

Sensory Entrainment, Paying Attention, and Keeping Beat: General Effects and Individual
Differences

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Abstract

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Neural entrainment is a phenomenon whereby neural oscillations adjust their frequency to synchronize with the periodic vibration of external stimuli. Research suggests that neural entrainment may help explain the relationship between music education and more optimal cognitive performance later in development. This dissertation tested whether sensory entrainment caused short-term cognitive and motor performance benefits in a young adult sample, and whether entrainment or performance were impacted by stimulus parameters like modality or rhythm or individual differences in attentional ability and music training. Participants (N= 47) were asked to report the extent and type (e.g. instrumental, vocal) of music experience and severity of ADHD symptoms, and then were exposed to repetitive 1.25-Hz or arrhythmic visual or auditory stimuli with interlaced Flanker test items, while EEG was recorded. At some points in the experiment participants were additionally tasked with tapping along to the 1.25-Hz beat through both beat stimuli and gaps. Some entrainment and performance effects were congruent with findings from prior literature, while many other hypotheses regarding entrainment effects were not supported. In terms of individual differences, neither music training nor ADHD symptoms impacted entrainment, but ADHD did impact the effects of entrainment stimuli on Flanker reaction time, with higher ADHD symptoms predicting worse performance during periods of rhythmic stimulation. Lastly and surprisingly, while neither entrainment, music training, nor ADHD symptoms impacted beat-keeping performance in general, ADHD symptoms predicted better beat-keeping during stimulus gap periods. Results in general paint a complicated picture of acute entrainment effects and individual differences.

General Audience Abstract

Jules Alex Faunce

Neural entrainment describes a phenomenon where brainwaves synchronize their rhythm with the rhythm of external stimuli. Research suggests that neural entrainment may help explain the why people with early and intensive music education develop better cognitive functioning. This dissertation tested whether sensory entrainment caused short-term cognitive and motor performance benefits in a sample of young adults, and whether entrainment or performance were impacted by things like type of stimulus (visual or auditory), stimulus rhythm, or participants' attentional ability and music training. Participants (N= 47) were asked to report the extent and type (e.g. instrumental, vocal) of music experience and severity of ADHD symptoms, and then were exposed to repetitive visual or auditory stimuli with interlaced attention test items, while brainwaves were recorded. At some points in the experiment participants were additionally tasked with tapping along to the stimulus beat, both when stimuli were presented and during gaps in stimuli. Some entrainment and performance effects were similar with findings from prior research, while many other hypotheses regarding entrainment effects were not supported. In terms of individual differences, neither music training nor ADHD symptoms impacted entrainment, but ADHD did impact the effects of entrainment stimuli on attention performance, with higher ADHD symptoms predicting worse performance during periods of rhythmic stimulation. Lastly and surprisingly, while neither entrainment, music training, nor ADHD symptoms impacted beat-keeping performance in general, ADHD symptoms predicted better beat-keeping during stimulus gap periods. Results in general paint a complicated picture of entrainment effects and individual differences.

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Introduction

Human cognition is profoundly rhythmic, as evidenced by the role of neural oscillations in perception of and attention to the environment. Neural synchronization to sensory stimuli may underlie temporally efficient processing of those stimuli, help explain individual differences in attention, and provide an avenue for enhancing attentional abilities. However, effects of entrainment on cognitive performance may vary by duration of exposure, entrainment-task phase alignment, and individual differences in attentional abilities and musical training. This dissertation fills gaps in the literature about whether, when, and for whom entrainment training may improve acute attentional performance in a young adult sample.

Entrainment exists in many physical and biological response systems (Rosenblum & Pikovsky, 2003). In electroencephalogram (EEG), entrainment manifests as steady-state evoked potentials (SSEPs) in a frequency corresponding directly (or at least linearly) to the stimulation frequencies (Picton et al., 2003). Stimuli used to induce entrainment are exogenous, but maintenance of entrainment can be endogenous as well (e.g. mentally tracking an imagined beat; Nozaradan et al., 2012b; Nozaradan et al., 2016; Tal et al., 2017). The latter is thought to involve more top-down attentional processes than the former (Nozaradan et al., 2016; Tal et al., 2017).

Research in neural entrainment helps demonstrate the causal relationship between rhythms and cognitive states (Herrmann et al., 2016), and supports the role of oscillations in promoting more temporally-efficient packaging and transmission of information (Buzsáki et al., 2013). Consequently, neural entrainment manipulations have enjoyed some popularity as potential methods for improving cognition. This paper begins with an overview of metrics, methods, and effects of entrainment, then outlines study methods and findings of my study.

Review of Literature

Calculating Entrainment

Successful entrainment involves two components: an increase in signal strength (power or amplitude) in the frequency corresponding to the stimulus frequency, and phase alignment of this activity to the entraining stimulus (Hanslmayr et al., 2019; Herrmann, 2001). Signal strength is often calculated by frequency tagging, i.e., measuring overall amplitude or power of steady-state evoked potentials in the same frequency as the entraining stimulus (Gomez-Ramirez et al., 2011; Nozaradan, 2014). Phase-locking, meanwhile, can be operationalized as intertrial phase coherence (ITPC; Gray et al., 2015; Rajendran & Schnupp, 2019; Spaak et al., 2014; Vernet et al., 2019). ITPC is a transformation of the responses' angular deviation from the expected phase of the wave. Values range from 0 to 1, with higher values showing higher coherence (Cohen, 2014). Although frequency-tagging methods are more common in entrainment research, some argue it is better to measure entrainment in a way that takes both signal strength and phase-locking measures into account (Rajendran & Schnupp, 2019). It is possible that phase alignment and magnitude of entrainment reflect different time courses and features of electrophysiological behavior.

