown to be more beneficial regarding the impact on HPA and SNS activity than other physical activities, breathwork and meditation might be more important for effects on stress biomarkers and may constitute the effective components of yoga interventions. Therefore, less physical forms of yoga might provoke larger effects on sCort and sAA than hatha yoga. Future research should focus on the comparison of different yoga interventions to identify the effective components of yoga interventions. It is thus important to describe and characterize administered yoga interventions by using standardized questionnaires like The Essential Properties of Yoga Questionnaire or similar measurements.

Additionally, the studied sample was relatively uniform, mostly consisting of females (79%) and university students (48%), limiting the generalizability of the results. The study also had a relatively high drop-out rate (36%), leading to a smaller sample size than intended. However, the sample size was big enough for our multilevel modelling approach (we used the power calculator for multi-level studies on https://kleimanlab.org/resources/power-curves/, January 2024). The per protocol analysis approach, excluding participants practicing less than three times per week, further reduced the sample size and might constitute a bias in the results because only adherent participants were investigated. This potential difference between groups might be reflected in participants' evaluation of the intervention, which differs between the intention-to-treat sample and the analyzed sample.

Another limitation is the absence of the preregistration of hypothesis 1, making those results exploratory. Our results could also be influenced by the inclusive nature of our design. While this approach enhances ecological validity, adopting more restrictive inclusion and exclusion criteria (e.g., including only free-cycling women) might have facilitated a clearer interpretation of the biological outcomes. Even though it is recommended to control for potentially influencing variables when analyzing salivary cortisol and salivary alpha-amylase (e.g., Strahler et al., 2017), this approach also carries the risk of overfitting the models. Moreover, using identical control variables for all three models enhances result comparability; nonetheless, it may come at the expense of not tailoring the models to the optimal specifications for each individual variable.

Conclusion

We found that an eight-week hatha yoga intervention significantly and widely reduced levels of subjective momentary stress; however, the intervention did not impact diurnal levels related to HPA axis (salivary cortisol) and autonomic nervous system activity (salivary alpha-amylase). We attribute our results to increased psychological coping with stressful events due to yoga; however, it may also be the case that diurnal levels of these biomarkers do not adequately reflect changes in the aforementioned systems, and that these may be restricted to changes in reactivity due to a stressor. Therefore, experimental paradigms carefully manipulating stress in individuals are needed in addition to measures of diurnal changes to make firm conclusions about hatha yoga's effect on stress systems.

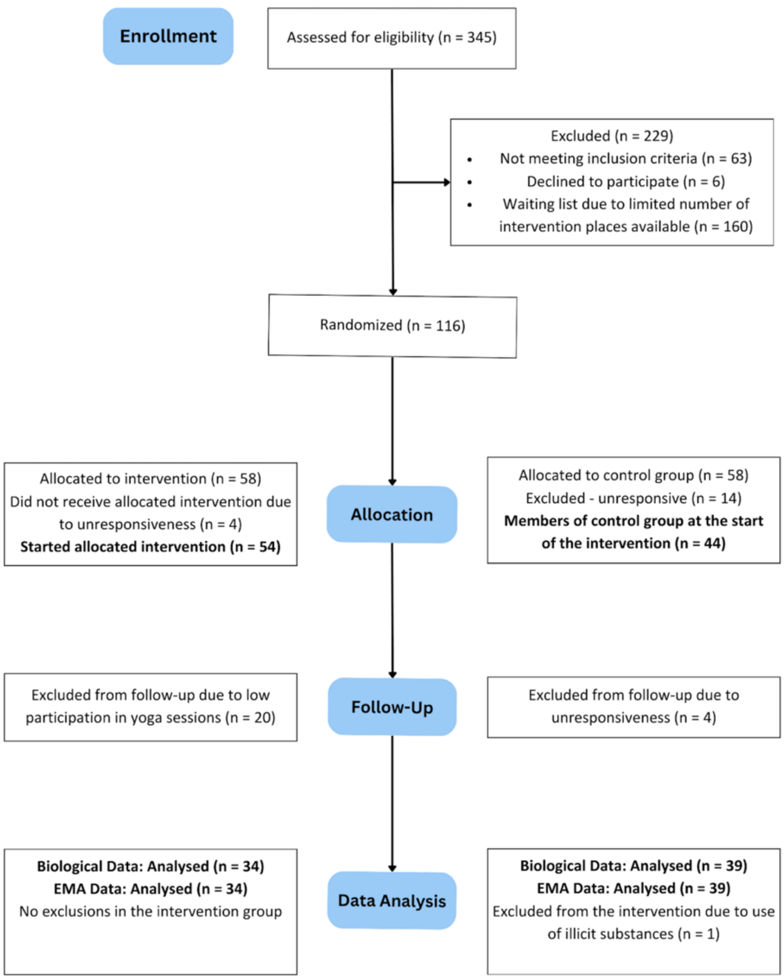
Declarations

No third-party funding was received from any organization for the work presented in this manuscript. We have no conflicts of interest to disclose.

Supplements

Supplement S1

Trial Profile



Note. Reasons for exclusion after the previous analysis step are listed below the number of analysed participants for each step. The participant excluded for the use of illicit substances was excluded from both EMA (of subjective momentary stress levels) and biological data analyses (of sCort and sAA levels). EMA: Ecological Momentary Assessment.

