EXAMINING THE IMPACTS OF MINDFULNESS MARTIAL ARTS INTERVENTION ON NEURAL INDICES OF AUDITORY SELECTIVE ATTENTION IN YOUTH WITH ADHD

by

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LIST OF ABBREVIATIONS

Abbreviation	Definition
ADHD	Attention-Deficit/Hyperactivity Disorder
ANOVA	Analysis of Variance
ANT	Attended Non-Target
ASD	Autism Spectrum Disorder
AT	Attended Target
BPT	Behavioural Parent Training
CAPD	Central Auditory Processing Disorder
CBT	Cognitive Behavioural Therapy
DSM	Diagnostic and Statistical Manual of Mental Disorders
EEG	Electroencephalography
EEG-IP-L	EEG Integrated Platform-Loss
EFP	Early Frontal Positivity
ERP	Event Related Potential
ICA	Independent Component Analysis
ITC	Inter-Trial Coherence
LD	Learning Disorder
M.I.N.I. KID-P	Mini International Neuropsychiatric Interview for Children and Adolescents, Parent Version
MATLAB	Matrix Laboratory
MBCT	Mindfulness-Based Cognitive Therapy
MBT	Mindfulness-Based Therapies
MMA	Mindfulness Martial Arts
N1	N100

Abbreviation	Definition
P2	P200
P3	P300
ROI	Regions of Interest
RT	Reaction time
SLD	Specific Learning Disorder
SLI	Specific Language Impairment
SPSS	Statistical Package for Social Sciences
UNT	Unattended non-Target
UT	Unattended Target

Abstract

Attention-deficit/hyperactivity disorder (ADHD) is a common neurodevelopmental disorder. Although mindfulness interventions may minimize attention difficulties in some individuals with ADHD, few studies have examined whether mindfulness impacts neurophysiological indices of attention. The present study examined whether mindfulness impacts neural indices, parent reports of symptom severity, and task performance markers of auditory selective attention in youth with ADHD. A sample of 39 youth receiving treatment and 27 waitlisted controls completed an auditory selective attention task while EEG was recorded. Evoked activity, task performance, and symptom severity data were collected and analysed. Significant changes in early attentional neurophysiological responses were found for the intervention group. There were no significant findings in relation to symptom severity or task performance. Results suggest that treatment impacts neural responses of early sensory processing. Findings offer methodological support for using neurophysiological measures when examining gains of mindfulness intervention.

CHAPTER ONE

LITERATURE REVIEW

This literature review will explore the current research on mindfulness interventions for youth with attention-deficit/hyperactivity disorder (ADHD), focusing on the role of neurophysiological measures in evaluating treatment outcomes. It will highlight critical studies that demonstrate the effectiveness of mindfulness practices in enhancing selective auditory attention and discuss the implications of these findings for clinical practice. Ultimately, this review aims to provide a comprehensive overview of how neurophysiological markers can be used to better understand the impacts of mindfulness interventions on selective attention allocation in youth with ADHD.

Attention

Attention is a cognitive process that involves selecting and focusing on specific sources of information (Broadbent, 1958; Hahn et al., 2008), typically for prioritising certain sensory features and/or inputs over others. Conceptually, attention is often divided into three subtypes: sustained, divided, and selective. Sustained attention is the ability to focus on a stimulus for a period of time (Sarter et al., 2001). Divided attention is the ability to rapidly shift between different stimuli or split focus between two or more stimuli (Parasuraman, 1985). Selective attention involves allocating resources to a specific sensory input, while ignoring irrelevant information sources and is critical for improving the accuracy and efficiency of information processing. Fundamentally, attention serves as an important data reduction mechanism to prioritise processing important information (Noyce et al., 2023).

Selective Attention

The ability to selectively attend to and prioritise task-relevant information (Astle & Scerif, 2009) plays a crucial role in academic achievement, mental health, and social competence and is imperative for learning new information and skills (Pagani et al., 2012). The process of selective attention involves initial stimulus detection and differentiation to prioritise specific features of simultaneous sensory inputs (Määttä et al., 2005). In the auditory domain, selective attention is essential for navigating complex auditory environments. The "cocktail party" phenomenon is often used to describe this process, where individuals can selectively attend to one speaker within a noisy environment (Cherry, 1953). In this example, the deployment of selective attention requires intentional prioritisation and facilitation of relevant stimuli, while simultaneously suppressing irrelevant stimuli (Fu et al., 2022).

Individual differences in selective attention capacity are most pronounced when cognitive demands are greatest, such as when it is difficult to segregate a target sound stream from competing streams (Choi et al., 2014). Behavioural research shows that individuals with clinically normal hearing vary widely in how well they can deploy selective attention (Anderson et al., 2013; Choi et al., 2014; Ruggles & Shinn-Cunningham, 2011). Many listeners with no apparent hearing deficits seek treatment from audiologists because of difficulties in settings where auditory selective attention is critical (Moore et al., 2013). Difficulty selectively attending to competing auditory streams has been observed in individuals with ADHD (Mayes & Calhoun, 2007; Qian et al., 2010; Varlamov et al., 2021; Wåhlstedt et al., 2009), autism spectrum disorder (ASD; Dunlop et al., 2016), specific learning disorders (SLD; Stevens et al., 2006), central auditory processing disorder (CAPD; Jerger & Musiek, 2022), and specific language impairment (SLI; Bishop et al., 2000; Neville et al., 1993; Rosen, 2003; Uwer et al., 2002). Understanding

the neural mechanisms in populations with selective attention difficulties is therefore important for early detection and tracking treatment outcomes, particularly in cases where behavioural measures may be less sensitive.

Attention-Deficit/Hyperactivity Disorder

ADHD is a neurodevelopmental disorder that includes both neurocognitive and behavioural difficulties that negatively affect educational achievement, social relations, and occupational functioning (Barkley, 2015; DuPaul & Jimerson, 2014). Canadian national prevalence rates for children and adolescents are estimated at 8.6% (Espinet et al., 2022). ADHD is characterized by developmentally inappropriate symptoms of inattention, hyperactivity, and impulsivity (DuPaul & Jimerson, 2014), which can manifest as challenges in planning, organization, self-evaluation, and mood stability (DuPaul & Jimerson, 2014; Wolraich et al., 2019). ADHD is diagnosed using the Diagnostic and Statistical Manual of Mental Disorders (DSM-5-TR; American Psychiatric Association, 2022) and generally involves a combination of screening questionnaires and interviews to determine whether symptoms meet diagnostic criteria.

ADHD Impairments in Selective Attention

Individuals with ADHD typically show executive dysfunction in several cognitive domains, such as visuospatial and verbal working memory, inhibitory control, vigilance, planning and reward regulation (Sergeant, 2005). Various neurophysiological studies comparing typically developing (TD) children to children with ADHD have reported atypicalities in auditory processing (Berry et al., 2014; Tsai et al., 2012), including stimulus differentiation and categorization (Bentin et al., 1995; Satterfield et al., 1990). Children with ADHD also perform poorly on auditory selective attention tasks when attending to target sounds in the presence of distractor sounds (Blomberg et al., 2019; Cook et al., 1993; Davidson & Prior, 1978; Gascon et

al., 1986; Geffner et al., 1996; Gomez & Condon, 1999; Keith et al., 1989; Lanzetta-Valdo et al., 2016; Michalek et al., 2014; Schäfer et al., 2013). These findings suggest that children with ADHD exhibit atypical auditory processing patterns and specific difficulties with selective auditory attention, impairing their ability to differentiate and categorize auditory stimuli accurately. Understanding these cognitive challenges may help inform treatment approaches for ADHD to support overall cognitive and behavioural outcomes.

Existing Evidence-Based Treatments for ADHD

Empirically supported treatments for ADHD include central nervous system stimulants, non-stimulant medication, behaviour modification, and combined medication with behavioural modification. Age and symptom severity are the main factors considered for deciding whether pharmacological treatment should be initiated, particularly in school-aged children (Mechler et al., 2022). General clinical guidelines recommend that those with low and moderate symptom severity *may* be offered pharmacological treatment, whereas those with severe symptoms *should* be offered pharmacological treatment (Mechler et al., 2022; Wolraich et al., 2019). Approved medications are stimulants such as amphetamines and methylphenidate and non-stimulants such as atomoxetine and extended-release clonidine and guanfacine (Mechler et al., 2022).

There is evidence that psychostimulants can significantly reduce the symptoms of inattention and hyperactivity in children with ADHD (Paton et al., 2014; Wigal et al., 2018). In addition, studies have found improvements when using stimulant medication in tasks that measure selective attention (Brodeur & Pond, 2001; Lubow et al., 2005; Pearson et al., 2020), sustained attention (Moreno-García et al., 2019; Mühlberger et al., 2020), working memory (Bedard & Tannock, 2008; Kobel et al., 2009), behavioural inhibition (Ghanizadeh, 2009; Kenemans et al., 2005) and executive control (Çetin et al., 2019; Hadar et al., 2021) in children

with ADHD. Non-stimulant medications have also become important therapeutic options and are often associated with fewer side effects, such as insomnia and appetite suppression, making it a promising option for children and youth with ADHD (Findling et al., 2022; Joseph et al., 2017). Non-stimulant medications are particularly useful for children who may not respond well to stimulants, experience side effects, or have coexisting conditions that make stimulants less suitable. Non-stimulants offer a variety of mechanisms for managing ADHD symptoms and can be effective as either standalone treatments or in combination with stimulants (Findling et al., 2022; Sallee et al., 2009; Storebø et al., 2018).

Although pharmacological treatment can be effective for some individuals, non-adherence to ADHD medication is common, especially in adolescents. Individuals who start pharmacological treatment often stop and resume medication again over several years or discontinue use altogether (Charach & Fernandez, 2013). Poor medication adherence may be in part due to experiencing adverse side effects from the medication (Brinkman et al., 2018; Charach & Fernandez, 2013), which include a loss of appetite, trouble sleeping, headaches, stomach aches, and nausea (Cortese, 2020; Toomey et al., 2012). The issues of stable compliance and undesirable side effects emphasise the importance of investigating additional non-pharmacological evidence-based treatments and interventions for ADHD.

Research on evidence-based psychosocial treatments for children and adolescents with ADHD show that behavioural parent training and behavioural interventions in schools can lead to better outcomes (Chronis et al., 2006; van der Oord et al., 2012). Behavioural parent and school-based training involves teaching parents and teachers how to apply behavioural modification techniques based on social learning theories, such as focusing on specific behaviours, using rewards and positive reinforcement to encourage good behaviour, and

employing strategies like ignoring, timeout, and non-physical discipline. Interventions like behavioural parent training (BPT) and school-based programs improve both behaviour and functioning. The evidence supporting the efficacy of BPT is strong, with numerous studies demonstrating positive outcomes for children with ADHD. For instance, a meta-analysis found that BPT significantly improved child behaviour and parent-child interactions (Weber et al., 2019). These interventions work by addressing the environmental factors that exacerbate ADHD symptoms, such as inconsistent discipline or lack of structure, and teaching parents how to implement more structured and supportive approaches. However, several factors can influence the outcome of this treatment. One key factor is that outcomes depend heavily on external factors such as parental engagement and the therapist's expertise (Fabiano, 2007; Sibley et al., 2023; Waschbusch & Hill, 2003). Parental engagement is critical, but factors like stress, time constraints, and prior mental health issues can hinder consistent implementation of strategies (Groenman et al., 2022). Additionally, children with more severe ADHD or co-occurring conditions may not respond as well, and the skill level of the therapist plays a key role in tailoring the intervention effectively (Dekkers et al., 2022). Research also shows that external factors such as socioeconomic status and family dynamics, including single-parent households, can affect treatment outcomes (Evans et al., 2018). These factors emphasise that while BPT can be highly effective for many families, the approach needs to be adaptable and sensitive to the individual challenges faced by parents and children.

Both medication and behavioural treatments have been shown to be effective, but these findings highlight the need to explore additional strategies and approaches to addressing these limitations. It is essential to consider other behavioural treatment options that may enhance selective attention while looking at the possible fundamental mechanisms that may result in overt

behaviours (e.g., poor attention skills) to allow for more effective training and support for these specific attention skills.

Mindfulness Treatments for ADHD

Mindfulness training has been identified as a promising treatment option for ADHD (Cairncross & Miller, 2020). Mindfulness is a practice derived from Buddhist meditation and teaches users to cultivate focus and awareness of the mind and body through meditation (Kabat-Zinn, 2003). It involves actively attending to the present moment with a mindset of acceptance (Kabat-Zinn, 2003). The core skills that mindfulness training targets include selective attention, sustained attention, non-reactivity, and calmness (Kabat-Zinn, 2003), all of which are common deficits experienced in ADHD (American Psychiatric Association, 2022). Thus, mindfulness may be uniquely suited to address ADHD symptomatology.

Over the last several decades, clinical practice has begun to include mindfulness-based therapies (MBTs) that focus on attitude, behaviour, and cognitive-affective processing and how these can affect functional health outcomes (Cairncross & Miller, 2020). When used as an intervention, mindfulness is described as self-regulating attention non-judgmentally to the present moment (Zylowska et al., 2008). Mindfulness interventions are intended to increase an individual's awareness and acceptance of experiences, including thoughts, emotions, and physiological sensations (Baer, 2003; Cash & Whittingham, 2010), most often involved in maladaptive behaviours and emotions (Bishop et al., 2004). Although research has demonstrated MBTs to be an effective treatment for internally focused disorders, such as depression (Khoury et al., 2013), it is still unclear whether MBTs can provide symptom relief and improved functioning for individuals with externalizing disorders such as ADHD (Cairncross & Miller, 2020).

One study of mindfulness training programs found that youth aged 11-15 benefitted from an eight-week mindfulness training program (van de Weijer-Bergsma et al., 2012). The training program teaches adolescents to focus and enhance their attention, awareness, and self-control through mindfulness exercises. These include sitting meditation, body scans (e.g., awareness of the body), and breathing space. The exercises are alternated with exercises addressing the specific issues of adolescents with ADHD, such as awareness of distractibility, impulsivity, and hyperactivity, and breathing is practised on such occasions (van de Weijer-Bergsma et al., 2012). Post-training, participants' self- and parent-rated inattention and behavioural problems decreased, and attentional control improved as evidenced by a decrease in reaction time on a visual sustained attention task and fewer false alarms and misses on an auditory sustained attention task (van de Weijer-Bergsma et al., 2012). Similarly, adolescents and adults self-reported decreased inattention and hyperactivity symptoms and improved performance on tasks measuring attention and cognitive inhibition following an 8-week mindfulness training program called MYmind, whereby parents and adolescents were trained separately (Bögels & Restifo, 2014; Schoenberg et al., 2014). In a recent meta-analysis examining the behavioural impact of MBTs for both adults and children with ADHD, medium-to-large effect sizes were found for decreases in both inattentive and hyperactivity/impulsivity symptoms (Cairncross & Miller, 2020). Results demonstrated that MBT significantly reduced inattention in individuals diagnosed with ADHD using self-reports and observer reports. A subgroup analysis was also performed to investigate the differences between self- and observer ratings, demonstrating that MBTs reduced inattention irrespective of the informant (Cairncross & Miller, 2020). Thus, recent research suggests that mindfulness may improve core symptoms of ADHD, including

attention and may be effective in improving functioning and reducing symptomology in individuals with ADHD.