Producing Entrainment

Primary methods of inducing entrainment fall into one of two categories: optogenetic (direct) stimulation of particular brain regions using transcranial magnetic stimulation or transcranial alternating current stimulation (Albouy et al., 2017; Neuling et al., 2012), or sensory stimulation (Spaak et al., 2014). These methods have similar behavioral effects but differ in anatomical precision (favoring optogenetic stimulation) and ease of implementation (favoring sensory entrainment). While optogenetic stimulation is useful, sensory entrainment will be

discussed in greater detail in this dissertation due to its relatively easier and cheaper implementation.

Sensory entrainment methods can differ in the amount of active engagement needed from the research participant. Passive stimulation, like rhythmic sensory stimulation (RSS; e.g. Stefanics et al., 2010) and binaural beats (e.g. Colzato et al., 2017), does not require any active participation from the person exposed to the stimuli. More active tasks, meanwhile, require some engagement with the stimulus rhythm (Albouy et al., 2017; Gomez-Ramirez et al., 2011; Nozaradan et al., 2016). In one clever application by Nozaradan and colleagues (2016), participants were instructed to follow along with delta frequency beats by tapping their fingers, through both actual beats and through occasional gaps in stimulation. In addition to being more engaging than passive sensory entrainment, the task in Nozaradan et al. (2016) was able to examine entrainment in different ways. Participants' synchrony with stimuli could be measured in a neural sense (EEG activity) and in a behavioral sense (beat-keeping task performance). The researchers were also able to examine delta power during actual beats (exogenous entrainment) and during gaps (endogenous entrainment; Tal et al., 2017). Results showed that optimal beat-tracking and entrainment occurred with inter-stimulus intervals between 500 and 900 ms, or 1.1 to 2 Hz. Moreover, participants with better beat-keeping task performance showed a smaller difference in entrainment between stimulus and gap trials.

The Physiology of Sensory Entrainment

Synchronization between neural firings and external stimuli is seen in both cortical and subcortical regions of the brain (Coffey et al., 2016; Hartmann & Weisz, 2019; Tzounopoulos & Kraus, 2009). Early sensory processing of auditory rhythm involves a frequency-following response in the brainstem, and also perhaps some early sensory cortex activity (Coffey et al.,

2016; Tzounopoulos & Kraus, 2009). Individual differences in the frequency following response may relate to bottom-up entrainment and perceptual acuity (Moreno & Bidelman, 2013). Longer latency cortical entrainment, on the other hand, may reflect more endogenous beat-tracking (Hanslmayr et al., 2019). This component of entrainment is more commonly studied than the frequency-following response, and is measured by steady state evoked potentials (SSEPs) in the entrainment frequency. This entrainment typically builds to full capacity over several cycles (Regan, 1989), and then continues for a few cycles after the stimuli are withdrawn (called an entrainment echo; Halbleib et al., 2012; Hanslmayr et al., 2019). SSEPs are also strongest in the sensory cortical areas related to the modality of the stimulation (e.g. frontocentral for audition, occipital for vision; Nozaradan et al., 2012a), but are also seen in cross-modal areas and in the frontal cortex (Bauer et al., 2020; Driver & Noesselt, 2008; Schroeder & Foxe, 2005).

Effects of Entrainment

The effects of sensory entrainment depend on the frequency of stimulation. When discussing “frequency”, it is important to clarify whether one is referring to the stimulus frequency, or the frequencies of oscillations affected by that stimulation, as the latter can be multifaceted and interactive. Stimulation in one frequency can cause SSEPs in both the stimulation frequency (fundamental frequency), and also in whole-number multiples of that frequency (i.e. harmonics; Picton et al., 2003). Another important physiological outcome from entrainment is increases in cross-frequency coupling, wherein the oscillations of a higher frequency nest within and lock phases with the oscillations of a lower frequency (Gomez-Ramirez et al., 2011; Lakatos et al., 2008; Wilson & Foxe, 2020). From a network perspective, lower frequency oscillations have been related to longer-distance, area-to-area interactions, and higher frequency oscillations to more local neuronal communication (von Stein et al., 2000).

Interactions among these bands may help coordinate their activity (e.g., Palva & Palva, 2007; for a review, see Canolty & Knight, 2010). Relatedly, greater coupling of alpha and low gamma (e.g. 36 Hz) amplitude to delta phase relates to better attentional performance, both theoretically (Canolty & Knight, 2010; Palva & Palva, 2007) and empirically (Gałol et al., 2018; Wilson & Foxe, 2020).

Effects of entrainment on the physiological and behavioral concomitants of attention can occur from stimulation in a variety of frequencies. The frequency band of particular interest in this dissertation is delta (1-4 Hz). While delta is classically associated with sleep (Steriade et al., 2001), more recent research highlights the importance of visual, auditory, and somatosensory delta while awake (Hromádka et al., 2013; Okun et al., 2010; Zhou et al. 2014). Relatedly, auditory stimulation in the delta range is associated with better task expectancy and faster reaction times during an attention task (Stefanics et al., 2010), as well as better speech perception (Boucher et al., 2019). Visual tasks delivered in delta intervals are associated with increased phase-amplitude coupling between delta and alpha (Gomez-Ramirez et al., 2011; Lakatos et al., 2008; Wilson & Foxe, 2020), which in turn correlates with better attention task performance (Wilson & Foxe, 2020). These effects highlight the role of delta oscillations in cyclic attention (Harmony, 2013). Theta (4-7Hz) entrainment is most classically associated with working memory effects (Albuoy et al., 2017); however, one study has found better attentional performance from frontoparietal theta stimulation (Huster et al., 2012). Alpha RSS (10 Hz) has been associated with better perceptual performance (Spaak et al., 2014), as well as better memory performance in older adults (Williams et al., 2006). The role of alpha in attention is inhibitory, and therefore alpha activity may be in antiphase with the attended stimulus onsets and with the peaks of other rhythms (Gomez-Ramirez et al., 2011; Strauß et al., 2014). Research

exploring the effects of beta stimulation (13-30Hz) have mostly used optogenetic stimulation rather than sensory stimuli. Nonetheless, research has shown effects of beta entrainment on attention, with 30 Hz transcranial magnetic stimulation (TMS) in the frontal eye field region causing improvements in visual attention (Vernet et al., 2019). The last band to consider is gamma (30-100 Hz), which is slightly more complicated. Sensory gamma entrainment has improved neurocognitive symptoms associated with Alzheimer's disease (Yang et al., 2021), stroke (Rodriguez-Fornells et al., 2012), and traumatic brain injury (Bradt et al., 2010). These effects may be especially enhanced with frequencies of 40 Hz and higher, which are particularly involved in fine-grained working memory and attention (Jensen et al., 2007).