Supplement S2

EMA Items (Translated English Version)

ID	Item	Response format	Range	Reference
Items administered at T_1 (wake-up), T_2 (30 minutes after wake-up), T_3 (11am), T_4 (2pm), and T_5 (7pm)				
1	Time of saliva sampling	Time		
2	Saliva sample code	Text		
3	At the moment I feel	7-staged Likert scale from "very tired" to "very awake"	1-7	Based on Wilhelm & Schoebi, 2007
4		7-staged Likert scale from "very content" to "very discontent"		
5		7-staged Likert scale from "very calm" to agitated"		
6		7-staged Likert scale from "full of energy" to "very low in energy"		
7		7-staged Likert scale from "very well" to "very unwell"		
8		7-staged Likert scale from "very relaxed" to "very tense"		
9	At the moment I feel exhausted.	5-staged Likert scale from "not at all" to "very much"	1-5	Based on MFI, Schwarz et al., 2003
10	At the moment I feel unmotivated.			
11	At the moment I feel active.			
12	At the moment I can concentrate well.			
13	At the moment I trust myself a lot physically.			
14	At the moment I feel stressed.	Visual analogue scale from "not at all" to "very much"	0-100	
15	At the moment I feel that I am unable to control the important things in my life.	5-staged Likert scale from "not at all" to "very much"	1-5	Adapted version PSS-4; Klein et al., 2016; Vallejo et al., 2018
16	At the moment I feel confident about my ability to handle my personal problems.			
17	At the moment I feel that things are going my way.			
18	At the moment I feel difficulties are piling up so high that I could not overcome them.			
19	What did you do before the assessment?	1) General (Sleeping, Relaxing, Personal Care, Eating/Drinking, On the go,...) 2) Work (Desk work, Job, Physical labor,...) 3) Leisure (Hobby, Sport, Conversation, Reading, Watching TV,...) 4) Other	1-4	
20	Where are you?	1) Own apartment 2) Someone else's apartment 3) On the way 4) At the workplace 5) Store 6) Pub/Restaurant 7) Public event space 8) Outdoors/in nature 9) At the doctor/hospital 10) Other	1-10	

ID	Item	Response format	Range	Reference
		Items administered at T_1 (wake-up), T_2 (30 minutes after wake-up), T_3 (11am), T_4 (2pm), and T_5 (7pm)		
21	Which people are present?	1) I am alone 2) Friends 3) Acquaintances 4) Family 5) Partner 6) Strangers	1-6	
22	What did you eat in the last hour?	1) Nothing 2) Main meal 3) Snack 4) Sweet 5) Other	1-5	
23	What did you drink in the last hour?	1) Water/unsweetened tea 2) Sweetened drink/fruit juice 3) Caffeinated drink 4) Alcoholic drink 5) Nothing	1-5	
24	Did you smoke in the last hour?	1) No 2) 1-5 cigarettes 3) Over 5 cigarettes	1-3	
		Items administered at T_6 (bedtime)		
25	When did you wake up today?	Time		
26	How did you wake up today?	1) Alarm 2) By myself 3) Other	1-3	
27	When did you go to bed yesterday?	Time		Based on PSQI, Buysse et al., 1988
28	Did it take you more than 15 minutes to fall asleep?	Yes/no	0-1	
29	How restful do you estimate your sleep was overall tonight?	Visual analogue scale from "not restful at all" to "very restful"	0-100	
30	Did you engage in any sports or physical activities today?	Yes/no	0-1	
30.1	If yes: Please specify the activity(ies) (including yoga).	Text		
30.2	If yes: When did you perform the activities?	Time		
30.3	If yes: How long did you perform the activities?	Hours, minutes		

ID	Item	Response format	Range	Reference
Items administered at T_1 (wake-up), T_2 (30 minutes after wake-up), T_3 (11am), T_4 (2pm), and T_5 (7pm)				
30.4	If yes: For what main reason did you engage in sports or physical activity?	17) Health promotion 18) Muscle building 19) Weight loss 20) Relaxation 21) Activation 22) Stress reduction 23) Without a specific reason 24) Other (text)	1-8	
31	Did you perform "Mind-Body activities" today?	Yes/no	0-1	
31.1	If yes: Which activities did you perform?	17) Progressive muscle relaxation 18) Autogenic training 19) Imaginative exercises/dream journey 20) Meditation 21) Mindfulness activity 22) Breathing activity 23) Activity with music 24) Other (text)	1-8	
31.2	If yes: When did you perform the activities?	Time		
31.3	If yes: How long did you perform the activities?	Hours, minutes		
31.4	If yes: For what main reason did you perform the activities?	13) Health promotion 14) Relaxation 15) Activation 16) Stress reduction 17) Without a specific reason 18) Other	1-6	
32	Was today a typical day in your life?	Yes/no	0-1	
32.1	If no: Please describe what was unusual.	Text		
33	Did you experience moments today where you felt stressed?	Yes/no	0-1	
33.1	If yes: How many stressful moments did you experience today?	11) 1 12) 2 13) 3 14) More than 3 15) I do not know	1-5	
33.2	If yes: Can you briefly describe the situation(s)? What happened? Who was involved? What were you doing/thinking/feeling before and during the situation, etc.	Text		

ID	Item	Response format	Range	Reference
Items administered at T_1 (wake-up), T_2 (30 minutes after wake-up), T_3 (11am), T_4 (2pm), and T_5 (7pm)				
34	How many cigarettes have you smoked today in total?	Number		
35	Have you taken any medication today?	Yes/no	0-1	
35.1	If yes: Name the medications that were taken.	Text		
35.2	If yes: Time of taking the medications.	Time		

Note. The assessment schedule was identical for the three pre and post assessment days.

Supplement S3

Missing Values and Valid Measurements

		Cortisol		Alpha-amylase		Momentary stress	
		n	%	*n*	%	*n*	%
Missing saliva samples	Control group	269	12.3	268	12.2		
	Intervention group	113	5.2	114	5.2		
	Total	382	17.4	382	17.4		
Missing values below measurement threshold	Control group	3	0.1	14	0.6		
	Intervention group	8	0.4	38	1.7		
	Total	11	0.5	52	2.4		
Overall missing values	Control group	272	12.4	282	12.9	138	6.3
	Intervention group	121	5.5	152	6.9	59	2.7
	Total	393	17.9	434	19.8	197	9.0
Valid measurements	Control group	898	41.0	888	40.5	1032	47.1
	Intervention group	899	41.1	868	39.6	961	43.9
	Total	1797	82.1	1756	80.2	1993	91.0

Note. N = 2,190 scheduled values of n = 73 participants, thereof 34 in the intervention group.