Measuring Mindfulness Treatment Effects Using Neurophysiological Measures

From a methodological perspective, several meta-analyses show that the majority of studies examining the effects of meditation on ADHD symptoms rely on self-, parent-, and teacher-reported measures, often supplemented by performance on behavioural tasks that assess attention and impulse control (Lee et al., 2022; Oliva et al., 2021; van der Oord et al., 2012; Vekety et al., 2021). Only a few studies have examined the neurophysiological correlates of selective attention in individuals with ADHD (Milligan et al., 2019; Schoenberg et al., 2014). These studies use electroencephalography (EEG) to examine neural differences in individuals with ADHD following mindfulness-based cognitive therapy (MBCT). EEGs measured before and after mindfulness treatment suggest improved attention allocation, including when tasks demanded inhibitory control in participants, along with improvements in parent-reported behavioural symptoms (Milligan et al., 2019; Schoenberg et al., 2014; Seward et al., under review; Sibalis et al., 2019).

Given that selective attention is highly malleable and can be enhanced under certain conditions (Diamond et al., 2007), there may be benefits to incorporating selective attention training activities into treatment options. A growing body of research suggests that mindfulness practices in non-clinical settings may enhance cognitive and emotional functioning (Brown et al., 2007; Brown & Ryan, 2003; Chiesa et al., 2013; Eberth & Sedlmeier, 2012; Guendelman et al., 2017; Lodha & Gupta, 2022; Tang et al., 2015). Several reviews and meta-analyses have investigated the effects of mindfulness on attention and executive functions (Chiesa et al., 2011; Eberth & Sedlmeier, 2012; Gallant, 2016; Prakash et al., 2020; Sumantry & Stewart, 2021).

Yakobi et al., 2021). For example, Chiesa et al. (2011) systematically reviewed 15 controlled or randomised controlled studies and eight case-control studies on the neuropsychological consequences of mindfulness meditation practices on attention and executive functions. The authors concluded that early stages of focused attention or a concentrative style of meditation are associated with significant improvement in reaction time (RT) during selective attention tasks. An additional meta-analysis examined the effects of mindfulness meditation on executive functioning in a comprehensive systematic review of 12 experimental or quasi-experimental studies. Findings showed that mindfulness meditators performed better on inhibition tasks than controls (Gallant, 2016). All studies involving inhibitory tasks, with the exception of one study using a modified Stroop task showed enhanced performance using behavioural (Allen et al., 2012; Heeren et al., 2009; Moore et al., 2013; Teper & Inzlicht, 2013) and neural measures (Allen et al., 2012; Teper & Inzlicht, 2013). These studies also showed that the gains remained at five months post-training (Gallant, 2016). In addition, the studies found positive associations between practice and inhibitory effects (Moore & Malinowski, 2009; Teper & Inzlicht, 2013), suggesting the effects may be mediated by the amount of practice the child does. Finally, studies examining a mindfulness martial arts program (MMA) indicated neurophysiological stability in selective attention measures in youth with ADHD (Milligan et al., 2019; Sibalis et al., 2019). The studies found that youth who underwent treatment showed stabilised neurophysiological responses six weeks post-treatment compared to waitlist controls, who showed increased neurophysiological atypicalities Seward et al., under review; Sibalis et al., 2019).

Neurophysiological Measures of Selective Auditory Attention

There are many tasks that measure the various facets of attention. Theoretical frameworks in cognitive psychology generally agree that attention is not a unitary construct, and

unique features can be measured independently. It is generally agreed that there is a distinction between obtaining and maintaining the alert state, orienting to sensory events, and regulating thoughts and behaviours. Neuroimaging has confirmed that these functions involve separate but overlapping areas and similar patterns of brain activity (Posner, 2008). One promising avenue for exploring the effects of mindfulness on ADHD is through the use of neurophysiological measures such as EEG.

Electroencephalography and Event-Related Potentials

EEG is a cost-effective and non-invasive tool for examining the rapid neural dynamics of information processing (Biasiucci et al., 2019). EEG is largely generated by postsynaptic field projections arising from synchronous activity in cortical pyramidal neurons (Henry, 2006). EEG signals are a complex mixture of oscillatory dynamics across a broad range of frequencies, which have been linked to various cognitive functions and stages of information processing (Lopes da Silva, 2013). Event-related potentials (ERPs) capture electrocortical activity that is time-locked to a behavioural response or stimulus (Blackwood & Muir, 1990) and provide psychophysiological correlates of mental processes. ERPs are often divided into two categories that reflect different stages of information processing; earlier components peak roughly within a few hundred milliseconds and are sensitive to stimulus characteristics (e.g., luminance, contrast, intensity) and reflect initial stages of sensory processing. In contrast, later ERP components typically reflect more elaborative processing linked to discrimination, evaluation, and categorization (Sur & Sinha, 2009). ERPs are denoted by polarity and time whereby P and N represent a positive or negative waveform, and the time point is represented in milliseconds post-stimulus (e.g., P100, or P1, is a positive waveform at the 100ms time point post-stimulus and N200, or N2, is a negative waveform at 200ms post-stimulus).

The source generation and topographical distribution of ERP components depends on the task and the stimuli used to elicit activity. In attention studies, the dichotic listening task is a commonly used experimental approach, which can involve an active paradigm whereby participants are asked to press a button to a target stimulus while passively ignoring other stimuli. In this paradigm, two classes of stimuli are presented, one occurring frequently (standard) and the other occurring infrequently (target). In the auditory domain, the rapid dynamics of information processing can be characterized using dichotic listening tasks and examining neural responses to target stimuli in the attended and unattended ears. The participant is required to distinguish between the two stimuli and to respond to the stimuli that are pre-designated as targets. Dual-task paradigms, which involve performing two tasks concurrently, may provide neural markers of selective attention and their potential links to the prioritization of target stimuli. The dual-task or dichotic listening task allows for examining psychophysiological expressions of selective attention in response to a deviant stimulus by comparing responses to target stimuli in the attended (AT) and unattended (UT) channels. The task allows for the comparison of accurate detection of target stimuli in the attended ear and the suppression of target stimuli in the unattended ear. A dichotic auditory task is commonly used for measuring auditory selective attention as it allows for discernment of both the target tone and the target ear (Sibalis et al., 2019).

Auditory stimuli commonly elicit the later P300 (P3) wave. The peak latency range is 250-400 msec for most adult participants and is usually interpreted as reflecting the speed of stimuli classification resulting from discrimination between auditory stimuli (Bachiller et al., 2015). The P3 amplitude is also associated with attention engagement, specifically with the orientation to environmental changes and the processing of novel information (Polich, 2007). P3

amplitudes are believed to be linked to the level of attention devoted to a task (Donchin et al., 1986; Kok, 2001). This theory is derived from research using dual-task paradigms, which consistently show a relationship between P3 amplitude and task demands (Kok, 2001; Polich, 2007). Additional studies have demonstrated that P3 amplitudes significantly decrease when participants are directed away from the task (Johnson, 1988; Mangun & Hillyard, 1990) and that P3 amplitudes are larger for attended target stimuli than unattended ones (Kok, 2001). Research has also identified a posterior P3 component that reflects neural decision-making processes tied to response execution (Kelly & O'Connell, 2013; Twomey et al., 2015).

Neurophysiological Markers of Selective Attention in ADHD

ERPs have been used to examine atypicality in neurophysiological markers of attention in ADHD, with studies showing reduced P200 (P2) and N200 (N2) amplitudes compared to healthy controls (Barry et al., 2003; Bocharov et al., 2019; Chen et al., 2021; Einziger et al., 2021; Suwazono et al., 2000). ERPs have been extensively studied in investigations on attention and cognition, with P3 responses being the most widely researched waveform in populations with ADHD (Tsai et al., 2012). In populations with ADHD, the most commonly observed ERP-related finding is a reduction in the amplitude of P3 during oddball tasks compared to healthy controls (Barry et al., 2003; Fu et al., 2022; Gomes et al., 2012; Johnstone et al., 2013; Määttä et al., 2005; Moavero et al., 2020; Tsai et al., 2012). However, few studies have investigated the underlying mechanisms of attenuated P3 ERPs in ADHD populations (Arnett et al., 2023). Understanding the physiological origins of this finding could significantly enhance etiological models for ADHD and guide treatment approaches. Atypical or highly variable timing (latency) of the P3 onset or peak potentially contributes to reduced amplitude (Arnett et al., 2023). Specifically, ERPs are generated by averaging signals across individual trials to isolate temporal

dynamics that are systematically evoked by the event of interest and activity that is not systematic is effectively "averaged out." However, this approach may not capture the morphology of the P3 component if an individual's peak latency is atypically fast or slow across all trials (inter-individual differences) or on a subset of trials (single trial variability; Arnett et al., 2023). This could result in a decreased ERP amplitude for that individual (Shucard et al., 2016). In addition to averaging out potentially meaningful activity at the single trial level, this technique also discards potentially important information about the spectral features of brain activity (Lakatos et al., 2008).

Time-Frequency Analysis

Time-frequency analyses supplement the ERP approach and reveal information about spectral dynamics. Examining perturbations across single trials provides a richer context for understanding the individual electrophysiological profile of attention in youth with behavioural symptoms of attention deficits. Neural oscillations are generally grouped into canonical frequency bands: delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–100 Hz).

The Role of Alpha Oscillations in Attention. Alpha oscillations (8-13 Hz) are the dominant rhythm in human EEG and are observed during a relaxed but awake state, especially with closed eyes, and are inversely related to attention. At rest, alpha is typically largest above posterior (occipital, temporal, and parietal) brain regions. Desynchronization, or a reduction in amplitude of alpha oscillations, is particularly noticeable when subjects are suddenly alerted or otherwise caused to increase their mental activity. Conversely, increased alpha synchrony has been observed over cortical regions associated with task-irrelevant stimuli (Haegens et al., 2012). Thus, alpha desynchronization (decreased alpha power) is thought to be a marker of cognitive or

neural engagement, while alpha synchronization (increased alpha power) may be associated with inhibition of distracting information (Weisz et al., 2011). Recent research has identified cortical oscillations in the alpha band as markers of intentional ignoring (Keller et al., 2017; Payne & Sekuler, 2014). Specifically, increased power in the alpha band has been associated with the suppression of distracting signals within sensory streams, such as vision or audition (Dubé et al., 2013; Kelly et al., 2006; Mazaheri et al., 2014; Payne et al., 2013). Inhibitory mechanisms are thought to be executed by reducing cortical excitability, which reduces the processing capacity of a specific area irrelevant to the ongoing processing (Klimesch, 2012; Sigala et al., 2014). A possible interpretation of this finding is that desynchronization corresponds to increased attention directed toward processing the target signal, while synchronization reflects the engagement of inhibitory mechanisms. In addition, alpha amplitude is thought to play a role in predictive processes which prepare the brain for incoming stimuli. Research suggests that alpha power may be modulated by the ability to predict the probability of occurrence of the incoming stimulus (Mayer et al., 2016; Romei et al., 2010; Samaha et al., 2017) Terasi et al., 2022) to suppress the processing of the noise signal (Dimitrijevic et al., 2017; Strauß et al., 2014).

The Role of Theta Oscillations in Attention. A growing body of research indicates that modulation of theta-band activity (4-8 Hz) is important for cognitive control (Cavanagh et al., 2012; Cavanagh & Shackman, 2015; Nigbur et al., 2011). Specifically, frontal midline theta (FMθ) is associated with attention and mental effort (Cacioppo et al., 2007), primarily cognitive control (Cavanagh & Shackman, 2015; Sauseng et al., 2010) and sustained attention (Clayton et al., 2015). Several studies have found an increase in theta activity in response to active tasks that require attention (Leroy et al., 2018; Missonnier et al., 2006), particularly studies finding increased frontal theta activity during active auditory oddball tasks (Leroy et al., 2018).

Concerning auditory attention more specifically, studies have shown an increase in theta oscillation power localized to frontal regions along with a simultaneous decrease in posterior alpha power when listening becomes more effortful (Wisniewski et al., 2017, 2018).

Alpha and Theta Oscillatory Patterns in Youth with ADHD. The study of oscillatory patterns of EEGs under resting conditions in children with ADHD has also provided valuable insights into the neurophysiology of ADHD. Earlier studies have consistently shown that, compared to control groups, ADHD children exhibit increased theta oscillations in the frontal and central regions and decreased alpha and beta oscillations in the posterior and temporal regions of the brain (Barry et al., 2003; Clarke et al., 2001). Some studies have examined the role of the alpha band in clinical populations who present with deficits in attention. A reduction in the alpha power over the occipital regions is also reported in children with ADHD (Bozhilova et al., 2022; Lenartowicz et al., 2019). A recent study with adult ADHD patients found a decrease in resting state alpha power, which the authors suggested as cortical hyperactivation (Deiber et al., 2020). The most robust EEG feature associated with ADHD is elevated power of theta oscillations (4-7 Hz) typically recorded over frontal-central electrodes (Barry et al., 2003; Lubar, 1991). Children with ADHD showed a greater elevated theta power difference between the task state and the resting state than TD children (Mann et al., 1992). In addition, the theta event-related synchronization in children with ADHD increased more than in TD children during visual working memory tasks (Lenartowicz & Loo, 2014). These patterns of neural variability are linked to greater behavioural variability in ADHD, such as inconsistent task performance and impulsivity (Aydin et al., 2023; Kember et al., 2023).

Inter-Trial Coherence

One measure of interest is Inter-trial Coherence (ITC), which captures the consistency in the phase of neuronal activity produced by task events. Spatial and temporal synchronization of neural oscillations is a fundamental mechanism for integrating information processing (Palva et al., 2005). ITC is a measure of cortical synchronization from trial to trial that is unavailable in ERPs (Delorme & Makeig, 2004). It can provide information on brain activity alignment in response to feedback and is sensitive to rapid electrophysiological changes in response to a stimulus.