General Effects.

Both behavioral and cortical effects of sensory entrainment tend to be tested in the same sensory modality as the entraining stimulus (Gomez-Ramirez et al., 2011; Nozaradan et al., 2012b; Nozaradan et al., 2016; Wilson & Foxe, 2020). Entrainment-like effects from sensory stimulation can be seen in primary cortical areas other than those associated with the entraining stimulus modality (Bauer et al., 2020; Driver & Noesselt, 2008; Schroeder & Foxe, 2005), but those are beyond the scope of this paper.

In terms of acute cognitive effects of entrainment stimulation, performance is best when task stimuli are in phase with entrainment stimulus onsets (Mathewson et al., 2010; Ng et al., 2012; Stefanics et al., 2010). Moreover, rhythmic tasks may be more effective than passive rhythmic stimulation at producing entrainment effects because they engage more attentional resources and recruit greater swaths of cortex (Albouy et al., 2017; Bugos, 2010). Work by Spaak et al. (2014) further suggests that enhancements in cognitive performance can outlast the

entraining stimulus by several cycles, coinciding suggestively with the entrainment echo period mentioned earlier.

Individual Differences

Not everyone entrains to rhythmic stimulation equally efficiently. Two variables that may impact one's ability to entrain are prior history of musical training (Albouy et al., 2017; Miendlarzewska & Tros, 2014; Nozaradan et al., 2012b) and attention deficit (Calderone et al., 2014). The relationship between musical training and entrainment is straightforward, with more musical training related to better behavioral entrainment and neural entrainment (Nozaradan et al., 2016). Some have argued (Miendlarzewska & Trost, 2014) that practice with auditory entrainment may mediate the robust relationship between musical training and better cognitive functioning (Criscuolo et al., 2019; Hanna-Pladdy & MacKay, 2011; Vuust et al., 2012), and perhaps especially auditory memory and selective attention (Peretz and Zatorre, 2005). Results of cross-sectional studies in this field should be viewed with caution though, given since music education, socioeconomic status, and cognitive functioning are highly intercorrelated (Criscuolo et al., 2019).

The relationship between attentional ability and entrainment is slightly more equivocal. An intuitive argument is that since entrainment to stimulus periodicity helps people to parse information better, people who pay attention better will show higher magnitude of entrainment. Somewhat in support of this hypothesis, people with Attention Deficit Hyperactivity Disorder (ADHD) have altered neural oscillations at rest (Arns et al., 2013) and during attentional tasks (Lenz et al., 2010; Missonnier et al., 2013), and show greater difficulties with beat detection than neurotypical people (Puyjarinet et al., 2017), both of which may in turn predict deficits in entrainment (Calderone et al., 2014). However, it is also possible that since people with ADHD

show lower baseline power in oscillations related to attention (e.g. beta; Arns et al., 2013), they also have more room for improvement due to stimulation. One study by Albuoy et al. (2017) supported this perspective somewhat, finding that worse baseline attentional performance predicted stronger performance benefits from RSS. Given prior evidence that successful ADHD treatments tend to alter oscillations (Gevensleben et al., 2009; Lofthouse et al., 2012), it follows that entrainment-based methods of altering neural oscillations may improve attention performance in people with ADHD (Calderone et al., 2014). Research has shown that audio-visual entrainment over multiple sessions improves ADHD symptoms, particularly in children (Joyce & Siever, 2000; Laffere et al., 2021), but research testing acute or long-term effects of sensory entrainment on adult ADHD symptoms is still lacking.

The Study

This study was the first to simultaneously examine entrainment and cognitive performance as a function of entrainment stimulus modality, task engagement (active vs passive methods), and level of analysis (general effects and individual differences). Participants were exposed to repetitive trains of stimuli that differed by stimulus modality (visual or auditory), rhythmicity, and task demands (sham RSS, RSS, or rhythm task). Participants were tested for attention performance and entrainment effects (amplitude and ITPC) throughout the experimental session. Performance on the rhythm task (tapping accuracy and variability) was also analyzed.

Study hypotheses were as follows:

- RSS and rhythm task conditions would cause stronger entrainment and better attentional performance than sham RSS did.

- The beat-keeping task would cause stronger entrainment and better attentional performance than RSS did.
- Prior history of musical training would be associated with stronger entrainment and better beat-keeping performance, even after controlling for SES.
- Attentional performance would improve after short-term entrainment using RSS and beat-keeping tasks (but not after sham RSS).
- Attentional performance would be better when attention task stimuli were delivered in phase with the entrainment stimuli.
- Rhythm task performance would be better in people who show higher endogenous entrainment during this task.

Additional tests explored effects of stimulus modality and the impact of ADHD symptom endorsement on entrainment and performance in both attention and beat-keeping tasks.