Supplement S4

Acceptability Ratings

ID	Item	Agree (*n*, %)	
		IG all *n* = 41	IG analyzed *n* = 32
1	Practicing yoga three times a week was too frequent for me.	17 (41.5%)	10 (31.3%)
2	The yoga sessions (approximately 60 minutes) were too long for me.	2 (4.9%)	2 (6.3%)
3	The yoga sessions (approximately 60 minutes) were too short for me.	6 (14.6%)	5 (15.6%)
4	The difficulty level of the yoga sessions was appropriate for me.	38 (92.7%)	29 (90.6%)
5	I was able to integrate the yoga sessions into my daily routine.	31 (75.6%)	26 (81.3%)
6	I would have needed more support from the yoga instructors to perform the exercises.	3 (7.3%)	3 (9.4%)
7	I continued to practice yoga after the 8-week yoga intervention, either at a studio or at home.	8 (19.5%)	6 (18.8%)
8	I plan to continue practicing yoga (at home or in a studio).	35 (85.4%)	30 (93.8%)
9	I generally found the yoga sessions helpful.	38 (92.7%)	32 (100%)
10	To what extent has practicing yoga changed your coping with stress?	*M* = 48.07 *SD* = 26.90 range: 0-100	*M* = 51.59, *SD* = 25.13, range: 10-100

Note. IG = intervention group. Two participants from the *n* = 34 analyzed participants in the intervention group did not fill out the online post questionnaire. Item 9 was answered on a 5-staged Likert scale. The answers “fully agree” and “rather agree” were grouped into “agree”. Item 10 was answered on a visual analogue scale ranging from 0 “not at all” to 100 “very much”.

5

General Discussion

5.1 Summary of the Present Findings

In the preceding three chapters, I demonstrated that the practice of hatha yoga can lead to profound changes in the wellbeing and cognitive capabilities of healthy participants without previous yoga experience. Together with the research team, I used a combination of behavioral, (electro)physiological, and self-reported measures in a randomized controlled trial to back up possible evidence from multiple points of view and to relate distinct, but potentially interrelated mechanisms to each other. Besides delivering important findings, this multipronged approach led to new perspectives, but also ambiguous results.

In our study, we showed that the practice of hatha yoga decreased self-reported, but not physiological stress levels, the latter measured by salivary cortisol and alpha-amylase. We also found a decrease in perceived stress reactivity levels due to the intervention. I attribute this discrepancy between self-reported and physiological levels to an increased coping ability with the negative effects of stress, leading to higher levels of resilience, but without changes in basal levels of HPA axis and SNS activity markers. Increased levels of trait mindfulness due to the intervention also point in this direction, as does decreased reactivity to sensory stimuli, as outlined in Chapter 3. Interestingly, the intervention, unlike many others using yoga as their method of choice, did not show effects on participants' state and/or trait anxiety levels. I will discuss the possible reasons of these findings together with their implications in Chapter 5.2.

In this dissertation, I also presented behavioral and neurophysiological evidence for the notion that hatha yoga can potentially enhance distinct executive functions. While Chapter 2 suggests that a yoga intervention did not improve participants' ability to inhibit irrelevant visual stimuli, the conclusion must be carefully reconsidered after the results from Chapter 3: Modality-specific differences in alpha amplitude suggested that participants could indeed better inhibit momentarily task-irrelevant stimuli that were presented in a distinct modality from the task-relevant stimuli. Two explanations for this finding will be proposed in Chapter 5.3: They are centered around cognitive load, as well as the suitability of the tasks and the related analyses.

In addition, we could not find straightforward evidence for our hypothesis that hatha yoga positively influenced shifting. Nevertheless, participants' efficiency or capability to hold representations of distinct targets in mind – a functionality that can be attributed more to working memory than to shifting proper – improved, as demonstrated in Chapter 3 by decreased mixing costs in Experiment 1, as well as increased midfrontal theta activity in Experiment 2. In Chapter 5.4, I discuss these findings in detail.

Finally, in Chapter 5.5, I attempt to answer the question whether the observed effects of our intervention on executive functions can be attributed to its parasympathetic effects, or rather the immediate effects of hatha yoga on cognitive functioning, with some arguments, like changes in perceived stress and working memory-related effects and their correlations, speaking for a stress-related effect, while others, like the lack of an effect on the shifting function, do not. In addition, I will also discuss the interdependence of the three core executive functions and their implications. Unfortunately, the lack of a significant effect of our intervention on participants state and trait anxiety levels does not simplify this discussion, ultimately limiting the conclusions I can make with regards to our hypotheses in this regard.

5.2 Positive Effects on Self-Reported Measures of Stress Due to Changes in Coping

The divide between physiological and self-reported measures of stress is evident when looking at our results: While perceived stress and stress reactivity decreased due to the intervention, the practice of yoga did not affect salivary markers of cortisol and alpha-amylase (representative for changes in the activity of the two most important bodily stress systems, the HPA axis and the autonomic nervous system) in our sample. This is not a surprising result because other studies employing a hatha (or closely related to hatha) yoga intervention employing clinical or healthy populations found similar results on stress biomarkers (Bower et al., 2014; Sieverdes et al., 2014). They did so, however, typically employing less exhaustive measurements of the physiological markers than we did in our study, with its repeated measurements for improved reliability and ecological validity. Some past studies have reported decreases of self-reported measures of stress and/or stress reactivity due to hatha yoga or closely related yoga styles (Benvenutti et al., 2017; Carusotto, 2023; Hartfiel et al., 2012; West et al., 2004; cf. Gothe et al., 2016). However, such self-reported results must be seen critically because a placebo-controlled double-blinded study in case of yoga interventions is hardly possible, leading to potential demand characteristics, where participants' expectations about the intervention may influence their self-reports, thus, negatively affecting the validity of the results. Also, social effects of the intervention on stress-related aspects should not be underestimated: Social support and being part of a community, especially evident in a study conducted during the COVID-19 pandemic, can by itself lead to positive mental health outcomes (Ni et al., 2020). Future studies should therefore employ active control groups with social affiliations to counteract such social-versus-non-social confounds between the intervention and the control group, as existed in the present study. Cognitive biases with regards to mindfulness-based practices are detailed in Grossman (2008). In addition, there have been only a few randomized controlled trials with adequate sample sizes investigating the relationship between hatha yoga and stress levels. It should also be noted that our focus was on assessing the effects of the intervention on the overall activity of the HPA axis and the SNS, without the induction of stress. It may therefore be the case that although the general activity of these systems did not change, they would have shown an altered response to a stressor. In fact, a study by Gothe et al. (2016) on sedentary older adults showed changes in cortisol in response to a stressor, but not in general salivary cortisol levels. These findings imply that changes in the stress system's (re)activity have taken place, but they were limited to situations in which participants were exposed to a stressor. Such stress-induction paradigms (like the Trier Social Stress Test; Kirschbaum et al., 1993) should, therefore, be included in future studies to be able to compare effects on general activity of the involved stress systems compared to their reactivity to a stressor.