Intra-individual variability in reaction times (RT) is commonly considered a measure of central nervous system functioning (Dykiert et al., 2012). Previous studies have indicated that increased variability in RT reflects the effectiveness of higher-level cognitive processes beyond motor functions (Papenberg et al., 2013). For example, reaction time variability in adults has been attributed to the decision-making aspect rather than the motor component of a task (Bunce et al., 2004). Higher RT variability from trial to trial is associated with poorer performance in various complex cognitive tasks (Hultsch et al., 2002) and has been found to predict cognitive decline in executive functioning during late adulthood (Lövdén et al., 2013). It is speculated that trial-to-trial behavioural variability may result from underlying neural variability (Papenberg et al., 2013). Neural variability was found to be greater at both ends of the lifespan (Papenberg et al., 2013), mimicking the pattern of behavioural variability in the lifespan (Dykiert et al., 2012; Li et al., 2017; Li et al., 2003, 2009; Tamnes et al., 2012, 2013; Williams et al., 2005). However, the extent to which neural and behavioural variability are related has not been extensively studied (Waschke et al., 2021).

Increased variability has been linked to several disorders (Dinstein et al., 2015). Behavioural research shows larger response time variability in individuals with cognitive impairments, including schizophrenia (Schwartz, 1998), autism (Adamo et al., 2014; Karalunas et al., 2014), and ADHD (Hervey et al., 2006; Kofler et al., 2013; Tamm et al., 2012). These studies include reports of increased RT variability in various tasks, including working memory, sustained attention, and inhibition tasks. RT variability is shown to increase with the severity of ADHD (Castellanos et al., 2005) and decrease with the use of psychostimulant medication (Ozdag et al., 2004; Sangal & Sangal, 2006; Spencer et al., 2015). Some studies have reported that individuals with ADHD exhibit larger trial-by-trial variability in task-evoked EEG responses (McLoughlin et al., 2014; Papenberg et al., 2013; Saville et al., 2015). One study reported that P3 responses were more variable in ADHD individuals (Saville et al., 2015). Other studies reported that frontal-midline theta oscillations were more variable across trials in individuals with ADHD (McLoughlin et al., 2014; Papenberg et al., 2013). These studies suggest that individuals with ADHD exhibit larger trial-by-trial neural variability than controls in specific cognitive processes that govern behavioural responses. This would explain the larger trial-by-trial RT variability across trials found in individuals with ADHD.

Findings in clinical populations with ASD suggest that reduced consistency in neural response may be a core feature of atypical information processing (David et al., 2016; Milne et al., 2011; van Noordt et al., 2022). Research shows that reduced consistency in ASD is observed developmentally and across several brain systems, and it is proposed that neural variability may disrupt information processing and, therefore, negatively affect learning and development and may be an early marker for ASD (David et al., 2016; Schwartz et al., 2018). Recent theories of ASD have proposed that increased neural noise at the level of small-scale neural circuits may

result in increased larger-scale trial-to-trial variability, which can be detected using EEG (Davis & Plaisted-Grant, 2015; Simmons & Milne, 2015). More research is needed to provide complete representations of neural variability at different levels of processing and stages of development to support these theories.

One possibility is that excessive neural noise levels in individuals' sensory systems may negatively affect perception (Neri, 2010). Research shows that larger noise levels may limit an individual's signal detection ability (Aihara et al., 2008). Although relationships between internal noise measures and neural variability have not yet been examined, research shows that individuals with varying disorders show larger levels of internal noise (Dinstein et al., 2015; Northway et al., 2010). Characterizing different forms of neural variability in populations who exhibit selective attention deficits may reveal crucial information about the underlying mechanisms of selective attention. Understanding underlying neural mechanisms may enable the development of additional measures for diagnosis and the ability to measure the efficacy of interventions to target selective attention better (Dinstein et al., 2015).

Conclusion

In conclusion, numerous neurophysiological markers and techniques are available to assess selective attention symptoms across diverse populations, revealing distinct patterns in populations with specific conditions such as ADHD, ASD, SLD, and schizophrenia compared to typically developing individuals. These differences are informative for understanding the underlying mechanisms of various disorders and present a promising avenue for treatment development. Examining how specific treatments influence neurophysiological markers could offer insight into their efficacy at a neurophysiology level, allowing the evaluation of treatment effectiveness in real-time and adapting strategies to optimize outcomes. This approach could lead

to more precise, targeted interventions, ultimately improving treatment planning and personalized care.

CHAPTER TWO

EXAMINING THE IMPACTS OF MINDFULNESS MARTIAL ARTS INTERVENTION ON NEURAL INDICES OF AUDITORY SELECTIVE ATTENTION IN YOUTH WITH ADHD

Attention-deficit/hyperactivity disorder (ADHD) is a prevalent neurodevelopmental disorder, commonly diagnosed during childhood or adolescence, and is characterized by developmentally inappropriate hyperactivity, inattentiveness, and impulsivity (Cabral et al., 2020; Durston, 2003). Children with ADHD are at a greater risk for school failure (Arnold et al., 2020; Barkley, 2006; Kent et al., 2011) and often have difficulties allocating their attention efficiently, and are more vulnerable to distraction (Hong et al., 2022; Kenemans et al., 2005; Stokes et al., 2022; van der Stelt et al., 2001; van Mourik et al., 2007). In school, the ability to selectively attend to the teacher, sustain attention through a lesson, and inhibit processing task-irrelevant information are critical for learning and academic success (Hazan-Liran & Miller, 2024; Markant & Amso, 2022; Pagani et al., 2012).

Selective Attention in ADHD

Selective attention involves allocating resources to a specific sensory input, while ignoring irrelevant information sources and is critical for improving the accuracy and efficiency of information processing. Fundamentally, attention serves as an important data reduction mechanism to prioritise processing important information (Noyce et al., 2023). The cascade of selective attention involves initial stimulus detection and differentiation in order to prioritize specific features of simultaneous sensory inputs (Määttä et al., 2005). Selective attention in the auditory domain is essential for navigating complex auditory environments. The "cocktail party" phenomenon is often used to describe this process, where individuals can selectively attend to one speaker within a noisy environment (Cherry, 1953). In this example, the deployment of

selective attention requires intentional prioritization and facilitation of relevant stimuli while also actively suppressing irrelevant stimuli. Individual differences in selective attention capacity are most pronounced when the cognitive demands are greatest, such as when it is difficult to segregate a target sound stream from competing streams (Choi et al., 2014). Difficulty selectively attending to competing auditory streams has been observed in individuals with attention-deficit hyperactivity disorder (ADHD) compared to controls (Mayes & Calhoun, 2007; Qian et al., 2010; Varlamov et al., 2021; Wåhlstedt et al., 2009). In the auditory domain, a dichotic auditory task which involves performing two tasks concurrently is commonly used for measuring selective attention as it allows for discernment of both the target tone and the target ear (Sibalis et al., 2019). The participant is required to distinguish between the two stimuli and to respond to the stimuli that are pre-designated as targets. The task allows for the comparison of accurate detection of target stimuli in the attended ear and the suppression of target stimuli in the unattended ear.

Current Treatment for ADHD

Empirically supported treatments for ADHD include central nervous system stimulants, non-stimulant medication, behaviour modification, and combined medication with behavioural modification (American Psychiatric Association, 2013). Pharmacological treatment is considered based on the severity of symptoms and the child's age (Mechler et al., 2022). Psychostimulants can significantly reduce ADHD symptoms (Paton et al., 2014; Wigal et al., 2018) and improve selective attention abilities (Brodeur & Pond, 2001; Lubow et al., 2005; Pearson et al., 2020). However, non-adherence to medication is common, and individuals often stop or start medication over several years or discontinue use altogether (Charach & Fernandez, 2013). Poor medication adherence may be in part due to experiencing adverse effects from the medication

(Charach & Fernandez, 2013), which include a loss of appetite, trouble sleeping, headaches, stomach aches, and nausea (Toomey et al., 2012), emphasizing the importance of offering and recommending additional non-pharmacological evidence-based treatment and interventions.

Mindfulness Intervention as a Promising Treatment for ADHD

Mindfulness training has been identified as a promising treatment option for ADHD (Cairncross & Miller, 2020). Mindfulness is a practice derived from Buddhist meditation and teaches participants to cultivate focus and awareness of the mind and body through meditation (Kabat-Zinn, 2003). It involves actively attending to the present moment with a mindset of acceptance (Kabat-Zinn, 2003). The core skills that mindfulness training targets include selective attention, sustained attention, non-reactivity, and calmness (Milligan et al., 2019), all of which are common deficits experienced in ADHD (American Psychiatric Association, 2022). Research has found that youth aged 11-15 have benefitted from 8-week mindfulness training programs, whereby self- and parent-rated inattention and behavioural problems decreased, and attentional ability improved, as evidenced by an increase in speed and accuracy in responses to an auditory attention task (van de Weijer-Bergsma et al., 2012). Similarly, both adolescents and adults self-reported decreased inattention and hyperactive symptoms and showed improved performance on tasks measuring attention and cognitive inhibition following mindfulness training (Mitchell et al., 2015). In addition, a meta-analysis examining the behavioural effects of mindfulness-based therapies for adults and children with ADHD found medium-to-large effect sizes for decreases in inattentive and hyperactive/impulsive symptoms on self and parent report measures (Cairncross & Miller, 2020). From a methodological perspective, changes in inattentive and hyperactive/impulsive symptoms have predominantly been assessed using self-, parent-, or teacher-report questionnaires assessing ADHD symptomatology (Cairncross & Miller, 2020; van

de Weijer-Bergsma et al., 2012; van der Oord et al., 2012) and performance on behavioural tasks that require sustained attention or impulse control (Zylowska et al., 2008). Few studies have examined the neurophysiological correlates of auditory selective attention in individuals with ADHD (Milligan et al., 2019; Schoenberg et al., 2014). The limited research on the neurophysiological correlates of auditory selective attention in individuals with ADHD, particularly within the context of mindfulness interventions, represents a significant gap in the field. Current studies predominantly focus on visual attention, likely due to its ease of control and measurement in experimental settings (Zeidan et al., 2010). However, auditory selective attention is critical in real-world contexts such as listening to instructions, participating in conversations, and maintaining focus in noisy environments; situations where individuals with ADHD frequently face challenges. A deeper understanding of the neurophysiological changes associated with mindfulness-based interventions could inform more targeted intervention for ADHD, especially in contexts that demand selective auditory attention, such as classroom settings or social interactions.

Using Neurophysiological Measures of Selective Attention for Treatment Outcome Effects

EEG markers provide a non-invasive means of examining the neurophysiology of selective attention. The high temporal resolution of electroencephalography (EEG) recordings allows for assessing the fundamental mechanisms of sensory processing during selective attention tasks. Because EEG is highly sensitive to attentional shifts (Sanger & Dorjee, 2015) and may capture the fundamental processes and reveal brain-based changes that might not be detectable from overt behaviour or questionnaire responses (Sanger & Dorjee, 2015), it may provide additional mechanistic information on selective attention-related treatment gains.

Selective attention leads to a cascade of neurophysiological processes generated by synchronizing neurons in response to a stimulus, called an event-related potential (ERP). ERPs are often divided into two categories that reflect different stages of information processing; earlier components peak roughly within a few hundred milliseconds and are sensitive to stimulus characteristics (e.g., luminance, contrast, intensity) and reflect initial stages of sensory processing. Later ERP components typically reflect more elaborative processing linked to evaluation and discrimination (Sur & Sinha, 2009). N1, P1, N2, P2, and P3 components are typically associated with attention allocation and are associated with attention tasks. In populations with ADHD, these components tend to be attenuated (Barry et al., 2003; Fu et al., 2022; Gomes et al., 2012; Johnstone et al., 2013; Määttä et al., 2005; Moavero et al., 2020; Tsai et al., 2012). Some studies have also found larger ERPs to distractor stimuli in populations with ADHD compared to control groups (Gomes et al., 2012; Lackner et al., 2013), suggesting that there is greater resource allocation to task-irrelevant events. Although ERPs provide information about the temporal cascade of information processing, the fixed-latency peak amplitude approach does not reveal information about the spectral dynamics of evoked activity.

Time Frequency Analysis

Time-frequency analysis is a common approach to analysing specific frequency dynamics in response to task events. Both alpha (~ 8 - 12 Hz) and theta (~ 4 - 7 Hz) oscillations have been linked to selective attention. Alpha activity is inversely associated with attention, whereby a desynchronization (decreased alpha power) is thought to be a marker of increased task-focus and cognitive load. In contrast, alpha synchronization (increased alpha power) is associated with inhibiting distracting information (Dubé et al., 2013; Kelly et al., 2006; Mazaheri et al., 2014; Payne et al., 2013; Weisz et al., 2011). Modulation of theta activity is a well-established marker

of cognitive control (Cavanagh et al., 2012; Cavanagh & Shackman, 2015; Nigbur et al., 2011). Several studies have found an increase in frontal theta activity in response to active tasks that require auditory attention (Leroy et al., 2018; Missonnier et al., 2006). In addition, several studies have shown an increase in frontal theta oscillation power along with a simultaneous decrease in posterior alpha power when listening becomes more effortful (van Noordt et al., 2017; Wisniewski et al., 2017, 2018).

Intertrial Coherence and Neural Variability

It has been suggested that variability in neuronal synchronization may indicate an individual's cognitive or perceptual ability (Dinstein et al., 2015). Increased variability has been shown in populations with ADHD (Hervey et al., 2006; Kofler et al., 2013; Tamm et al., 2012). These studies include reports of increased reaction time (RT) variability in working memory, sustained attention, and inhibition tasks (Hervey et al., 2006; Kofler et al., 2013; Tamm et al., 2012). RT variability is positively correlated with ADHD symptom severity (Castellanos et al., 2005) and decreases with the use of psychostimulant medication (Ozdag et al., 2004; Sangal & Sangal, 2006; Spencer et al., 2015). RT variability may be due, in part, to inconsistency in neural activity related to stimulus processing. Some studies have reported that individuals with ADHD exhibit larger trial-by-trial variability in task-evoked EEG responses. One study reported that P3 responses were more variable in ADHD individuals (Saville et al., 2015), with others reporting greater variability in frontal-midline theta oscillations in individuals with ADHD compared to healthy controls (McLoughlin et al., 2014; Papenberg et al., 2013). These studies suggest that individuals with ADHD exhibit larger trial-by-trial neural variability than controls in specific cognitive processes that govern behavioural responses. Variability can be measured using Inter-

trial coherence (ITC). ITC measures cortical synchronization from trial to trial and can detect consistency in spectral dynamics across trials (Delorme & Makeig, 2004).