Method

Participants

The aim was to collect 60 young adult participants with usable data, based on power analysis with results from Nozaradan et al., 2016. Participants consisted of undergraduate students and age-matched non-students, recruited using online advertisements and fliers to participate in exchange for either course credit or monetary compensation. Two hundred and forty-seven (247) participants filled out an initial online survey. Of these, I invited seventy-nine eligible participants to participate in the lab session, selecting them in a manner to ensure similar numbers across all combinations of main demographic factors (low versus high attentional difficulty, and low vs high musical training). Of these participants' sessions, three were canceled due to crania that were too small for the sensor strips, one was canceled due to failure to control

impedance in any channel, twenty-three were excluded from the current analyses because they were missing too much physiological data for reliable mean imputation and analysis (i.e. fewer than half of channels, or missing over 20% data from good channels), and three were excluded because they had missing behavioral data. This left 47 participants with usable data for the EEG analyses. To create relatively equal groups for comparison, I defined high music training as having more than 3 years of experience playing one or more musical instruments (22 in low-music group, 25 in high-music group).

Measures and Stimuli

Demographic Questionnaire

The demographic questions asked participants about race, ethnicity, gender, handedness, socioeconomic status (SES), and musical training experience. The SES measure consisted of a slider scale for family income, and a checkbox for the highest educational attainment of the respondent's parents. Highest educational attainment was converted from a category measure into the associated number of years in school, according to guidelines by The National Committee on Vital and Health Statistics (NCVHS; Carr, 2012). Questions about musical experience, meanwhile, asked participants about the number of years of regular practice, as well as type of musical training experience (i.e. no experience, instrumental experience only, vocal experience only, or both instrumental and vocal training).

Neurological Status Questions

Questions regarding neurological status asked participants to endorse any neurological or neuropsychological conditions that applied to them, as well as whether they were currently taking stimulant medication (e.g. Adderall).

Attention Deficit Symptoms

Attention deficit symptoms were calculated from responses from the Adult ADHD Self-Report Scale (ASRS; Kessler et al., 2005). Participants report the prevalence of different symptoms over a 6-month span, using the response options *never*, *rarely*, *sometimes*, *often*, or *very often*. Item responses that pass predetermined thresholds for clinical relevance are summed to equal a total score with a possible range of 0-18. Of these 18 items, 6 of them were designed by Kessler (2005) for use as a screener for assigning individuals into strata based on symptom severity. Recruitment efforts for the in-lab portion of the study prioritized recruiting participants with screener scores above 3 out of 6, as these participants were expected to have a higher-than-average attrition rate. See Appendix B for a more detailed list of ASRS items.

Hearing Test

I tested hearing by delivering 30 dB[A] tones at frequencies ranging from 8k to 22k Hz and asking the participant to correctly identify when they hear the tones by raising their hand.

Electroencephalogram

We recorded EEG at 256 Hz sampling rate using the B-Alert X24 wireless headset (Advanced Brain Monitoring; Carlsbad, CA), a device with 20 electrodes configured in the standard 10-20 system. Electrode sites on the scalp were lightly abraded and scrubbed with cotton soaked in rubbing alcohol to reduce impedance. Researchers then saturated foam electrode pads with Synapse conductive paste (Kustomer Kinetics, Arcadia, CA) before placing sensor head strips on the scalp. Sensor head strips were available in three different sizes (small, medium, and large), and the size for each participant was selected based on head measurements according to manufacturer instructions. We placed reference electrodes on the right and left mastoid bones. To mitigate issues from Bluetooth interference disrupting the B-Alert system's

recording, I wallpapered low-impedance areas of the study room with aluminum foil, and the research team reminded participants to turn off Bluetooth on their personal devices before we began with the recording.

Activity from 20 scalp channels was monitored in real time using B-Alert Live software (Advanced Brain Monitoring; Carlsbad, CA). After recording, I marked outlier data (e.g., single-channel outliers, peaks 5 standard deviations above the mean, sudden precipitous and long-lasting drops of signal, etc.) for replacement and when appropriate, imputed missing data using mean imputation. I then decomposed channel data using independent component analysis, extended-Infomax method, and manually removed eyeblink and other muscle artifact components from the data using the EEGLAB Toolkit (Delorme & Makeig, 2004) for Matlab version 2022.1 (Mathworks; Natick, Massachusetts). After this I band-pass filtered the ICA-pruned EEG data between .5 and 120 Hz using the finite impulse response method.

For the 1.25-Hz entrainment measures, data from all channels were averaged, and then band-pass filtered from 1.249 to 1.251Hz. SSEP amplitude and latency were then calculated in the time domain, based on peak voltage between -200ms and +200ms relative to the 1.25 Hz beat generated by the entrainment stimulation. Latency was converted to phase angles (expressed in radians) of length 1, and intertrial phase coherence was calculated as the absolute value of the vector length of the averaged angle vector, according to the following formula:

$$ITPC(f_o, t) = \frac{1}{N} \left| \sum_{k=1}^N e^{i\phi^k(f_o, t)} \right|$$

where n is the number of trials, e is Euler's number, i is an imaginary number whose square root equals -1, and ϕ^k is the phase angle.

Stimuli

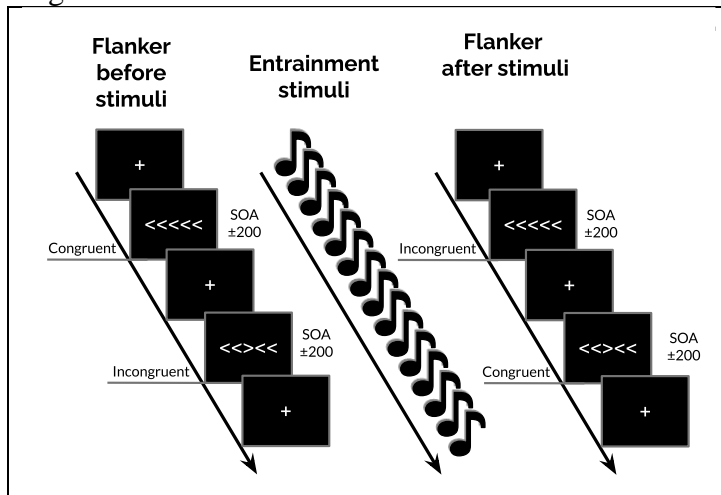
All stimuli were delivered and their onsets recorded using python code in Psychopy software.