One important mechanism that may explain the disparity between self-reported and physiological results is the development or practice of emotion-focused stress-coping techniques or strategies through the practice of (hatha) yoga, changing how stress psychologically affects the individual, ultimately leading to processes of cognitive reappraisal, acceptance of the inevitable, emotional nonreactivity, and relaxation (Hayes et al., 1999; Holahan & Moos, 1990; Hylander et al., 2017; Lazarus & Folkman, 1984; Maddux et al., 2018; Schmalzl et al., 2015; Tellhed et al., 2019). Consider this perspective: By consciously accepting, maybe even finding something rewarding about the upcoming sensations experienced during a cold shower, you can mitigate the psychological stress associated with it, despite your body being subjected to conditions identical to those experienced by individuals without such cognitive acceptance. A similar mechanism might be at play when practicing uncomfortable body postures during yoga's asanas. Such stress-coping techniques can also lead to reduced physiological arousal (e.g., less norepinephrine rushing to your body during showering), but, also to a decreased attentional bias toward negative information (Jamieson et al., 2012). As suggested by the present data, reduced physiological arousal may also not be necessary in order to experience less stress: In a paradigm involving the Cold Pressor Test (Hines & Brown, 1932), in which participants are asked to hold their hands in ice-cold water – an experience that is commonly perceived as painful (von Baeyer et al., 2005) and that acts as a physiological stressor (Cui et al., 2002; Wirch et al., 2006) – experienced yoga practitioners did not exhibit higher pain tolerance, but could nevertheless keep their hands in the water for more than twice as long as controls unexperienced with yoga (Villemure et al., 2014). Also, experienced practitioners of yoga do not seem to be negatively influenced in their affect, even though they still show significant amygdala activation in response to emotionally negative stimuli (Froeliger et al., 2012). The comparatively slow breathing rhythm throughout the appearance of practice- and non-practice-related challenges during yoga additionally helps to establish and train such non-reactive awareness facing stress (Schmalzl et al., 2015). Also, reframing stress arousal as beneficial can improve behavioral displays of affect without attenuating SNS activity together with increased appraisals of coping resources (Beltzer et al., 2014; Webb et al., 2012).

The lack of an increase in spectral power of the visual evoked potential in the intervention group compared to the control group, once participants had to switch to the visual modality, may also be reflective of this nonreactivity, albeit in the sensory domain. Increased focused attention due to various mindfulness-related exercises may then contribute to such sensory nonreactivity by increasing the effectivity of attentional allocation (Jha et al., 2007; MacLean et al., 2010), perhaps in cooperation with emotional processes. Increased nonreactivity may also be explained by improved self-regulation positively affecting the balance between bottom-up and top-down mechanisms (Chiesa et al., 2013), where less reactivity also goes hand in hand with an improved ability to relax. It is possible that the increased alpha power we found in Experiment 2 of Chapter 3, besides increased sensory shielding against irrelevant input, at least partly reflected increased relaxation ability (Stancák & Kuna, 1994; Trakroo et al., 2013), although some objections (see Chapter 5.3) may arise.

It has been reported that increased mindfulness and practicing pranayama can help cope with stress (Brown & Gerbarg, 2009; Christmann et al., 2017; Tellhed et al., 2019), ultimately leading to increased psychological health benefits. Interestingly, we not only found that trait mindfulness increased due to the intervention, but that the higher the trait mindfulness levels before the intervention, the higher the reduction of perceived stress levels from before to after the intervention. This result strengthens the impression that increased mindfulness is an important mediator when it comes to the effectivity of the intervention on perceived stress and, together with the discrepancy between the physiological and psychological results mentioned above, suggests that mindfulness can help with the development of effective coping (rather than buffering) strategies against the negative psychological effects of stress. Future research could delve deeper into the mechanisms through which (hatha) yoga influences emotion-focused coping strategies and cognitive reappraisal, and whether it can completely take place without changes in physiological arousal by measuring more diverse indicators of autonomic nervous system activity (heart rate variability, skin conductance, pupil dilation, all in addition to hormonal markers).

The fact that, contrary to perceived stress and stress reactivity, both trait and state anxiety levels did not change through the intervention, also speaks for our account of improved emotional coping: Trait anxiety is a rather stable characteristic of personality (Spielberger, 1971), while state anxiety might not decrease due to the rather deeply ingrained and, thus, more change-resistant structures and processes it is governed by (genetic predisposition, past prolonged or profound life experiences, and neurobiological factors like differences in brain chemistry influencing trait anxiety, which in turn influences state anxiety together with situational stress; Eysenck, 1992; Gidron, 2013; Millan, 2003; Smith & Pollak, 2020) compared to those involved in perceiving stress and coping with it. Also, the construct of state anxiety is centered around how one feels presently. There are many reasons for having experienced stress in the last four weeks (the timeframe to which the Perceived Stress Scale refers). However, there is potentially less reason to feel anxious at the very moment of filling in the questionnaire. Thus, the questionnaire might not be ideally sensitive to test state anxiety to begin with. Also, anxiety levels might have been too low to be significantly decreased at all in our healthy sample. In fact, a meta-analysis by Hofmann and colleagues (2016) showed that the higher the anxiety levels, the higher the benefits of a hatha yoga intervention, with people with clinically elevated anxiety levels profiting the most. Future studies could therefore use an ecological momentary approach to measure state anxiety levels on a more fine-grained time scale as well, to provide an improved, more sensitive and more valid measure of this construct.