The current study aims to examine whether neurophysiological and behavioural markers of selective attention are impacted by mindfulness intervention in youth with ADHD. Understanding the neurophysiological effects of mindfulness-based treatments for youth with ADHD and how best to measure treatment-related gains may help inform treatment options for this population, shed light on the complex neural and behavioural difficulties experienced by this population, and provide insight into what degree these difficulties can be ameliorated.

It is expected that mindfulness treatment will positively impact auditory selective attention. Specifically, we hypothesize that participants who undergo treatment will show increased/greater (1) target detection accuracy, (2) ERP amplitudes to target tones in the attended ear compared to the unattended ear, (3) theta phase coherence, and (4) reduced/less alpha phase coherence. Given that other studies have found increased variability in other attention disorders, we will examine whether greater variability is associated with more severe symptoms. It is hypothesized that alpha and theta ITC will be negatively correlated with symptom severity.

Method

Participants

The current study used pre-existing data. The sample consisted of 66 participants aged 11-17 years, including 39 treatment participants and 27 waitlist control participants. The treatment group was recruited from youth registered for Integra MMA at an urban community-based children's mental health treatment centre. The control group was recruited from youth who had indicated interest in participating in Integra MMA and were on the waitlist for the program. All treatment and control participants met criteria for ADHD (American Psychiatric Association,

2013), identified through a diagnostic interview with parents (Mini International Neuropsychiatric Interview for Children and Adolescents, Parent Version 6.0, M.I.N.I. KID-P; Sheehan et al., 2010). 31% of the participants were taking stimulant medication and 1.5% were taking non-stimulant medication. All treatment and control participants had a comorbid diagnosis of a learning disability (LD) diagnosed by a registered psychologist/psychological associate. For this study, LD was defined as having average to above-average cognitive ability with significantly lower levels of academic achievement and information processing (e.g., memory, executive functions, processing speed; LDAC, 2002). In addition to ADHD and LD, many participants also met criteria for additional mental health diagnoses such as anxiety, depression, oppositional defiant disorder, and conduct disorder.

Measures

Selective Auditory Attention Task

Participants were administered a dual-channel auditory oddball task, identical to the task used by Lackner et al., (2013). External speakers were situated to the left and right of the computer screen. From the speakers, 200-ms tones were emitted and included a 1000 Hz non-target tone and a 2000 Hz target tone. Non-target tones were emitted 88% of the time, and target tones were produced 12%, with a varying interstimulus interval of 600-800ms. Target tones were presented to the attended ear 12 times per block to both the attended (attended target trials; AT) and the unattended (unattended target trials; UT) ear. Non-target tones were presented 88 times per block to both the attended (attended non-target trials, ANT) and unattended (unattended non-target, UNT) ear. Target tones are commonly examined for measuring auditory selective attention as it allows for discernment of both the target tone and the target ear (Sibalis et al., 2019). For this study, only the target tones were examined for the comparison of accurate

detection of target stimuli in the attended ear and the suppression of target stimuli in the unattended ear.

Conners-3 Parent Questionnaire

The Conners 3-Parent (Conners 3-P; Conners 2008) is a 110-item parent screening questionnaire assessing a child's ADHD symptom presence and severity. Items are scored on a four-point Likert scale (0 = never, 1 = occasionally, 2 = often, 3 = very often). Internal consistency is good, with coefficients ranging from .77 to .97. Parents were asked to complete the Conners 3-P at two time points 20 weeks apart: pre-treatment at the first session and immediately post-treatment.

Procedures

Participants attended two testing sessions approximately 20 weeks apart. For the treatment group, testing sessions occurred before and immediately following participation in Integra MMA™. Parents completed a diagnostic interview (M.I.N.I. KID-P) at the first session and provided demographic information. Testing sessions were scheduled at 8 am, and 11 am. Computer tasks were presented in a soundproof booth. Participants completed three computerized tasks at both testing sessions while EEGs were recorded. EEG was recorded using the BioSemi ActiveTwo system, with 64 scalp channels plus eight facial and body electrodes measuring eye blinks and jaw and neck muscle activity.

Selective Auditory Attention Task

EEG was continuously recorded while the participants were seated in a soundproof booth with a computer screen. The task included four blocks of 200 trials each; in two blocks, participants were instructed to push a response button whenever the target tone was emitted from the right speaker (2 blocks) or the left speaker (2 blocks). All participants began the task by

attending to the speaker on their right side. After each block, participants were given a 20-second break and told which speaker to attend to during the upcoming block. The task lasted approximately 12 minutes.

Integra Mindfulness Martial Arts intervention

Integra Mindfulness Martial Arts (Integra MMA; Badali, 2011) is a manualized group intervention designed to address attention, inhibitory control, and self-regulation difficulties in youth with ADHD. The program incorporates mindfulness meditation instruction and practice with yoga, cognitive behavioural therapy (CBT), and martial arts. Youth attended a 90-minute session once a week for 20 weeks. The sessions were led by one of two trained instructors. Each group session comprised 6-10 youth, one instructor, and one volunteer assistant. Program instructors were child and family therapists with master's degrees in social work, advanced martial arts and yoga training, and training in mindfulness meditation. Volunteer assistants were university-age adults with backgrounds in martial arts and working with children. All program instructors received weekly supervision from the supervisor of the MMA program.

Sessions centred around various forms of mindful meditation, including sitting meditation, walking meditation, and body scans (e.g. youth were taught to direct attention toward body parts such as fingers). The length of time committed to meditation increased each week. During meditation, youth were encouraged to focus on their breath and body awareness and redirect their thoughts to their breath whenever their mind wandered. During body scans, youth were guided to direct their attention toward a specific body part (e.g., fingers) and then gradually shift their focus to other body parts. The central concepts emphasized during all meditations were non-judgement, acceptance, non-striving, awareness, and letting go.

Elements of CBT were introduced during each session, including recognizing and naming thoughts and feelings, using helpful self-talk, noticing self-defeating thoughts, and understanding how thoughts and feelings influence actions and interpersonal relationships. The participants outlined individual goals, and progress was monitored through discussions with instructors at each session. Instructors also encouraged and rewarded meditation home practice (e.g., in-the-moment praise, points towards yellow belt attainment). Yoga and martial arts were integrated into the therapeutic components to provide an opportunity to practise coping with a physical and mental challenge, which included practising attentional control, self-monitoring, nonjudgement, softening into discomfort, and self-talk. Thus, youth were challenged to stay present, focused, and persistent during difficult tasks.

EEG Pre-Processing and Data Reduction

EEG data were processed using the EEG Integrated Platform-Loss (EEG-IP-L) pipeline (Desjardins et al., 2021). The EEG-IP-L uses a standardized and semi-automated approach to assess signal quality through comprehensive data annotation of channels, time periods, and independent component analysis (ICA) to isolate sources of stereotypical artifacts (e.g., eye blinks, cardiac responses, muscle tension) and time periods of relative non-stationarity. In addition, the pipeline includes interactive quality control review and has been shown to increase data retention without compromising common ERP effects.

EEG Post-Processing and Signal Extraction

Channels, time points, and independent components were removed from the continuous data if flagged during pre-processing or quality control review. The remaining data were segmented by condition, time-locked to the onset of the auditory stimuli and baseline corrected using the 200 msec pre-stimulus window.

ERPs and ITC: Regions of Interest

Regions of interest (ROIs) were selected based on grand average ERP waveforms and topographies (collapsed across conditions and groups) in order to minimize bias in selecting portions of the signal showing the largest differences between conditions or groups (as recommended by Kappenman & Luck, 2016). The cascade of ERP component revealed an early medial frontal positivity (EFP) and medial posterior negativity (N1), followed by a bilateral frontal-temporal negativity (N2), and the medial posterior positivity (P3). Peak amplitudes were extracted from these ROIs for the EFP/N1 (80-120 ms), N2 (130-330 ms), and P3 (330-830 ms) and used for hypothesis testing. See Figure 1 for a summary of the grand averaged ERP waveforms and topographical maps.

Theta ITC waveforms revealed an early bilateral frontal-temporal and late posterior cluster, whereas alpha ITC revealed an early medial frontal cluster. Peak amplitudes were extracted from these ROIs during the 20-420 ms. See Figure 2 for a summary of the grand averaged ITC waveforms and topographical maps.

Statistical Analysis

Statistical analyses of EEG data involved testing effects using robust statistics, which refer to a broad range of techniques that produce more stable parameter estimates compared to non-robust estimators (e.g., sample mean, sample variance). Robust methods provide greater control over nominal alpha level and lower standard error compared to conventional parametric approaches that rely on assumptions regarding the distribution of data (e.g., ANOVA; Wilcox, 2017; Wilcox & Keselman, 2003). In turn, robust methods provide an advantage of power and accuracy. Specifically, percentile bootstrapping with trimmed means were used in the current study (Rousselet et al., 2021). The bootstrapping technique uses the data to estimate sampling

distributions using computer-based simulations, sampling from the data with replacement. The standard t-test assumes the data and theoretical t-distribution conforms to a particular shape, given some assumptions about the population. However, a wealth of empirical evidence shows that even slight deviations from model assumptions (e.g., non-normality) results in poorer control over alpha levels, standard errors, and a lack of statistical power. The percentile bootstrap has been shown to be more robust when model assumptions are violated and in smaller sample sizes, (Rousselet et al., 2017, 2021; Wilcox, 2017). The heterogeneity in the current sample makes the interpretation of direct comparisons between groups for individual task conditions and time points less clear (e.g, large individual differences in time one baseline EEG activity). As such, the inferential statistics for EEG measures focused on condition effects to ensure within participant comparisons to minimize heterogeneity. The within participant task effects can then be more meaningfully interpreted in relation to groups status and time points.

Robust ERP Calculation

Robust ERPs were generated using MATLAB and the STATSLAB toolbox (Campopiano et al., 2018). The procedure involved random resampling, with replacement, from the original pool of single trials to generate a surrogate set of single trials. The 10% trimmed means were taken from these surrogate sets at each time point. Specifically, the distribution of voltages was sorted at each time point, and the highest 10% and lowest 10% values were removed before calculating the mean. This re-sampling, trimming, and averaging process was repeated 1000 times to generate a robust ERP waveform.

Robust Theta and Alpha ITC Calculation

Robust measures of ITC were generated using MATLAB and the STATSLAB toolbox (Campopiano et al., 2018). The procedure involved random resampling, with replacement, from

the original pool of single trials to generate a surrogate set of single trials. The 10% trimmed mean was taken from this surrogate set at each time point. Specifically, the distribution of values was sorted at each time point, and the highest 10% and lowest 10% values were removed before calculating ITC. This process of re-sampling, trimming, and averaging was repeated 1000 times to generate a robust measure of ITC for theta (4-8 Hz) and alpha (8-13 Hz).

Symptom Severity and Neural Variability Calculation

A pairwise sample t-test was performed to assess any differences between symptom severity across time for each condition and an independent samples t-test was performed to assess for condition differences at time 1 and time 2. To explore the relationships between theta ITC, alpha ITC, and symptom severity on the Conners P3 subscales, bivariate Pearson's correlation analyses were conducted. This analysis aimed to determine whether neural variability in theta and alpha frequencies, measured by ITC, was associated with parent-reported ADHD symptom severity, as reflected in the Inattention, Hyperactivity/Impulsivity, and Executive Function subscales of the Conners P3. These correlations were assessed within and between groups. Each correlation was assessed at an alpha level of 0.05, and two-tailed tests were used to determine significance. The strength of the correlations was interpreted using Cohen's guidelines for Pearson's *r*. Correlation matrices were generated to summarise the relationships between theta and alpha ITC with the three symptom severity subscales. All statistical analyses for correlations were conducted using SPSS.

Symptom Severity and Task Behaviour Calculations

A series of mixed Analysis of Variance (ANOVA) tests were conducted to examine the effects of Time (Time 1, Time 2) and Condition (Treatment, Control) on task accuracy, reaction time, and symptom severity measured by the Conners subscales of Inattention,

Hyperactivity/Impulsivity, and Executive Function. Separate ANOVAs were performed for each dependent variable to evaluate the main effect of time, condition, and time-by-condition interaction. For all ANOVAs, the alpha level was set at 0.05. Effect sizes were calculated using partial eta-squared (η^2) to provide an estimate of the magnitude of any observed effects. Post hoc comparisons were conducted where appropriate using Bonferroni corrections to control for multiple comparisons. All statistical analyses for ANOVAs were conducted using SPSS.

Results

ERP Results

EFP

For AT at time 1, the mean difference between the groups was not statistically significant, ($M_{difference}$ = -0.12, 95% CIs [-0.28, 0.04]). For UT at time 1, the EFP component was significantly larger for the control group than the intervention group, ($M_{difference}$ = 0.24, p <.05, 95% CIs [0.06, 0.43]). At time 2, AT for the EFP component was significantly larger for the control group ($M_{difference}$ = 0.24, p <.05, 95% CIs [0.04, 0.44]). For UT at time 2, no significant difference was found between the groups, ($M_{difference}$ = 0.05, 95% CIs [-0.12, 0.23]).

Results showed a 3-way interaction showing that the condition differences over time were larger in the intervention than the control group ($M_{difference}$ = 0.56, p <.05, 95% CIs [0.19, 0.92]). In the control group, the EFP component was significantly larger for the UT stimuli at time 1 ($M_{difference}$ = -0.44, p <.05, 95% CIs [-0.75, -0.14]). The pattern reversed at time 2 such that the EFP component was significantly larger for AT stimuli ($M_{difference}$ = 0.38, p <.05, 95% CIs [0.06, 0.71]), indicating an interaction between condition and time ($M_{difference}$ = -0.81, p <.05, 95% CIs [-1.26, -0.35]). In the intervention group, there was no reliable condition difference in the EFP component at time 1. At time 2, the EFP component was significantly larger for AT

stimuli ($M_{difference}$ = 0.18, p <.05, 95% CIs [0.02, 0.33]), indicating an interaction between condition and time ($M_{difference}$ = -0.25, p <.05, 95% CIs [-0.59, -0.04]). See Figure 3 for a summary of EFP effects.