Entrainment Stimuli. For both the RSS and active entrainment conditions, stimulus design was informed by prior work in the field of sensory entrainment (Gomez-Ramirez et al., 2011; Nozaradan et al., 2016; Spaak et al., 2014). All visual and auditory stimuli were presented in 400 ms bursts with 10 ms rise and fall times. Non-sham stimuli were spaced exactly 800ms apart. Sham stimuli had intervals ranging from 450 to 1150 ms, in a discrete uniform distribution of values that differed in increments of 50ms. Visual stimuli consisted of white circle shapes presented binocularly on a black monitor screen in between periods with a fixation cross. Based on prior work (Nozaradan et al., 2016; Stefanics et al., 2010), auditory stimuli were 1000-Hz pure tones delivered in 70 dB SPL, constructed using Audacity version 3.0.5 (Muse Group; Limassol, Cyprus), and delivered binaurally through over-ear headphones.

Flanker Task. I measured selective attention performance using a more granular adaptation of the Eriksen Flanker Test (Eriksen & Eriksen, 1974). A visualization of this procedure is presented in Figure 1. For each Flanker test item, participants were instructed to quickly indicate using arrow keys whether a central chevron shape in a line of chevrons (“<” or “>”) pointed left or right. For congruent Flanker stimuli, the central chevron was facing the same direction as the chevrons surrounding it. For incongruent Flanker stimuli, the central chevron was facing in the opposite direction of the chevrons surrounding it. Flanker items were delivered in pairs of congruent and incongruent stimuli, with stimuli in the pairs spaced 1600 ms apart and with counterbalanced order of congruent vs incongruent stimuli in each pair. Each train of 15 entrainment stimuli had one pair of Flanker stimuli delivered before it, and one pair of Flanker

stimuli after it, to test for improvements in attentional performance after the entrainment stimuli. Individual Flanker stimuli were delivered with onset asynchronies of -200ms, 0ms, or 200ms relative to the anticipated 1.25-Hz beats created by the entrainment stimuli, to test for entrainment phase effects on performance as referenced in prior work (Stefanics et al., 2010). Altogether, each participant was presented with 120 Flanker stimulus pairs, represented equally among the two stimulus modalities and three entrainment stimulus conditions. The Flanker effect, measuring attentional performance deficits while responding to incongruent stimuli, was calculated for each Flanker pair by subtracting the reaction time of the response to the congruent stimulus from the reaction time of the response to the incongruent stimulus. Only correct responses were used for analysis.

Figure 1. *Stimuli used in Flanker task*



Note. Flanker stimulus pairs, consisting of one congruent Flanker and one incongruent Flanker, were presented before and after each train of entrainment stimuli, to test for changes in overall reaction time and Flanker effect (RT incongruent – RT congruent) changes due to entrainment stimulation. Congruent and incongruent stimuli were counterbalanced by order. Stimulus onset asynchrony (SOA) is expressed as milliseconds offset (-200, 0, or 200) relative to entrainment rhythm.

Rhythm Task. During the rhythm task, participants were asked to tap along with the beat of entrainment stimulation using the space bar of a computer keyboard, mimicking the methods from Nozaradan et al. (2016). Accuracy was defined in similar fashion as intertrial phase coherence, as the absolute value of the mean radial vector length of taps relative to beat stimuli. Precision (or more appropriately, imprecision or response variance) was defined as mean circular

variance of taps relative to beat onsets. SSEPs during gaps in stimulation measured endogenous entrainment, while SSEPs during actual beats measured exogenous entrainment.

Procedure

The initial survey recruitment was posted on Virginia Tech's online research participation portal (Sona Systems; Harjumaa, Estonia). The survey contained the demographic and neurological status questions, as well as the Adult ADHD Self-Report Scale.

In-lab exclusion criteria included screening positive for COVID-19 prior to or during the experimental session or failing the in-lab hearing test. After placing EEG sensors, we commenced recording when at least six channels had impedances below 40kOhms (we were not able to do better than this, due to poor impedance control of the electrode surfaces over multiple uses). The experimental procedure, totaling 35 minutes, consisted of a control condition, followed by one round of sham RSS, one round of true RSS, and one round of rhythm task for each of the two stimulus modalities (auditory and visual). Stimulus modality was counterbalanced such that half of participants had 3 visual stimulus conditions followed by 3 auditory stimulus conditions, and the other half had 3 auditory stimulus conditions followed by 3 visual stimulus conditions. In total, the experiment thus consisted of 7 within-person stimulus conditions, each lasting 5 minutes total and consisting of a 12-second habituation and training period, 228 seconds of stimulation, and 60 seconds of rest. Each stimulation combination consisted of 10 reps of 15 entrainment stimuli, with pairs of Flanker task items before and after entrainment stimuli, as illustrated in Figures 2 and 3 below.