5.3 Potential Influence of Yoga on Inhibition

Regarding the effects of hatha yoga on inhibition, our findings were, at first glance, somewhat ambiguous. The first published article contained in this dissertation (Chapter 2), looking at electrophysiological evidence of one of our experiments, did not find any clues supporting the hypothesis that the practice of hatha yoga may actually improve inhibition: When we expected an irrelevant feature (the color red or green) to be proactively suppressed (Haegens et al., 2011), ERP evidence together with measures of preparatory alpha power indicated that this was done equally efficient before and after the intervention. However, Experiment 2 of Chapter 3 painted an entirely different picture (even though the aim of this experiment was not to look at inhibition itself), with increased alpha activity, particularly when participants had to attend the auditory modality, while ignoring visual stimuli.

Why this discrepancy? In the former experiment, the effort needed to suppress irrelevant stimuli was relatively low, and proactive suppression did indeed take place all the time, independent from groups or measurement time points. Targets were never shown together with irrelevant distractors in the same display (this was done in order to be able to extract the respective ERPs of attentional capture – the N2pc – and of inhibition – the Pd – without confounding each other). In Experiment 2 outlined in Chapter 3, the not-to-be-attended modality had to be continuously suppressed, which also goes hand in hand with higher top-down effort to suppress the stimuli from the irrelevant modality. Also, keep in mind that after a switch in modality, the same stimuli functioned as targets, meaning that participants not only had to inhibit the irrelevant stimuli, but also their response to potential targets from the not-to-be-attended modality. The failure of such response inhibition can also be predicted by changes in alpha activity (Bengson et al., 2012; Roche et al., 2004). Thus, the changes in alpha activity we observed here may reflect a combination of increased sensory inhibition and response inhibition. It is also plausible that the yoga practice inherently trained participants in body-focused attention, leading to an enhancement in attentional control of the alpha rhythm (Kerr et al., 2013), and resulting in more efficient filtering of sensory input and improved executive control. In fact, participants can even be trained to induce alpha waves with attention focused inward (Green et al., 1979).

Higher alpha activity during attend-to-auditory compared to attend-to-visual trials can also be indicative of both sensory and response inhibition: For sensory inhibition, greater parietooccipital alpha activity, after cueing for an auditory trial compared to cueing for a visual trial, has been observed in multiple studies using cross-modal paradigms (e.g., Foxe et al., 1998; Mazaheri et al., 2014b), indicating disengagement of the visual dorsal stream to maintain current task-related information in working memory (Tuladhar et al., 2007). However, to date, only a few studies have worked with concurrent stimulus streams present in both modalities. To my knowledge, our experiment is the only one working with a sustained continuous stream of concurrent information. Saupe et al. (2009) created a similar paradigm with stimuli evoking steady-state responses in both modalities, with their paradigm, however, divided into distinct trials, and to-be-attended modalities cued before each trial. Our findings therefore support the theory that there is indeed interference between the auditory and visual modalities during stimulus processing (Jolicoeur, 1999; but see Duncan et al., 1997, for results to the contrary, and Martens et al., 2010, for an account in terms of individual differences). For response inhibition, significantly higher false alarm rates in the attend-auditory condition clearly indicate that participants had more difficulties with the auditory than with the visual task (see also Pomper et al., 2023, for similar results in a crossmodal paradigm). Performance may thus profit from increased response inhibition of the auditory task, suggesting a potential adaptive role of executive control to optimize task execution. Future studies should concentrate on disentangling the potential effects of yoga on sensory versus response inhibition by careful manipulation of the two functions where only one, but not the other and vice versa are required (i.e., the testbed for a double dissociation).

Alternatively, higher alpha power due to the intervention could solely reflect improved relaxation ability (Trakroo et al., 2013), which could go hand in hand with a general, non-intervention-related effect of higher suppression of irrelevant visual input when needed. However, the modality-specific differences observed in Experiment 2 rather speak against this interpretation.

5.4 Yoga's Effects on Shifting, Working Memory, and Executive Control

From the present study, we cannot confidently conclude that the intervention improved participants' shifting abilities. In Experiment 2 of Chapter 3, we expected that intervention-related improvements of the shifting function would result in changes of spectral power at the respective stimulation frequencies (with increased [decreased] spectral power for the tagging frequency – or its harmonic – of the modality of the stimulus concordant [incompatible] with the to-be-attended-to modality). This was, contrary to some of the previous studies (Gothe et al., 2014, 2016), not the case.