N1

No significant differences were found between groups for AT at time 1 ($M_{difference}$ = 0.06, 95% CIs [-0.12, 0.23]), UT at time 1 ($M_{difference}$ = -0.09, 95% CIs [-0.28, 0.10]), or AT at time 2 ($M_{difference}$ = 0.11, 95% CIs [-0.10, 0.32]). However, the N1 component for the UT at time 2 was significantly larger for the intervention group ($M_{difference}$ = -0.36, p < .05, 95% CIs [-0.55, -0.16]. In the control group, the N1 was not reliably different between AT and UT stimuli at either time point. In the intervention group, there was no reliable condition difference in the N1 component at time 1. At time 2, the N1 component was significantly larger for AT stimuli ($M_{difference}$ = -0.35, p <.05, 95% CIs [0.11, 0.58]), indicating an interaction between condition and time ($M_{difference}$ = 0.51, p <.05, 95% CIs [0.16, 0.86]). See Figure 4 for a summary of N1 effects.

N2

For the N2 component, no significant difference was found between groups for AT at time 1 ($M_{difference}$ = -0.06, 95% CIs [-0.22, 0.13]). For UT at time 1, the N2 component was significantly larger for the control group, ($M_{difference}$ = -0.59, p < .05, 95% CIs [-0.78, -0.40]. There was a significant difference between groups for the AT at time 2, whereby N2 was significantly larger for the control group, ($M_{difference}$ = -0.29, p < .05, 95% CIs [-0.48, -0.10]. At time 2, no significant difference between groups was found for UT ($M_{difference}$ = 0.17, 95% CIs [-0.03, 0.37]). In the control group, the N2 component was significantly larger for the AT stimuli at time 1 ($M_{difference}$ = -0.41, p <.05, 95% CIs [-0.73, -0.08]) and time 2 ($M_{difference}$ = -0.54, p <.05, 95% CIs [-0.84, -0.23]). In the intervention group, the N2 was significantly larger for the AT

stimuli at time 1 ($M_{difference}$ = -0.94, p <.05, 95% CIs [-1.19, -0.68]). At time 2, the N2 component was not reliably different between AT and UT stimuli, indicating a condition by time interaction ($M_{difference}$ = -0.78, p <.05, 95% CIs [-1.07, -0.49]). See Figure 5 for a summary of N2 effects.

P3

For AT, there was a significant difference between groups at time 1, with a larger P3 component for the control group, ($M_{difference}$ = 0.63, p < .05, 95% CIs [0.29, 0.99]). No significant difference was found for AT at time 2, ($M_{difference}$ = 0.19, 95% CIs [-0.19, 0.56]). For UT, no significant differences were observed at time 1 ($M_{difference}$ = -0.02, 95% CIs [-0.31, 0.26]) or time 2, ($M_{difference}$ = -0.004, 95% CIs [-0.33, 0.32]).

In the control group, the P3 component was significantly larger for the AT stimuli at time 1 ($M_{difference}$ = 2.16, p <.05, 95% CIs [1.66, 2.67]) and time 2 ($M_{difference}$ = -1.92, p <.05, 95% CIs [1.30, 2.53]). The same pattern was observed in the intervention group, such that the P3 component was significantly larger for the AT stimuli at time 1 ($M_{difference}$ = 1.52, p <.05, 95% CIs [1.06, 1.96]) and time 2 ($M_{difference}$ = 1.73, p <.05, 95% CIs [1.45, 2.01]). See Figure 6 for a summary of P3 effects.

ITC Results

Theta

At time 1, there was a significant difference between groups for both AT ($M_{difference}$ = 0.02, p < .05, 95% CIs [0.006, 0.03]) and UT ($M_{difference}$ = 0.05, p < .05, 95% CIs [0.03, 0.06]) with the control group showing a larger theta ITC. At time 2, the control group had a significantly larger theta ITC for AT ($M_{difference}$ = 0.06, 95% CIs [0.05, 0.08]). No significant difference between groups was observed for UT stimuli at time 2 ($M_{difference}$ = 0.006, 95% CIs [-0.005, 0.017]).

There was a 3-way interaction for Theta ITC, indicating that the condition difference was larger at time 1 for the intervention group, whereas the condition difference was larger at time 2 for the control group ($M_{difference}$ = 0.08, p <.05, 95% CIs [-0.09, -0.04]). In the control group, there was no difference in theta ITC at time 1. At time 2, theta ITC was significantly larger for the AT stimuli at time 2 ($M_{difference}$ = 0.08, p <.05, 95% CIs [0.06, 0.09]), indicating an interaction that was driven by increased theta ITC to AT and decreased theta ITC to UT at time 2 compared to time 1 ($M_{difference}$ = -0.07, p <.05, 95% CIs [-0.09, -0.05]). In the intervention group, theta ITC was significantly larger for AT stimuli at both time 1 ($M_{difference}$ = 0.04, p <.05, 95% CIs [0.02, 0.05]) and time 2 ($M_{difference}$ = 0.02, p <.05, 95% CIs [0.006, 0.04]). There was also a condition by time interaction, indicating that the difference between AT and UT was greater at time 1 compared to time 2 ($M_{difference}$ = 0.02, p <.05, 95% CIs [-0.09, -0.05]). See Figure 7 for a summary of theta ITC effects.

Alpha

Significant differences between groups were found at time 1 for both AT ($M_{difference}$ = 0.04, p < .05, 95% CIs [0.03, 0.06]) and UT ($M_{difference}$ = 0.02, p < .05, 95% CIs [0.003, 0.04]) with the control group showing a larger alpha ITC. No significant differences were observed for AT ($M_{difference}$ = -0.004, 95% CIs [-0.02, 0.01]) or UT ($M_{difference}$ = 0.009, 95% CIs [0.0002, 0.02]) at time 2.

In the control group, alpha ITC was significantly greater for AT compared to UT stimuli at time 1 ($M_{difference}$ = 0.03, 95% CIs [0.007, 0.05]) and time 2 ($M_{difference}$ = 0.01, 95% CIs [0.002, 0.02). In the intervention group, alpha ITC was significantly larger for AT stimuli at time 2 ($M_{difference}$ = 0.03, 95% CIs [0.01, 0.04]). See Figure 8 for a summary of alpha ITC effects.

Behavioural Results

Symptom Severity and Neural Variability

There were no differences found in Conners scores over time for the control group or the intervention group. Likewise, no differences were found between the groups at time 1 or time 2. See tables 1-4 for detailed results. Bivariate correlation analysis between symptom severity on the Conners P3 subscales (inattention, hyperactivity/impulsivity, and executive function) and neural variability measures in theta and alpha inter-trial coherence (ITC) did not yield any statistically significant results. Correlations were assessed between groups as well and did not yield any significant results. See tables 5 and 6 for results.

Symptom Severity and Task Performance

None of the ANOVA analyses yielded significant main effects or interaction effects for Time or Condition on task performance measures of accuracy and reaction time. Similarly, no significant effects were found for symptom severity on the Conners P3 subtests for inattention, hyperactivity/impulsivity, and executive function. See Tables 3-7 for detailed results.

Discussion

The present study examined whether a mindfulness martial arts training intervention impacts neural indices, parent reports of symptom severity, and auditory selective attention in youth with ADHD. Despite the increasing body of research demonstrating the advantages of mindfulness interventions for addressing attentional challenges in some individuals with ADHD, few studies have focused on these factors in youth. Overall, the results suggest that treatment primarily impacts neural responses associated with early sensory processing, with limited impacts on later processing stages.

EFP

To better understand how mindfulness treatment impacts early sensory processing, we first examined early frontocentral positivity (EFP), a neural marker associated with attentional engagement during the initial stages of stimulus processing. Both groups showed changes over time such that the EFP component was larger to AT compared to UT stimuli suggesting that frontally mediated mechanisms are rapidly engaged toward task-relevant stimuli. A larger EFP amplitude for attended targets implies that the brain is more sensitive to target stimuli. Given that both intervention and control groups showed similar early sensory engagement to task-relevant stimuli, and comparable levels of task performance, the change in EFP overtime likely reflects a common change due to testing effects. However, the improvement was significantly larger for the intervention group, suggesting that mindfulness may play a role in facilitating attention allocation to relevant stimuli. These findings align with other research showing that mindfulness training enhances selective attention and attention allocation to target stimuli (Moore & Malinowski, 2009; Zeidan et al., 2010).

N1

To assess the effects of mindfulness treatment on early auditory processing, we next examined the N1 component, a well-established marker of early sensory and attentional processes in response to auditory stimuli. The N1 reflects the brain's ability to detect and selectively attend to relevant sounds, with increased amplitudes indicating enhanced attention to task-relevant stimuli (Näätänen & Picton, 1987). The control group did not show any modulation of the N1 component to task stimuli at either time point. The treatment group, however, showed significantly larger N1 components to AT compared to UT at time 2, suggesting that mindfulness training may benefit early sensory sensitivity to task-relevant target

stimuli. Enhanced N1 amplitude to the attended auditory stream is typically observed in healthy individuals (Schwent & Hillyard, 1975; Woods et al., 1992). Our findings also align with previous research showing larger N1 amplitudes post-mindfulness training (Isbel et al., 2020; Lutz et al., 2009). This change in activity is thought to result from the increase of an attentional response to attended tones and improved sensory discrimination (Isbel et al., 2020; Lutz et al., 2009). In the intervention group, the N1 component was the same for AT and UT at time 1. However, at time 2, the N1 component showed significant changes, reflected by both an increase for AT and a decrease for UT. By increasing attentional focus on specific auditory stimuli, mindfulness training may help individuals more effectively differentiate between relevant and irrelevant sounds (Kerr et al., 2013). Furthermore, mindfulness has been linked to increased activity in the prefrontal cortex, which is crucial for attention regulation (Hölzel et al., 2011). Given that the timing of the N1 corresponds to the EFP, likely reflecting a similar dipole source projection, the larger N1 amplitude after mindfulness training could reflect enhanced coordination between the prefrontal and posterior cortices, leading to improved attentional modulation of sensory input.

N2

The N2 ERP component is associated with the neural mechanisms underlying auditory discrimination and attention, indicating enhanced sensitivity to novel or unexpected auditory events. It plays a critical role in auditory processing and is essential for the discrimination of novel stimuli in auditory tasks (Bruneau et al., 2015). For the N2 component, both groups showed a larger amplitude to the attended target at time one. Only the control group continued to show significantly larger N2 amplitudes to the attended targets at time two. Given that the intervention group showed greater sensitivity to AT targets in the earlier stages (EFP and N1),

the later differentiation process indexed by the N2 may not have been as pronounced. This suggests that mindfulness training allows participants to detect potential conflicts between attended and unattended stimuli at an earlier stage of processing, reducing the need for engagement of later, more effortful mechanisms of stimulus categorization.

Both groups showed a decrease in N2 post-intervention, indicating that attention allocation becomes more efficient over time. In the early stages of learning or in individuals with cognitive deficits, selective attention to target tones may require active cognitive engagement, reflected in a larger N2 (Fu et al., 2022). However, over time, when participants become more proficient at the task or when attentional capacities are improved, the processing of target tones may become more automatic, requiring less active control or inhibition (Swallow & Jiang, 2013).

P3

To investigate the effects of mindfulness treatment on later cognitive processing, we analysed the P3 component, a well-documented index of higher-order attentional processes and stimulus evaluation. The P3 reflects the allocation of cognitive resources to task-relevant stimuli and is typically larger for attended stimuli, indicating heightened awareness and categorization (Polich, 2007). There was no impact of treatment or time on P3 amplitudes; both groups consistently showed a larger P3 to the attended compared to unattended target tones. Typically, before mindfulness training, individuals often show a moderate differentiation in the P3 response between attended and unattended tones. Following mindfulness training, however, the difference between the P3 to attended and unattended stimuli often becomes larger, reflecting improved selective attention (Moore et al., 2012; Slagter et al., 2007, 2011). This pattern was not found in this study and may be due to the type of task used. The auditory selective attention task may not have been sensitive enough to detect subtle changes in cognitive processing following

mindfulness training. The task may not have been sufficiently challenging or engaged attentional processes in a way that would evoke larger changes in the P3 component after training. Other research has found similar results and has suggested that post-mindfulness, individuals may benefit in more broad attentional gains rather than gains specific to selective attention (Tang et al., 2015). Other studies suggest that mindfulness may lead to more passive processing whereby both the attended and unattended stimuli are treated similarly (Hölzel et al., 2011). A more demanding or complex task might be necessary to reveal changes in later neural processing following mindfulness (Lutz et al., 2009).

Theta ITC

In the control group, there was no significant difference in theta ITC between attended and unattended tones at Time 1. However, by Time 2, theta ITC was significantly larger for attended compared to unattended ones. This change was driven by an increase in theta ITC to attended tones and a decrease in theta ITC to unattended tones, suggesting that there may be a natural improvement in the brain's capacity to focus on relevant stimuli that may occur over time, potentially due to repeated task exposure.

In contrast, the intervention group demonstrated a different pattern. At both Time 1 and Time 2, theta ITC was significantly larger for attended tones than unattended tones, suggesting that participants in the intervention group initially had a more consistent brain response to task-relevant stimuli. Mindfulness practice has been shown to decrease neural responses that reflect effortful control during tasks by encouraging a more balanced and open engagement with both external and internal stimuli (Schuman-Olivier et al., 2020). The reduction in theta ITC in the mindfulness group may indicate less reliance on top-down control mechanisms for attended tones as participants become more proficient at maintaining non-judgmental awareness without

needing sustained high-effort attention which may explain the divergence between the intervention and control groups, with the control group relying more on effortful attentional strategies.

Alpha ITC

The intervention group showed no significant difference between attended and unattended tones at Time 1, but a significant difference emerged by Time 2, with alpha ITC being larger for attended tones. The significant interaction effect at Time 2 in the intervention group was driven by a reduction in ITC for unattended tones, suggesting that participants became better at suppressing irrelevant stimuli post-treatment. However, in the control group, the largest difference between alpha ITC for attended and unattended tones occurred at Time 1, driven by lower ITC for unattended tones, suggesting that the control group initially exhibited stronger suppression of irrelevant stimuli. Therefore, it is not clear whether the improvement seen in the intervention group is due to mindfulness training or if participants became better at suppressing irrelevant information over time. Distinguishing whether these improvements are purely attributable to mindfulness training or represent natural developmental changes poses a challenge. Adolescents naturally undergo significant changes in attentional processes, as brain maturation leads to better management of cognitive resources (Casey et al., 2008). As children transition into adolescence, they often develop more sophisticated mechanisms for suppressing irrelevant information which could potentially contribute to the observed changes in the intervention group. The observed differences in alpha ITC patterns between the groups underscore the need to consider both intervention effects and the potential for natural maturation effects when interpreting the results. It has been shown that control groups often exhibit different developmental trajectories than intervention groups, especially when the intervention is designed

to enhance cognitive processes that are already in flux during adolescence (Kurz et al., 2019). Thus, while the intervention group showed improvements in attentional focus over time, it is critical to contextualize these findings within the broader framework of developmental psychology and neurodevelopmental changes.