Figure 2. *Experimental procedure*

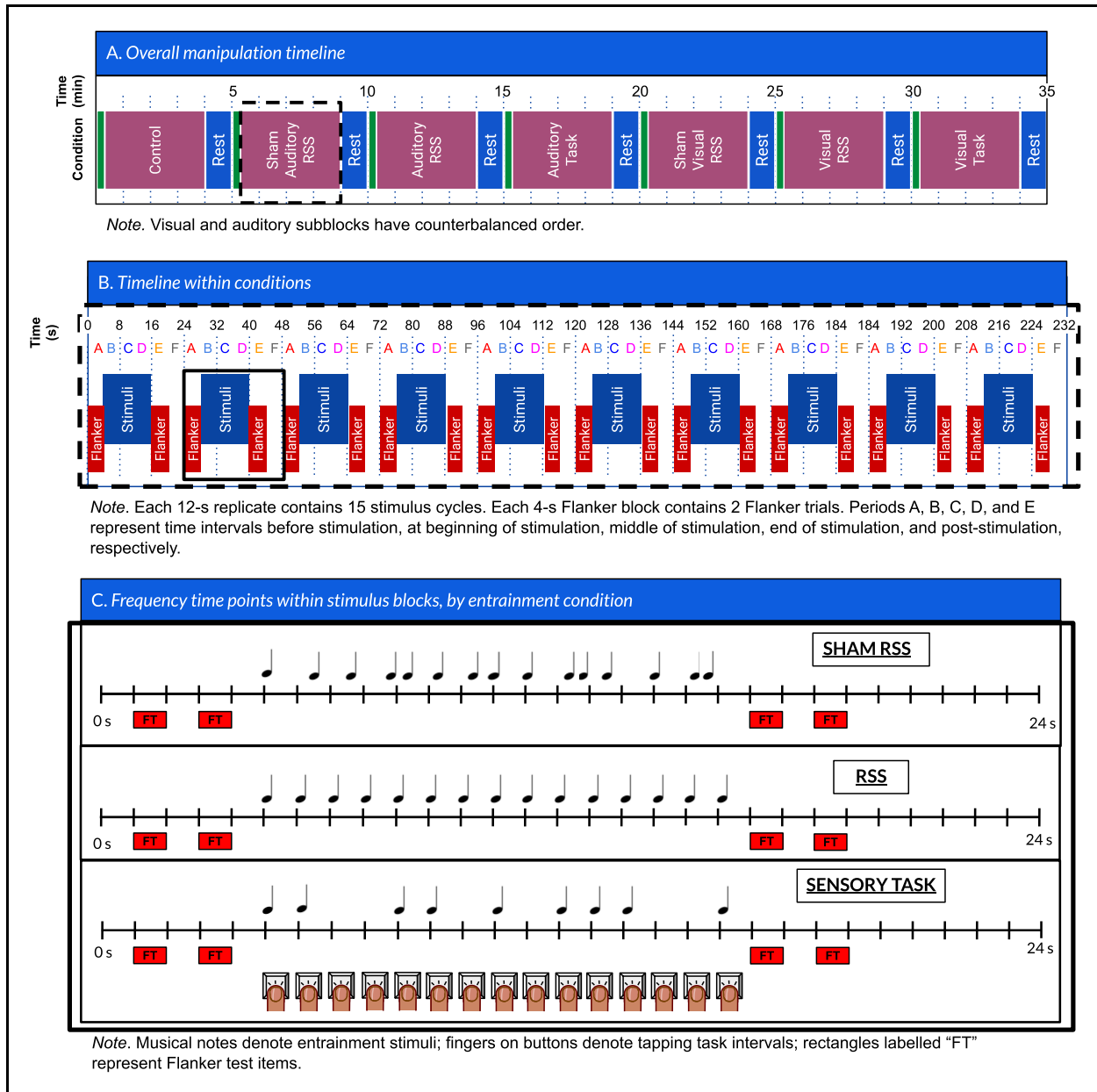


Figure 3. *Within-subject treatment combinations*

Control	Sham RSS					RSS					Task													
	Visual		Auditory			Visual		Auditory			Visual		Auditory											
A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E

Note. A= Pre-entrainment; B= first 5 entrainment stimuli; C= second 5 entrainment stimuli; D= third 5 entrainment stimuli; E= Post-entrainment. Each condition combination contains 25 1.25Hz frequency-time points.

Analysis

To reduce type 1 error inflation due to the high number of time points for each person, I conducted all analyses using mixed models with nested random effects. Due to multiple within-subject variables, effects of study manipulations could be tested at a variety of levels, from the more granular focus of individual time point and stimulus stage to the whole block of stimuli. For each main analysis, instead of analyzing all factors together in full factorial, I built the model gradually and deliberately by first examining random effects of different within-person variables nested within individuals before adding other variables to the model.

Entrainment. For analysis using SSEPs, I modeled within-person effects of block (2), entrainment condition (3), replicate (10), stage of stimulation (5), and trial (25). After inspecting these within-participant effects, I intended to pare down the model to only the most relevant data and variables before adding individual difference variables to the model. EEG from the control period was too noisy to analyze with the methods used in this project, so I did not conduct any comparisons between study conditions and control.

In the full model, I used a priori contrasts to test for differences in amplitude and ITPC between Sham RSS and rhythmic conditions (testing the impact of stable stimulus rhythm), and between RSS and rhythm task (testing the impact of task engagement). Sensory entrainment amplitude and ITPC during the rhythm task were also analyzed in a mixed model as a function of stimulus type (gap or stimulus) nested within participant, to test the hypothesis that entrainment during the rhythm task was higher during stimulus trials than during gap trials.

Flanker Task Performance. I first fit a mixed model predicting Flanker reaction time from block, entrainment condition, pre- vs post-stimulation, Flanker offset (“synchronized” or “offset” relative to the anticipated 1.25-Hz rhythm), pair order (which stimulus in a pair came

first), direction of correct answer (left or right), and stimulus congruency (whether the attended-to stimulus in the Flanker was congruent with its background). A priori contrasts between entrainment conditions tested hypotheses that Flanker task performance would be better after rhythmic stimulation than after nonrhythmic stimulation, and that Flanker task performance would be better after rhythm task than after RSS. Another contrast from pre- vs. post-stimulation tested the hypothesis that Flanker reaction would decrease after exposure to entrainment stimuli. For the full model, I retained variables estimating Flanker reaction time, Flanker effect, and changes after entrainment stimulation, as well as any variable with both significant variance components and significant fixed effects. I then added between-person effects of participant's amount of musical training (low or high) and ASRS score (low or high), on their own and in interaction with the within-person variables. The model was able to estimate variation in both the raw Flanker reaction times, and the Flanker effect (congruency effects).