The lack of a switching cost for distinct attentional control or task sets in Experiment 1 (Chapter 3) also speaks against such an effect of our intervention on shifting. In our opinion, the behavioral effects obtained in this experiment (decreased mixing costs due to the intervention) cannot be traced back to a direct improvement of the shifting function. To note, switching, but not mixing costs can be attributed to the reconfiguration of task sets (Rogers & Monsell, 1995) and processes of interference control (Wylie & Allport, 2000). Decreased mixing costs in our study are therefore rather indicative of an increase in the efficiency of holding distinct feature representations in (but not of retrieving these task sets from) working memory (Kiesel et al., 2010; Los, 1996; Monsell, 2003; Rogers & Monsell, 1995). Movement during yoga engages the basal ganglia (a group of subcortical gray matter nuclei; Martin, 2003), which in turn supports various executive functions like shifting and working memory through loops with corticostriatal projections (Arsalidou et al., 2013; Schmalzl et al., 2015). The impact of yoga on working memory and executive control is also supported by our electrophysiological evidence in Experiment 2, namely an increase in frontocentral theta, due to the intervention, that we could observe not only in our spectral analyses, but also during the aforementioned 2 s cueing period, when switching to the attend-to-auditory condition. The latter finding makes perfect sense in light of the discrepancy in difficulty between conditions, showing that participants could devote their newly increased executive resources to a task precisely when demands increased, resulting in an increased need for proactive executive control (Cavanagh & Frank, 2014; Cohen, 2014; Nigbur et al., 2012). McKewen et al. (2020) could observe similar results, with phase-locked theta activity emerging 250-350 ms after cue onset at midfrontal and parietal sites, with higher amplitude in switch than in repeat trials. (In our case, we have observed the increase in frontocentral theta already 150 ms after cue onset.) In the same article, frontocentral theta was also negatively correlated with mixing costs, further corroborating our reasoning that decreased mixing costs reflected working-memory related changes due to the intervention. This finding was also replicated by McKewen et al. (2021), who also found that frontoparietal theta connectivity was mainly involved in goal setting (switch or repeat), indicative of mixing costs, while parietal-occipital connectivity was involved in task-set reconfiguration during switch preparation, indicative of switching costs. The neuronal changes reflected in decreased mixing costs may then affect the shifting function through mechanisms mentioned in Chapter 1.2.1., namely increased proactive executive control and better updating or reactivation of working memory and task set memory content (e.g., Cunillera et al., 2012; Gladwin & de Jong, 2005; Itthipuripat et al., 2013; van Noordt et al., 2017). Increased theta, however, is, in our opinion, not a direct indicator of increased shifting ability.

To note, greater executive control represented by midfrontal theta can also affect emotional processing, potentially contributing to the increased nonreactivity discussed above: when negative stimuli are present, activation of midfrontal brain structures is said to implement top-down modulation of negative affective responses (Schmalzl et al., 2015; Wager et al., 2008). In fact, the aforementioned study by Froeliger et al. (2012) reporting affective nonreactivity to emotional stimuli found greater midfrontal activation in case of high cognitive demand (cognitively demanding task plus viewing of negative emotional stimuli versus simple viewing of emotional stimuli), also reporting that experienced practitioners had higher volumes of gray matter in medial prefrontal cortex. Future research could therefore focus more on the implications of increased executive control on health and wellbeing, and provide practical, easy-to-implement and open-source tools to increase executive control, instead of having to rely on expensive training programs and software providers.

5.5 The Brain is Not a Model: Linking the Buckets of Executive Functioning and Stress

Regarding our question of which pillars have potentially contributed to increased executive functioning (potentially through increased self-regulation) and, thus, are responsible for the results we obtained, we can summarize that we do not have sufficient evidence to unequivocally support the notion that our cognitive effects were due to changes on participants' stress or anxiety levels.

Some evidence, indeed, can be reported for the effects of yoga on executive function through the pillars of stress and anxiety, but this is merely correlational in nature. In fact, as anxiety levels did not change due to the intervention, it is difficult to test the implications of the central hypothesis of Attentional Control Theory (Eysenck et al., 2007), namely that anxiety mainly impairs the functions of inhibition and shifting, while leaving out the updating function of working memory. We observed a significant negative correlation between the change in theta levels in Experiment 2 and state anxiety levels from pre- to posttest, (d =0.36, p = .017), and another significant negative correlation between the change in the magnitude of mixing costs (RTs) in Experiment 1 and perceived stress levels from pre- to posttest (d = 0.27, p = .023). Importantly, when looking into whether these effects were due to the intervention, by considering group membership using linear regression, effects involving group membership were not significant (although it can be argued that these analyses may have had insufficient power to detect such a complex interaction). Nevertheless, these results speak for a potential parasympathetic effect on executive functioning.

One aspect that should not be underestimated, when it comes to changes in cognitive performance, is the role of diaphragmatic breathing, which is, in turn, deeply linked to stress-reducing effects via parasympathetic activity (Vempati & Telles 2002; Zaccaro et al., 2018). Diaphragmatic breathing also promotes synchronization of cortical areas by stimulating the thalamic nuclei, positively impacting executive functioning (Calabrese et al., 2000; Tsigos & Chrousos, 2002). In a randomized controlled pilot study, Schmalzl et al. (2018) showed, in yoga-naïve university students (similar to our sample), that both breath-focused yoga practice and a movement-focused yoga practice (also including regulation of breath to some degree, albeit involving faster breathing cycles than in the breathing group) reduced perceived stress and salivary cortisol, but only the breath-focused practice led to improved response inhibition. Interestingly, in that study, increased response inhibition was correlated with perceived stress level reduction, but not with reduction of salivary cortisol. This is a relatively similar effect to what we have obtained, with some evidence for increased inhibition, decreased perceived stress levels, but no differences in salivary cortisol, although our intervention was somewhat similar to that employed in Schmalzl et al.'s movement-based group. They also deliver corroborating evidence for the aforementioned mechanism of increased psychological coping with stress. It could be the case that our intervention, as it was specifically designed for novices and included rather slow movements, led to similarly slow breathing patterns as in Schmalzl et al.'s breathing group, although this cannot be verified. The similarity of results on perceived stress levels in both groups of Schmalzl et al., however, raises the point (as stated by the authors) that the movement patterns were not necessary for subjective stress reduction (and, apparently, somewhat faster breathing and/or movement detrimental for physiologically mediated stress decrease as well as selective attentional processes). Careful manipulation of movement and breathing speed/patterns could provide further information on the role of these two elements of yoga, ultimately bringing us closer to the answer to the question of whether they work synergistically, and to which extent they are individually responsible for the observed effects.

The strongest case can be made for the rather immediate effect of yoga on executive functioning by improved selective attention (which is essentially the flipside of sensory inhibition), working memory performance in particular, and executive control in general.

Before we continue, it should be pointed out again that the brain does not work the same box-and-arrow way the models of some cognitive scientists may do. Thus, it is not surprising that various core executive functions rely on and interact with each other to varying degrees, depending on the task and an individual's capabilities. It could also be the case that the various pillars mentioned above (sustained attention, nonreactivity, effects of stress on cognition) are all affected by yoga, albeit to different degrees. It would also be a mistake to think about the brain as an I/O device, switching on and off its different modules in a relatively all-or-nothing fashion (Anderson, 2011; Newell, 1973). In contrast, we should think about the brain more as a net of distributed control devices, some grouping together by joint functionality, but each device being dynamically adjustable in a potentially unique way, depending on several variables, like its exact time scale of operation, its connectivity, or the availability of its key neurochemical agents.