Symptom Severity and Task Performance

We did not find any evidence that accuracy or reaction time on the auditory selective attention task was associated with ADHD symptoms assessed by the Conners P-3. While the task measures specific aspects of attention (e.g., focusing on auditory stimuli), the Conners P-3 assesses a wide range of behavioural symptoms, including hyperactivity, impulsivity, inattention, and emotional regulation. These broader symptoms may not directly correlate with the performance metrics (reaction time and accuracy) from the selective attention task. The auditory task assesses a specific cognitive skill, while the Conners P-3 captures parent-reported behaviours across various contexts (e.g., home, school). Therefore, the task may not be sensitive enough to reflect the broader behavioural patterns captured by the Conners P-3 (Toplak et al., 2013).

The Conners P-3 is based on parent reports, which can introduce subjectivity. Parents may assess their child's behaviour based on factors not directly observable in a structured task environment. Reaction time and accuracy on the auditory task provide more objective, controlled measures of selective attention, potentially leading to a disconnect between these two types of assessments (Achenbach et al., 2003). Furthermore, as children develop, neural networks continue to mature, leading to fluctuations in both symptom expression and cognitive performance. These changes might result in a non-linear relationship between symptom severity and behavioural performance on cognitive tasks (Shaw et al., 2007). In addition, the symptoms

reported on the Conners P-3 reflect behaviour across various settings over an extended period (e.g., weeks or months). However, performance on a single laboratory task (like the auditory selective attention task) may reflect more short-term fluctuations in attention and may account for the lack of association. Individuals with ADHD may have more difficulty maintaining attention in naturalistic settings (as observed by parents) than the focused demands of a short-duration laboratory task (Geurts et al., 2004). Laboratory tasks, often designed with minimal distractions and a direct, single focus, can provide an artificial environment that may fail to reflect the cognitive load or stimuli encountered in daily life (Geurts et al., 2004). Such structured tasks may inadvertently mask the full extent of attentional difficulties because they lack the dynamic, often chaotic demands of real-world settings, where distractions are plentiful, and tasks may not be explicitly defined or reinforced (Nigg, 2006). Combining neurophysiological data with reports from parents, teachers, and self-reports could enhance the ecological validity of ADHD research by capturing how symptoms fluctuate across different contexts. Parents and teachers often provide crucial information about how an individual behaves in naturalistic settings, which may differ from laboratory assessments in terms of both attention demands and environmental complexity making behavioural reports essential for contextualising neurophysiological findings, helping to bridge the gap between brain activity and everyday challenges faced by individuals with ADHD (Cortese et al., 2021; Fair et al., 2021), thus underscoring the importance of using multiple data sources to gain a clearer and more accurate understanding of ADHD.

Symptom Severity and Neural Variability

This study did not find any correlations between symptom severity and neural variability. There are several possible reasons for these findings. First, the Conners P-3 captures broad

behavioural categories (e.g., inattention, hyperactivity, executive functioning), but neural variability in alpha and theta may be more relevant to specific ADHD subtypes (e.g., inattentive vs. hyperactive/impulsive types). This heterogeneity could dilute the relationships between brain activity and parent-reported symptom severity (Fair et al., 2012). The small sample size and limited number of youth with hyperactive/impulsive type ADHD in the current study limited the ability to examine these subtype-specific effects. Parent-reported symptoms on the Conners P-3 can also be influenced by subjective biases, such as parental perception or expectations, which may not fully align with objective measures of neural activity. Consequently, these discrepancies could partially account for the lack of observed correlation.

Furthermore, the relationship between neural variability and behaviour may not be linear or direct. Symptom severity captured by the Conners P-3 may emerge from interactions between multiple neural systems rather than variability in a single frequency band (Uhlhaas & Singer, 2010). Finally, neural variability and the relationship between brain activity and behaviour may be particularly dynamic during periods of development. As individuals mature, both neural oscillations and symptom expression can evolve at different rates, which may complicate the ability to detect stable correlations. These developmental changes introduce variability in brain-behaviour relationships, making it more challenging to capture consistent patterns, especially in populations like children and adolescents where brain systems are still maturing (Shaw et al., 2007).

Limitations

The current study is not without limitations. First, the MMA program is integrated with elements of cognitive and behavioural therapy. Therefore, results may be due to other treatment components that impact attention independent of mindfulness training. Examining studies that

have implemented “pure” mindfulness-based interventions (MBIs) without additional therapeutic elements is crucial to address this. Several meta-analyses on Mindfulness-Based Stress Reduction (MBSR) and MBI programs found that mindfulness programs significantly improve attention and executive functioning in both clinical and non-clinical populations (Chiesa et al., 2011; Khoury et al., 2013; Prakash et al., 2020; Sumantry & Stewart, 2021; Verhaeghen, 2021). These findings collectively indicate that mindfulness training, even when implemented as a standalone intervention, has some measurable impact on attentional processes. Future research should continue to isolate the specific effects of mindfulness from other therapeutic components to better understand its direct influence on cognitive functioning.

Similarly, the mindfulness program incorporated aspects of physical activity in martial arts and yoga practice. Changes may have been due to, or exacerbated by, the physical activity portion of the program. Research shows that exercise positively affects neurophysiological measures of attention (Chang et al., 2018; Drollette et al., 2014; Hillman et al., 2014). Future research should use a randomized control trial design with a control group doing physical activity without the mindfulness component to address these limitations. However, using a qualitative approach, Milligan et al. (2015) emphasized the importance of integrating these components for engaging youth and promoting the meaning of mindfulness strategies. Therefore, the impact of the integrated components may be an essential feature of the MMA program (Milligan et al., 2015). Furthermore, the treatment and control groups continued to participate in other activities or treatments that may improve attention, including participation in other therapies and medication use (Milligan et al., 2019). Single-subject methods that record these factors in depth may help understand the influence of these factors better.

Given that other research using Integra MMA has found more impactful changes in other selective attention paradigms in youth with ADHD, it is important to consider that the auditory attention task may not be as sensitive to changes in selective attention as compared to other measures of selective attention (e.g., visual selective attention tasks). Research on Integra MMA has shown stabilized effects in treatment groups, while controls displayed significantly worsening symptoms using a visual selective attention task (Sibalis et al., 2019). A possible reason for this discrepancy in results may relate to the severity of attention deficit for visual versus auditory stimuli. Children with ADHD have been noted to show more significant impairments in visual attention tasks compared with auditory attention tasks (Lin et al., 2017, 2021; Wang et al., 2021). In addition, when taking methylphenidate, children with ADHD show more significant performance improvements on visual as opposed to auditory attention tasks (Lin et al., 2017). It may be that performance on visual attention tasks allows for greater room for improvement, explaining why post-test differences have been noted in other studies using visual tasks but not in this study using an auditory task. Alternatively, these results may be reflective of the well-supported finding that attentional deficits for individuals with ADHD are most evident during repetitive, uninteresting, and low-reward tasks (Barkley, 1990; Morsink et al., 2017; Sonuga-Barke et al., 2010). Visual selective attention tasks use colourful, engaging characters that provide a concrete focus point and direct feedback regarding performance (e.g., providing a red x when incorrect). In contrast, the auditory task used in this study provided more repetitive and less engaging stimuli and had a low presentation rate of target tones requiring a response (12%). The lower stimulation level provided by the auditory task may have resulted in higher levels of disengagement and inattention than the visual task. Future research should consider

these possible challenges when designing studies examining auditory selective attention changes in individuals with ADHD and should consider using more complex auditory tasks.

Finally, participants in this study were diagnostically complex. The youth had, on average, 2.3 diagnoses in addition to ADHD, the most common being comorbid learning disorder (LD). Comorbidity is prevalent in youth with ADHD, with research indicating that up to 58% of individuals with ADHD have at least one additional diagnosis, such as anxiety, depression or LD (Barkley, 2006; Cuffe et al., 2020; Mak et al., 2022). The presence of multiple comorbidities can complicate both diagnosis and treatment, as symptoms of ADHD may overlap or be exacerbated by the symptoms of other disorders (Elwin et al., 2020). Learning disorders, in particular, can influence cognitive and behavioural functioning, potentially impacting the outcomes of interventions such as mindfulness training. These comorbid conditions often lead to greater impairment in academic and social functioning and can affect the neurophysiological responses observed in studies involving cognitive tasks and interventions (Mansour et al., 2021; Medrano Nava et al., 2024). Therefore, given the complexity of the sample, it is possible that the groups differ in ways that make them inherently non-comparable, which could influence these findings. Future research should account for potential baseline differences to better interpret group effects. Future research with larger samples is needed to better understand how mental health diagnosis may moderate outcomes and, ultimately, how mindfulness interventions may need to be tailored to specific populations.

Implications for School Psychologists

Mindfulness interventions show some potential benefits for attention for youth with ADHD. However, the current research remains inconclusive and lacks the robust evidence necessary to recommend mindfulness as a first-line treatment. For school psychologists and

clinicians, this presents a unique challenge in guiding families and students toward effective support strategies. Given the mixed results on the efficacy of mindfulness for ADHD symptoms, practitioners must be prepared to discuss with parents and educators why mindfulness alone may not provide sufficient support and why evidence-based treatments, such as behavioural therapy and medication, should typically be prioritized.

Clinicians may encounter situations where parents express interest in mindfulness due to its increasing popularity or a desire for non-medication-based treatments. In these cases, it is essential for practitioners to convey that mindfulness can be a valuable complementary practice; however, current best practices suggest beginning with interventions that are more consistently supported by research. School psychologists and clinicians must also be equipped to discuss how mindfulness might be integrated later in treatment to enhance skills in attention rather than relying on it as the primary treatment. This balanced, evidence-informed approach ensures that students with ADHD receive the most effective, research-backed support for their unique needs.

Conclusion

A growing body of research shows promising results for the use of mindfulness as a treatment for attentional improvement in individuals with ADHD. However, studies focusing on treatments for young people have shown inconsistent results regarding attention (Chiesa et al., 2011; Mak et al., 2018). This study investigated whether a mindfulness martial arts training intervention affects neural indicators, parental reports of symptom severity, and behavioural indicators of changes in auditory selective attention in youth with ADHD. Similar to previous studies, we found evidence of a change in attention in early neural indices, although the findings were somewhat inconsistent. This study adds to the growing body of research that uses EEG indicators of selective attention and supports the feasibility of this research approach. Future

research should focus on methodological improvements, including the use of an active control group, selecting tasks that are more sensitive to selective attention improvements, and conducting randomized and longitudinal studies to explore changes in these measures over longer periods. Addressing these limitations in future research may help us better understand the mixed results of mindfulness treatments on youth with ADHD.

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Tables

Table 1

Descriptive Statistics for Conners P-3 Subscales at Time 1 and Time 2 for Control Group

	N	Mean	SD
Inattention Time 1	27	74.07	12.11
Hyperactivity/Impulsivity Time 1	27	68.89	17.57
Executive Function Time 1	27	67.15	9.51
Inattention Time 2	19	72.68	13.62
Hyperactivity/Impulsivity Time 2	19	66.68	16.84
Executive Function Time 2	19	67.95	13.09

Table 2

Descriptive Statistics for Conners P-3 Subscales at Time 1 and Time 2 for Intervention Group

	N	Mean	SD
Inattention Time 1	39	71.44	10.98
Hyperactivity/Impulsivity Time 1	39	71.51	13.49
Executive Function Time 1	39	64.87	10.17
Inattention Time 2	31	69.26	11.33
Hyperactivity/Impulsivity Time 2	31	68.16	14.17
Executive Function Time 2	31	63.77	11.87

Table 3

Paired Samples Test for Differences Across Time and Condition for Conners P-3 Subscales

	Mean	SD	t	df	Sig.
Control					
Inattention	.157	11.490	.060	18	.953
Hyperactivity/Impulsivity	.421	10.621	.173	18	.865
Executive Function	-2.157	10.678	-.881	18	.390
Intervention					
Inattention	1.580	8.827	.997	30	.327
Hyperactivity/Impulsivity	2.612	10.778	1.350	30	.187
Executive Function	1.580	9.680	.909	30	.371

Table 4

Independent Samples Test for Condition Differences at Time 1 and Time 2 for the Conners P-3 Subscales

	t	df	Mean Difference	Sig.
Inattention Time 1	-.920	64	-2.638	.361
Hyperactivity/Impulsivity Time 1	.686	64	2.623	.495
Executive Function Time 1	-.918	64	-2.276	.362
Inattention Time 2	-.961	48	-3.426	.341
Hyperactivity/Impulsivity Time 2	.333	48	1.477	.741
Executive Function Time 2	-1.161	48	-4.173	.251

Table 5

Correlations Between Symptom Severity and ITC Correlations Time 1

		Inattention	Hyperactivity/ impulsivity	Executive Function	Theta AT	Alpha AT	Theta UT	Alpha UT
Inattention	Pearson Correlation	--						
	Sig. (2-tailed)							
	N	66						
Hyperactivity/impulsivity	Pearson Correlation	.460**	--					
	Sig. (2-tailed)	<.001						
	N	66	66					
Executive Function	Pearson Correlation	.636**	.207	--				
	Sig. (2-tailed)	<.001	.095					
	N	66	66	66				
Theta AT	Pearson Correlation	.068	-.036	-.266*	--			
	Sig. (2-tailed)	.588	.775	.031				
	N	66	66	66	66			
Alpha AT	Pearson Correlation	.097	.016	-.180	.469**	--		
	Sig. (2-tailed)	.436	.901	.149	<.001			
	N	66	66	66	66	66		
Theta UT	Pearson Correlation	-.157	-.039	-.151	.048	-.212	--	
	Sig. (2-tailed)	.209	.755	.228	.705	.087		
	N	66	66	66	66	66	66	
Alpha UT	Pearson Correlation	-.207	-.141	.034	-.040	-.095	.278*	--
	Sig. (2-tailed)	.096	.259	.785	.752	.450	.024	
	N	66	66	66	66	66	66	66