Rhythm Task Performance. Because the first 2 trials always consisted of real stimuli rather than gaps, the effects of Trial and Stimulus Type were somewhat confounded with one another, so I analyzed reaction time data only using trials 3-15. Reaction time data were converted to phase angles and angular vector lengths relative to stimulus onsets, and then beat-keeping accuracy and variability were calculated respectively based on mean and variance of these vector lengths for each combination of participant, block, replicate, and stimulus type (stimulus or gap).

Similar to the SSEP and Flanker analyses, the models predicting accuracy and variance on the rhythm task were built incrementally starting with within-person variables (block, replicate, and stimulus type) before adding individual difference variables of interest.

Rhythm task accuracy and variance during gap periods were then analyzed in a priori contrasts to test for the impact of endogenous entrainment amplitude and ITPC on beat-keeping performance.

Results

Descriptives

Sample demographic statistics are displayed in Table 1 and Table 2. The sample skewed white (72%), cisgender (100%), female (64%), and undergraduate (68%). Twelve participants (26%) had ASRS screener scores above the clinical threshold, compared to 47% of initial survey respondents. Years of music experience were very positively skewed, which further validated the decision to operationalize musical training in terms of discrete levels.

Table 1. *Group frequencies*

<u>Sex</u>	<u>Race and ethnicity</u>	<u>Music training</u>	<u>Parents' education</u>
Female 30	White non-Hispanic 34	Instrumental only 18	High school 4
Male 17	Non-white Hispanic 4	Instrumental & vocal 14	Some college 12
	Black 3	No music training 14	2-year degree 2
	Asian 3	Vocal only 1	4-year degree 9
	Asian & White 2		Some grad work 1
	White Hispanic 1		Master's degree 13
			Doctorate 6

Table 2. *Sample descriptives*

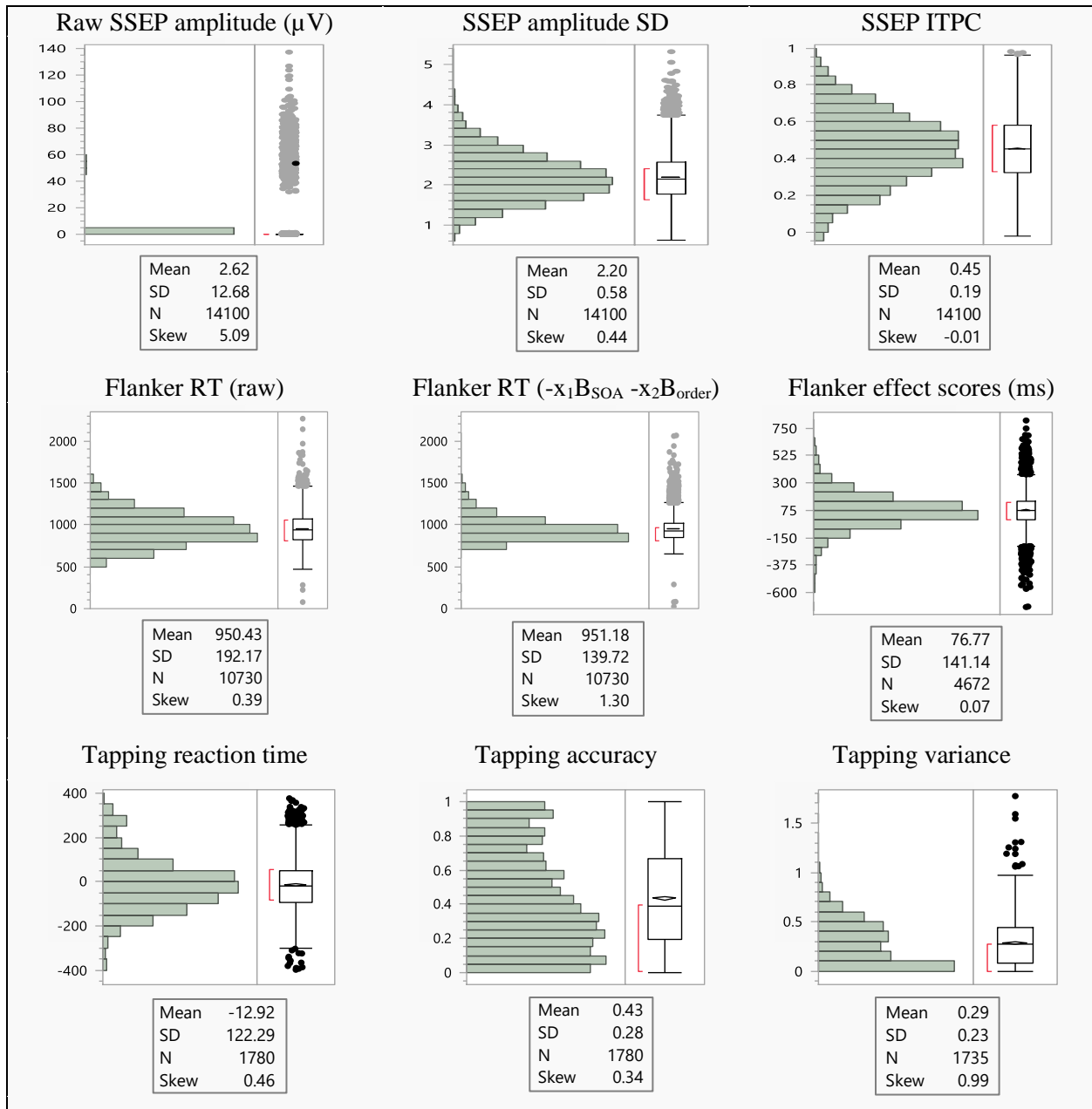
	<u>Age (years)</u>	<u>Parents' education (years)</u>	<u>Household income</u>	<u>Music training (years)</u>	<u>ASRS score</u>
N	41	46	47	47	47
Mean	20.24	8.13	\$150,532	5.74	5.87
Median	19	8	\$140,000	5	6
SD	2.48	2.44	\$81,179	5.79	3.77
Skew	1.97	0.02	0.51	1.12	0.09

Note. Years of education are calculated based on the typical number of years to achieve particular degrees (e.g. high school diploma = 4 years, doctorate = 12 years). ASRS = Adult ADHD Self-Report Scale.