In order to optimize mental performance, cognitive flexibility, inhibition, and working memory all jointly work together to maintain executive control that guides cognitive processes in line with internal goals (Miller, 2000; Miller & Cohen, 2001). Think about it for a second: How could you efficiently shift between task sets if there were no "task sets" for holding information in your working memory versus for shifting between information to begin with? This example alone shows that executive functions are intertwined rather than entirely independent. How could you even define switching between distinct objects or features if inhibition would not support to draw a rather arbitrary line to distinguish between different degrees of relevance (vs. irrelevance) of one and the same objects or one and the same features in different tasks?

One syndrome in which executive control works suboptimally is attention-deficit/hyperactivity disorder, or ADHD (American Psychiatric Association, 2013). Mazaheri et al. (2014a), using EEG, found cross-frequency coupling of frontocentral theta and occipital alpha for adolescents with ADHD, implying that the reduced top-down control could account for the inability to gate or filter out irrelevant external information, leading to symptoms of distractibility among these patients. This finding aligns well with our observation of concurrent increase in frontocentral theta both directly after switches and generally during the task, implying that higher executive control also covaries with increased suppressive ability.

As pointed out in the Introduction, focused attention on the asanas, while inhibiting everything else around oneself, can lead to changes in central executive and frontoparietal networks, fitting with our observations of increased frontocentral theta, decreased mixing costs, and increased inhibition. These changes may go hand in hand with increased working memory performance, as described in Chapter 5.4. The lack of effects on shifting also speaks for a relatively direct effect of yoga on executive performance. To note, Attentional Control Theory only explicitly notes a negative effect of anxiety on shifting (Eysenck et al., 2007), but there is in general a strong correlation between trait anxiety and perceived stress (in this study: $d = 0.50$, $p < .001$); as mentioned, state anxiety relies on the interaction between trait anxiety and situational stress (Eysenck, 1992; Gidron, 2013), pointing out a potential negative effect of stress on the shifting function as well. Thus, if stress impairs shifting and yoga practice decreases stress, based on the theory that yoga improves executive functioning through its effects on stress, shifting performance should benefit as well. This is not what we found. Computational modeling provides tools to investigate how separate mechanisms of executive control are adjusted to current task demands (Chatham et al., 2011; O'Reilly et al., 2010; Wiecki & Frank, 2013). Thus, in the future, computational modelling potentially plays a large role in understanding the interplay of these mechanisms, but also with stress-related mechanisms.

5.6 Conclusion

The present dissertation investigated the effects of an eight-week hatha yoga intervention on executive functioning and stress/anxiety-related parameters, also looking at the interplay of these mechanisms. We found some evidence for an intervention-related increase in inhibitory control, particularly under high cognitive load, while our data did not indicate changes in participants' shifting function. Both EEG and behavioral results from our two shifting paradigms can be explained by increased efficiency of working memory in holding multiple feature representations at the same time in mind. Decreases in self-reported measures of stress and stress reactivity, but not of physiological stress measures pointed towards improvements in psychological coping mechanisms when dealing with stressors, although the validity of these findings should be determined by future research additionally employing a stress-induction paradigm after a yoga intervention. Our work contributes to a growing body of evidence supporting the integration of traditional practices like yoga into modern health and wellness paradigms, offering a complementary approach to enhancing cognitive function and managing stress.

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Appendix A

Correlation and Regression Analyses

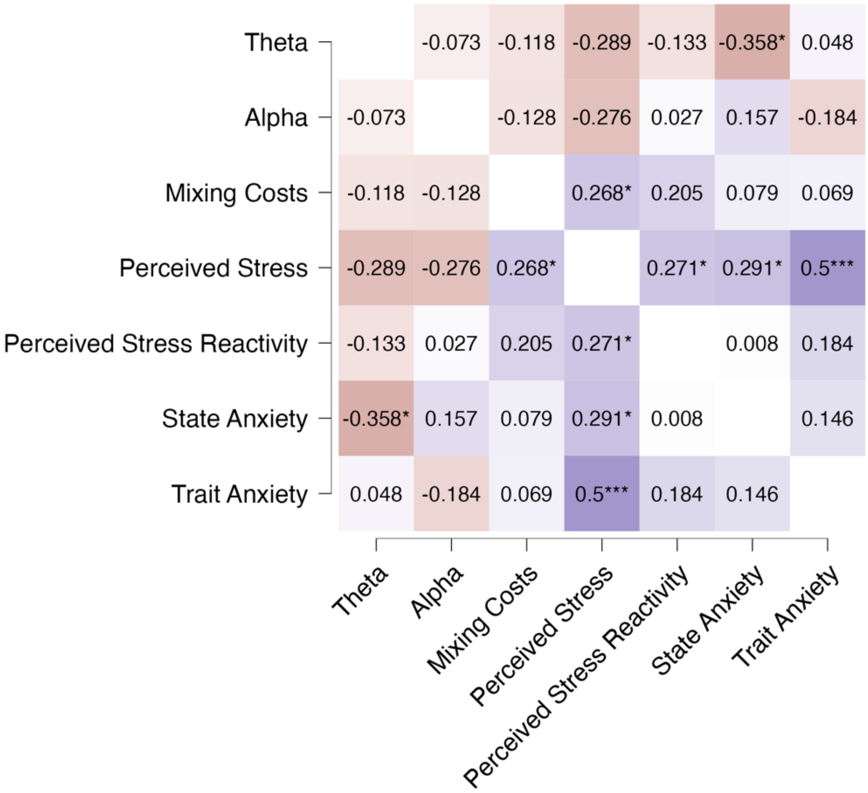
We were additonally interested in how our behavioral and electrophysiological data, as well as the results from stress- and anxiety-related questionnaires are interrelated. Therefore, we first obtained correlations between each of the following variables: our questionnaires (pre- to posttest difference values), the RT difference in mixing costs from the attentional switching experiment, and the change in theta and alpha SNR. The correlation matrix between all variables is depicted in Figure A1. Interestingly, there was a significant negative correlation between the change in state anxiety levels and the change in theta activity, p = .017; perceived stress levels and mixing costs, p = .023 were also significantly correlated, while this only marginally seemed to reflect relations between perceived stress and alpha, p = .074, as well as theta activity, p = .060.