**p < .01, two-tailed.
*p < .05, two-tailed.

Table 6

Correlations Between Symptom Severity and ITC Correlations Time 2

		Inattention	Hyperactivity/ impulsivity	Executive Function	Theta AT	Alpha AT	Theta UT	Alpha UT
Inattention	Pearson Correlation	--						
	Sig. (2-tailed)							
	N	50						
Hyperactivity/ impulsivity	Pearson Correlation	.648**	--					
	Sig. (2-tailed)	<.001						
	N	50	50					
Executive Function	Pearson Correlation	.811**	.520**	--				
	Sig. (2-tailed)	<.001	<.001					
	N	50	50	50				
Theta AT	Pearson Correlation	.023	-.022	-.191	--			
	Sig. (2-tailed)	.877	.884	.198				
	N	47	47	47	50			
Alpha AT	Pearson Correlation	-.176	-.123	-.166	.407	--		
	Sig. (2-tailed)	.237	.410	.264	.003*			
	N	47	47	47	50	50		
Theta UT	Pearson Correlation	-.087	-.279	-.054	.282	.172	--	
	Sig. (2-tailed)	.593	.081	.742	.082	.295		
	N	40	40	40	39	39	50	
Alpha UT	Pearson Correlation	-.180	-.070	-.143	-.108	.030	.058	--
	Sig. (2-tailed)	.266	.670	.379	.7511	.858	.691	
	N	40	40	39	39	39	50	50

**p < .01, two-tailed.
*p < .05, two-tailed.

Table 7

Effects of Time and Condition for Inattention Symptoms on the Conners-P3

Source	df	F	Sig.	Partial Eta Squared
Time	1	.210	.649	.005
Group	1	.550	.462	.012
Time*Group	1	.411	.525	.009
Error	44			

Table 8

Effects of Time and Condition for Hyperactivity/Impulsivity Symptoms on the Conners P-3

Source	df	F	Sig.	Partial Eta Squared
Time	1	.472	.496	.011
Group	1	.729	.378	.018
Time*Group	1	.065	.800	.001
Error	44			

Table 9

Effects of Time and Condition for Executive Function Symptoms on the Conners P-3

Source	df	F	Sig.	Partial Eta Squared
Time	1	.622	.435	.014
Group	1	.108	.744	.002
Time*Group	1	2.266	.139	.049
Error	44			

Table 10

Effects of Time and Condition for Behavioural Task Accuracy on the Auditory Selective Attention Task

Source	df	F	Sig.	Partial Eta Squared
Time	1	1.436	.237	.029
Group	1	1.937	.170	.039
Time*Group	1	.375	.543	.008
Error	48			

Table 11

Effects of Time and Condition for Behavioural Reaction Time on the Auditory Selective Attention Task

Source	df	F	Sig.	Partial Eta Squared
Time	1	1.296	.261	.027
Group	1	.400	.530	.008
Time*Group	1	.080	.778	.002
Error	47			

Figures

Figure 1

Grand Averaged ERP Waveforms and Topographical Maps

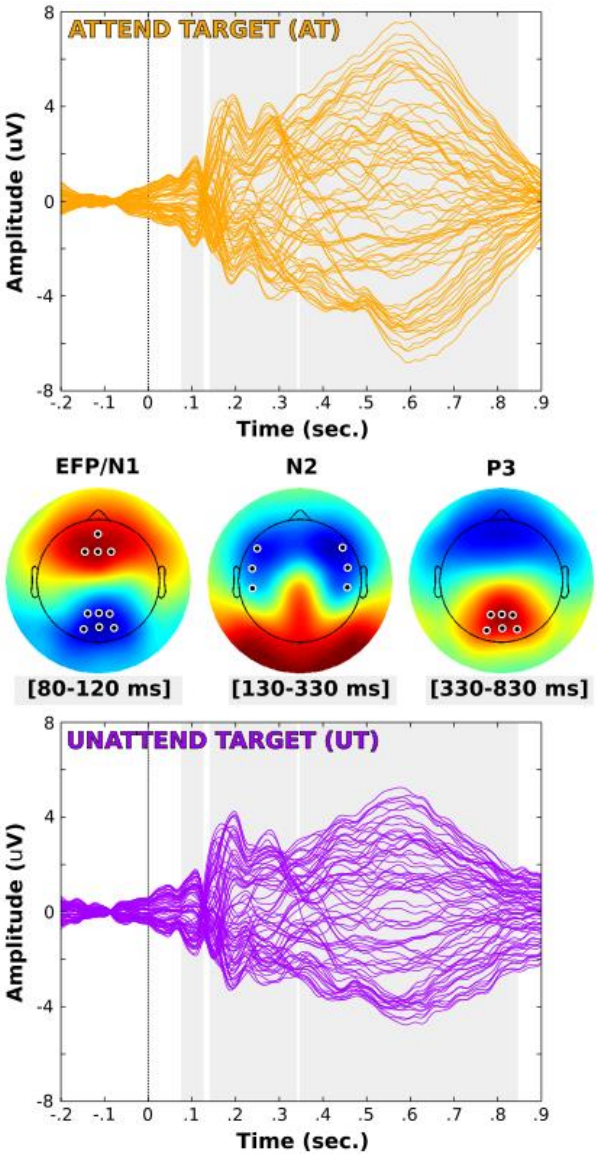


Figure 2

Summary of the Grand Averaged ITC Waveforms and Topographical Maps

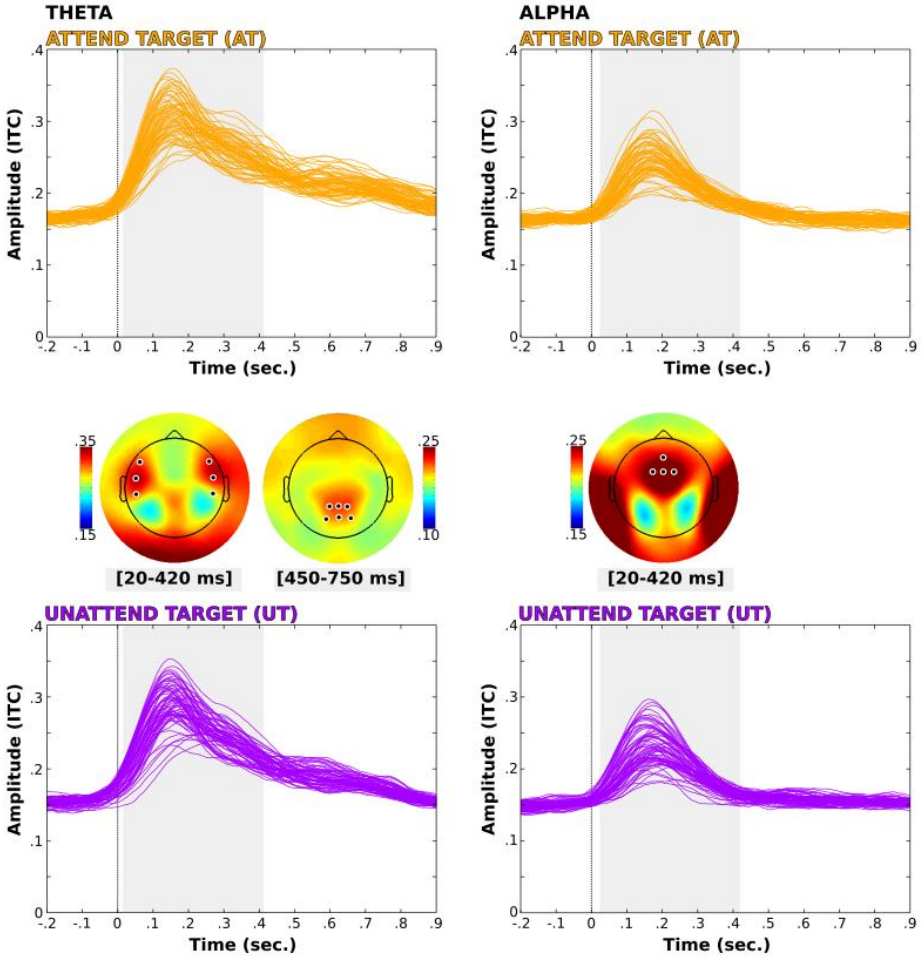
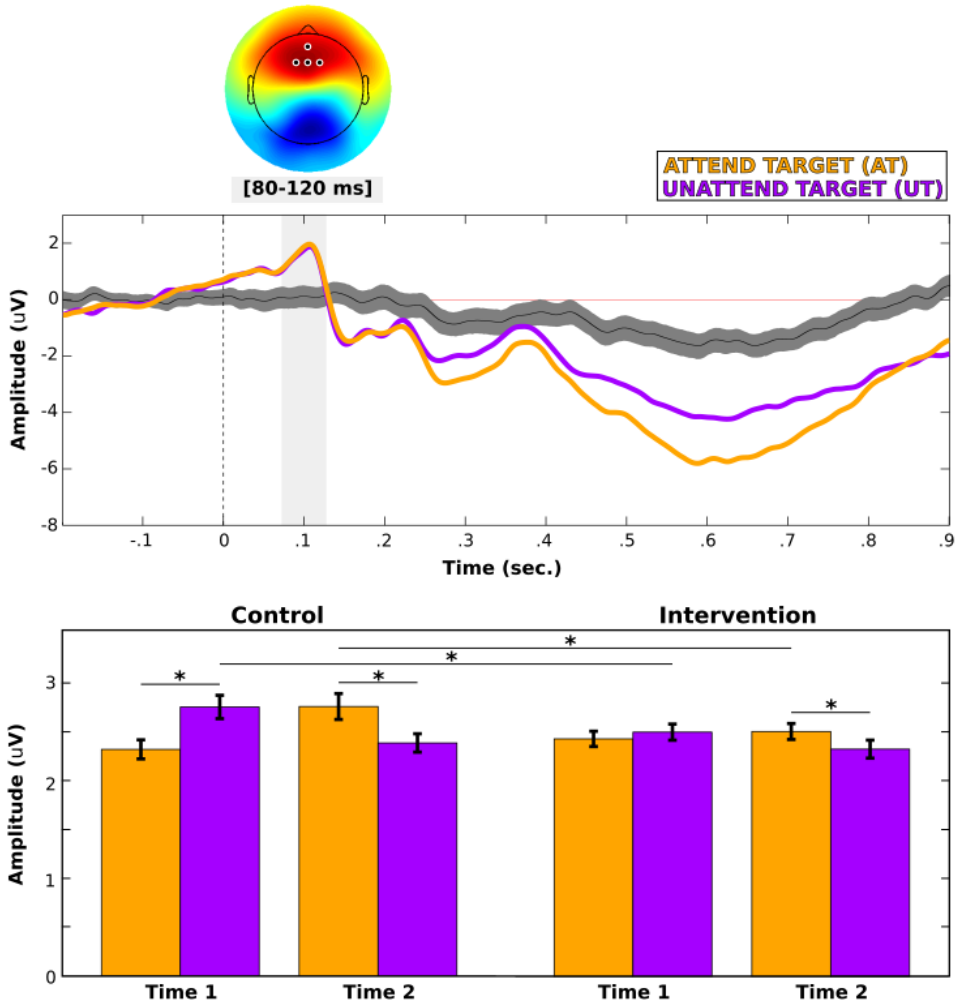


Figure 3

Summary of EFP Effects

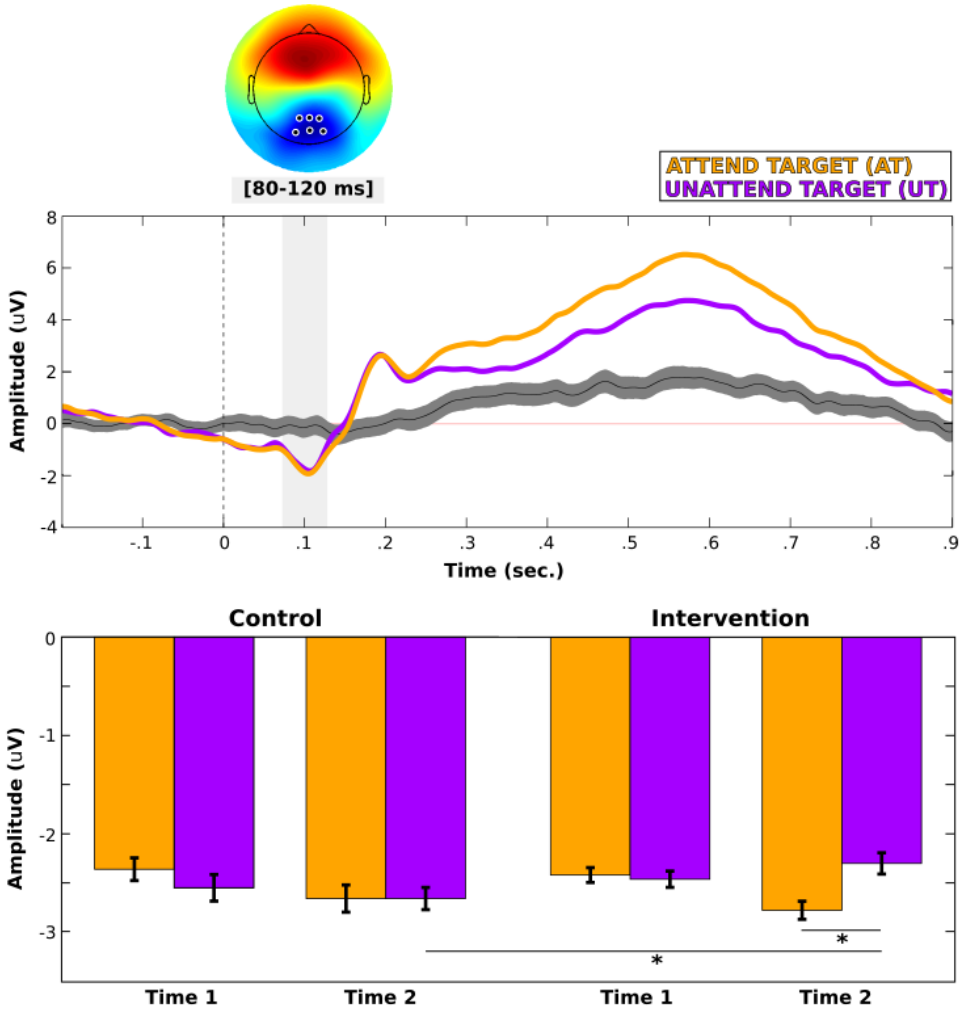


Note. The top panel displays grand-averaged ERP waveforms for the EFP component in Attend Target (AT; orange) and Unattend Target (UT; purple) conditions. Topography for the EFP component highlights positivity in the medial frontal regions. The bottom panel presents group means for AT and UT conditions at time 1 and time 2, between and within group.