We then conducted multiple regression analyses on whether stress and anxiety could have mediated the change in behavioral and electrophysiological outcomes (here, changes in theta and alpha activity, as well as a change in mixing costs). In our self-reported measures (presented in Szaszkó et al., 2023), we found significant decreases in perceived stress, as well as perceived stress reactivity, but no changes in state or trait anxiety. Here, first, we were interested in whether the change in state anxiety levels modulated theta change. We entered predictors (change in state anxiety levels, group membership, as well as their interaction) stepwise into a regression, with the model containing the change in state anxiety levels as well as group membership, but not the interaction emerging at best, adjusted R^2 = 0.221, p = .006, with both state anxiety change, standardized β = −.38, SD = 0.16, p = .024, and group, standardized β = .62, SD = 0.28, p = .032, being significant, suggesting that both group membership and the change in state anxiety (but not through the intervention only) significantly influence the change in theta activity.

The stepwise multiple regression with perceived stress level change as well as group membership (and their interactions) as predictors on participants' mixing costs resulted in the model including only perceived stress level change as predictor, β = .27, SD = 0.12, p = .023, emerging as the best model, adjusted R^2 = 0.058, p = .023. Decreases in perceived stress level, therefore, seemed to diminish mixing costs in the attentional switching experiment.

Figure A1

Correlational Matrix of Selected Self-Reported, Behavioral, and Electrophysiological Variables



Note. Correlations between pre- to posttest differences of 1) stress- and anxiety-related self-reported variables (Perceived Stress = PSS score difference; Perceived Stress Reactivity = PSRS score difference; State Anxiety = STAI-ST score difference; Trait Anxiety = STAI-TR score difference), 2) behavioral variables (Mixing Costs = dual- vs. single-color RT differences in Experiment 1), and 3) electrophysiological variables (Theta: Change in mean 4-7 Hz signal-to-noise ratio; Alpha: Change in mean 8-12 Hz signal-to-noise ratio). $p < .05$ are marked with *, $p < .01$ with **, and $p < .001$ with ***.

Zusammenfassung

Yoga wird häufig wegen seiner angeblichen Vorteile für Gesundheit, Wohlbefinden und Kognition praktiziert. Trotz zahlreicher Studien, die diese Wirkungen erforschen, haben nur wenige den Zusammenhang zwischen Kognition und Gesundheit untersucht, und noch weniger haben eine Randomisierung und/oder eine Kontrollgruppe verwendet. Daher haben wir eine randomisierte kontrollierte Studie mit 98 Proband*innen durchgeführt, die das Rückgrat dieser Dissertation bildet, um die Frage zu beantworten, ob das Üben von Hatha-Yoga dreimal oder öfter pro jeder von acht Wochen die exekutiven Funktionen verbessert und ob dieser Effekt auf eine mögliche Verringerung von Stress- und/oder Angstzuständen, eine verbesserte exekutive Kontrolle oder beides zurückzuführen ist. Wir verwendeten drei Experimente (von denen zwei elektrophysiologische Messungen verwendeten), um die exekutive Funktion zu operationalisieren; physiologische Messungen und Selbstauskünfte zu stress- und angstbezogenen Variablen wurden mit einem innovativen „Ecological Momentary Assessment“-Ansatz erhoben.

Wir fanden weder verhaltensbiologische noch elektrophysiologische Hinweise auf Veränderungen in der Aufgabenwechselfunktion der Teilnehmer*innen; stattdessen deuteten eine erhöhte frontozentrale Theta-Aktivität und verringerte Mischkosten darauf hin, dass sich die Fähigkeit der Teilnehmer*innen, mehrere Aufgabenkontrollrepräsentationen gleichzeitig im Kopf zu behalten, verbesserte, was auf Veränderungen im Zusammenhang mit der Funktion des Arbeitsgedächtnisses hindeutet. Unser Experiment zur Untersuchung der inhibitorischen Kontrolle zeigte keine Auswirkungen der Intervention; erhöhte modalitätsspezifische Alpha-Power beim Beachten visueller und dem Ignorieren auditiver Reize (die wahrscheinlich die Inhibition ablenkender visueller Reize darstellt), spricht jedoch für eine erhöhte inhibitorische Fähigkeit in Folge der Intervention unter Bedingungen hoher kognitiver Belastung. Die Intervention senkte das Niveau des selbstberichteten, wahrgenommenen Stresses und der Stressreaktivität und steigerte die Achtsamkeit, wobei Personen, die bereits eine hohe Achtsamkeitsdisposition aufwiesen, am meisten von den stressreduzierenden Effekten der Intervention profitierten. Hatha-Yoga zeigte jedoch keine Auswirkungen auf die Stress-Biomarker im Speichel und auf die selbstberichteten Werte von Eigenschafts- oder Zustandsangst. In Übereinstimmung mit aktuellen Forschungsergebnissen deuten diese Ergebnisse darauf hin, dass die Intervention zu einer verbesserten psychologischen

Stressbewältigung und zu einer erhöhten Nichtreaktivität geführt hat. Obwohl nur korrelative Belege für eine stressvermittelte Wirkung auf die exekutiven Funktionen in der vorliegenden Dissertation gefunden wurden, in der eine Rolle der eher direkten Auswirkungen von Yoga über eine verbesserte exekutive Kontrolle offensichtlicher erschient, kann eine Interaktion zwischen diesen beiden Mechanismen oder Prinzipien nicht sicher ausgeschlossen werden. Wie die Philosophie des Yoga uns immer wieder sagt: Alles ist miteinander verbunden.