*p <.05

Figure 4

Summary of N1 Effects

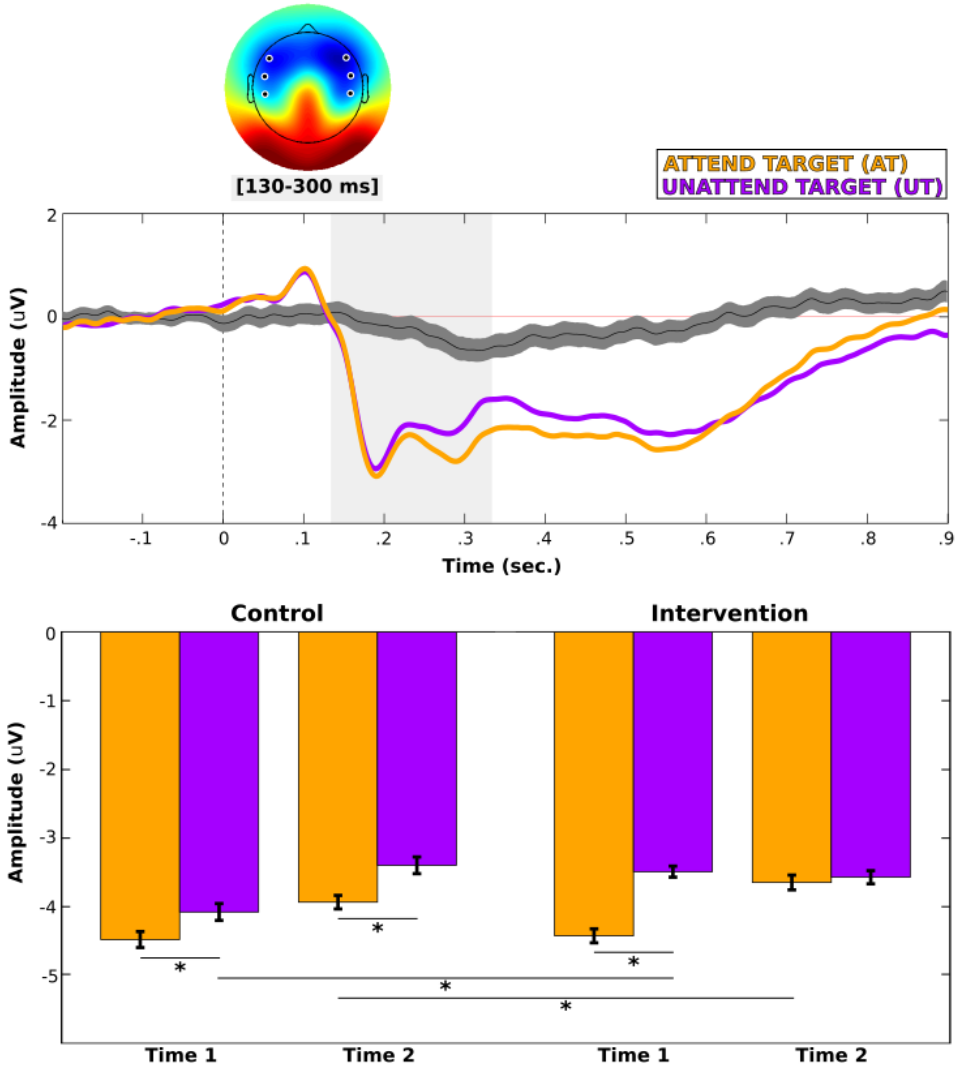


Note. The top panel displays grand-averaged ERP waveforms for the N1 component in Attend Target (AT; orange) and Unattend Target (UT; purple) conditions. Topography for the N1 component highlights negativity in the medial posterior regions. The bottom panel presents group means for AT and UT conditions at time 1 and time 2, between and within group.

*p <.05

Figure 5

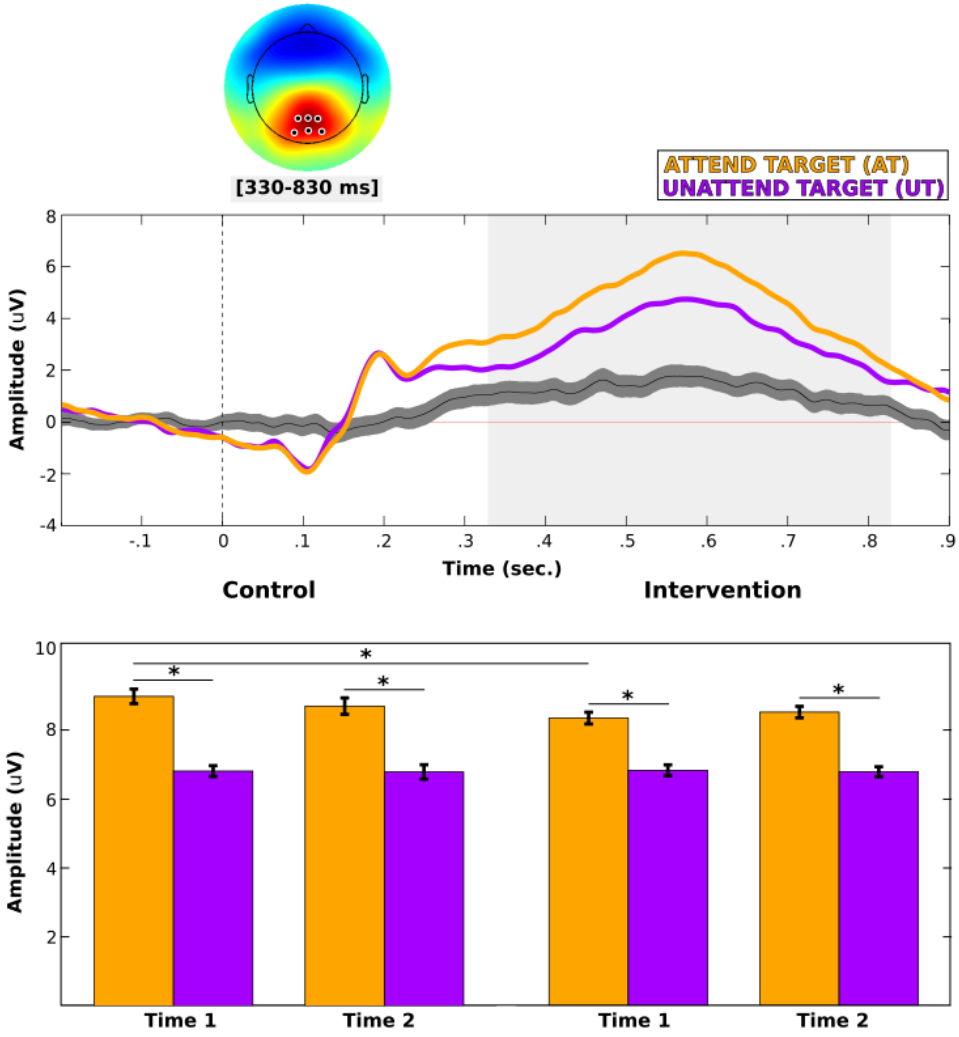
Summary of N2 Effects



Note. The top panel displays grand-averaged ERP waveforms for the N2 component in Attend Target (AT; orange) and Unattend Target (UT; purple) conditions. Topography for the N2 component highlights negativity in the bilateral frontal-temporal regions. The bottom panel presents group means for AT and UT conditions at time 1 and time 2, between and within group. *p <.05

Figure 6

Summary of P3 Effects

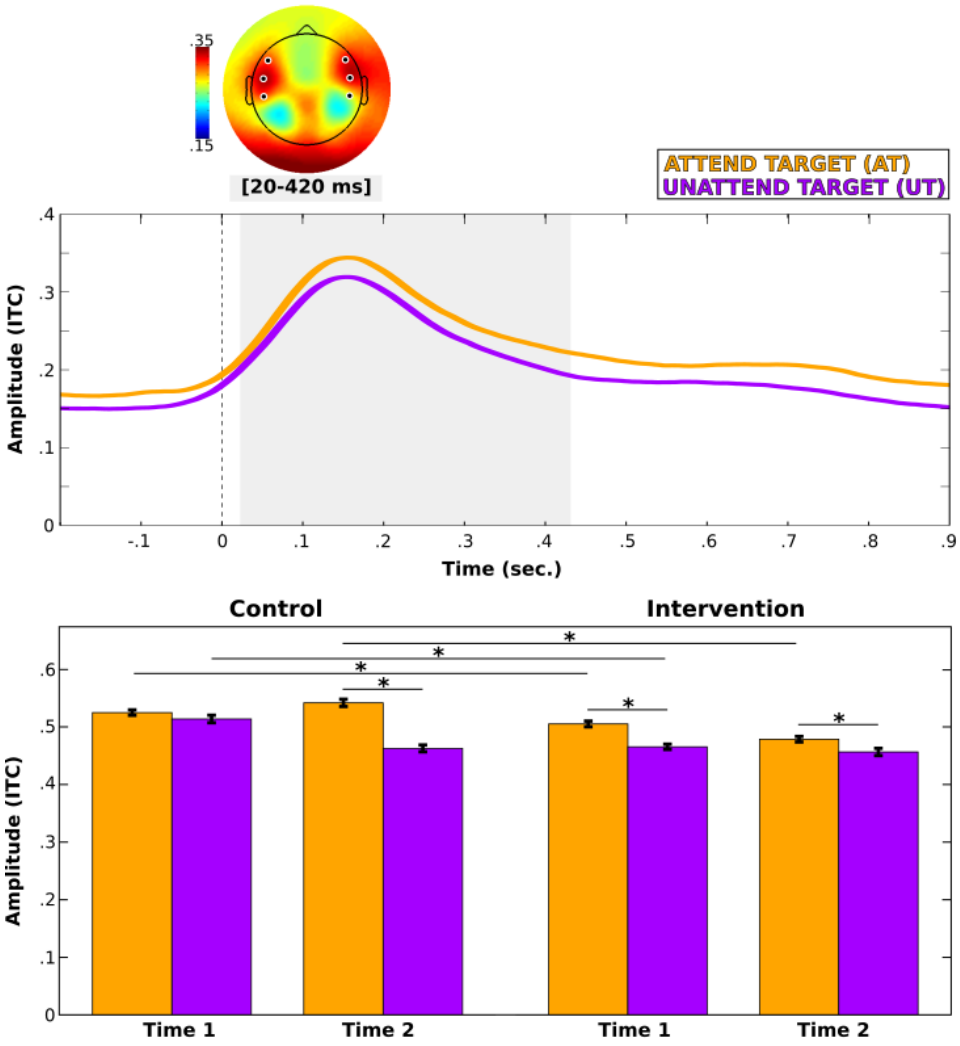


Note. The top panel displays grand-averaged ERP waveforms for the P3 component in Attend Target (AT; orange) and Unattend Target (UT; purple) conditions. Topography for the P3 component highlights positivity in the medial posterior regions. The bottom panel presents group means for AT and UT conditions at time 1 and time 2, between and within group.

*p <.05

Figure 7

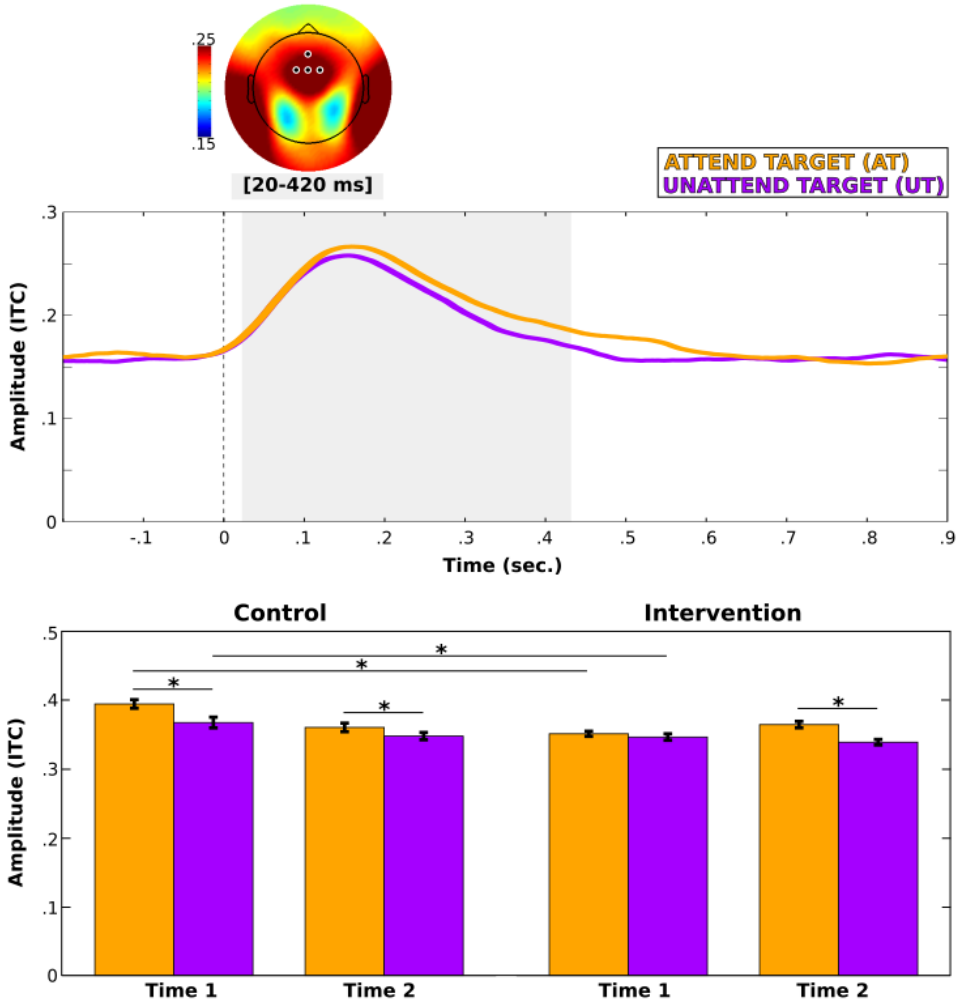
Summary of Theta ITC Effects



Note. The top panel displays grand-averaged inter-trial coherence (ITC) waveforms for theta-band activity in the Attend Target (AT; orange) and Unattend Target (UT; purple) conditions. Scalp topography highlights activation in the bilateral fronal-temporal regions. The bottom panel presents group means for AT and UT conditions at time 1 and time 2, between and within group. *p <.05

Figure 8

Summary of Alpha ITC Effects



Note. The top panel displays grand-averaged inter-trial coherence (ITC) waveforms for alpha-band activity in the Attend Target (AT; orange) and Unattend Target (UT; purple) conditions. Scalp topography highlights activation in the medial frontal regions. The bottom panel presents group means for AT and UT conditions at time 1 and time 2, between and within group.
*p <.05