Multiple logistic regression analyses suggested that group counts did not differ across levels of relevant categorical study variables (stimulus presentation order, musical training groups, ADHD severity groups, gender, or race). More years of parent's education predicted higher family income ($r = .48$, $t(46) = 3.65$, $p < .001$), but neither household income nor parental education level predicted the number of years that participants reported practicing music (income $\beta = .02$, $t(43) = 0.11$, $p = .91$; education $\beta = .31$, $t(43) = 1.91$, $p = .06$).

Distributions of dependent variables are presented in Figure 4. To correct for the massive range and skew of raw SSEP amplitudes (range from 0 to $189\mu\text{V}$, skewness= 6.0), individual values were divided by participant-wise standard deviation and expressed as standard deviations for later analyses.

Figure 4. *Entrainment and rhythm task general stats*



Note. SSEP = steady state evoked potentials; SD= standard deviation; ITPC= intertrial phase coherence. All reaction time measures are in milliseconds.

Entrainment Effects

In initial model building, models predicting both SSEP amplitude and ITPC had significant variance components for participant-nested block (amplitude $R^2 = .19$, Wald $\chi^2 = 6.56$, $p < .001$; ITPC $R^2 = .02$, Wald $\chi^2 = 4.69$, $p < .001$) and participant-nested entrainment condition

(amplitude $R^2 = .01$, Wald $\chi^2 = 2.31$, $p = .021$; ITPC $R^2 = .01$, Wald $\chi^2 = 3.43$, $p < .001$). Variance components for replicate, stage of stimulation, and time point were all negative, so only block and entrainment condition were retained for model building. I then added fixed effects for block, entrainment condition, modality, and their interactions to the model, along with a repeated measures effect and individual difference variables.

Effects of study variables on entrainment are presented in Tables 3 and 4. Both models had significant effects for entrainment condition (amplitude $F(2,86) = 13.97$, $p < .001$; ITPC $F(2,67) = 3.35$, $p = .041$) and the block*condition interaction (amplitude $F(2, 94) = 42.63$, $p < .001$; ITPC $F(2,103) = 19.66$, $p < .001$). Entrainment ITPC was also lower in participants with higher household income ($t(82) = -3.97$, $p < .01$). Effects of all other variables were not significant at $p < .05$.

Table 3. *Effects of study variables on entrainment amplitude*

<u>Variance components</u>	<u>R²</u>	<u>Estimate</u>	<u>SE</u>	<u>Wald χ^2</u>	<u>sig</u>
Block	.22	0.07	0.01	6.26	<.001*
Condition	~ 0	~ 0	0.00	~ 0	~.999
Block*Condition	.04	0.01	0.00	4.44	<.001*
<u>Covariance parameters</u>	<u>R²</u>	<u>Estimate</u>	<u>SE</u>	<u>Wald χ^2</u>	<u>sig</u>
Repeated measures	.34	0.13	0.01	15.40	----
Residual	.66	0.25	0.00	----	----
<u>Fixed effects</u>	<u>d</u>	<u>df 1</u>	<u>df 2</u>	<u>F</u>	<u>sig</u>
Block	-0.09	1	91.7	0.80	.374
Condition	----	2	86.2	13.97	<.001*
Block*Condition	----	2	93.9	42.63	<.001*
Modality	-0.00	1	91.7	0.00	.977
Music	-0.09	1	82.6	2.11	.150
Block*Music	----	1	91.7	0.10	.759
Condition*Music	----	2	86.2	0.26	.775
Block*Condition*Music	----	2	93.9	0.82	.443
Modality*Music	----	1	91.7	0.04	.837
ADHD	0.02	1	82.6	0.11	.737
Block*ADHD	----	1	91.7	0.16	.686
Condition*ADHD	----	2	86.2	2.55	.084
Block*Condition*ADHD	----	2	93.9	1.35	.265
Modality*ADHD	----	1	91.7	0.03	.862
Parents' education	----	1	82.6	2.54	.115
Household income	----	1	82.6	1.75	.190

Note. Condition = entrainment condition (Sham RSS, RSS, or rhythm task); ADHD = ADHD symptom severity according to Adult ADHD Self-Report Scale; *= significant at the .05 level; d = Cohen's d. Cohen's d is reported for effects with only two levels. Condition variance components were negative in the full model, so these statistics were represented as null effects.

Table 4. *Effects of study variables on entrainment ITPC*

<u>Variance components</u>	<u>R²</u>	<u>Estimate</u>	<u>SE</u>	<u>Wald χ^2</u>	<u>sig</u>
Block	.03	0.00	0.00	4.38	<.001*
Condition	.00	0.00	0.00	0.19	.848
Block*Condition	.01	0.00	0.00	1.91	.056
Residual	.97	0.03	0.00	82.96	----
<u>Covariance parameters</u>	<u>R²</u>	<u>Estimate</u>	<u>SE</u>	<u>Wald χ^2</u>	<u>sig</u>
Repeated measures	.41	0.02	0.01	2.62	----
Residual	.59	0.03	0.00	82.96	----
<u>Fixed effects</u>	<u>d</u>	<u>df 1</u>	<u>df 2</u>	<u>F</u>	<u>sig</u>
Block	0.01	1	64.6	0.13	.721
Condition	----	2	66.9	3.35	.041*
Block*Condition	----	2	103.1	19.66	<.001*
Modality	0.00	1	64.6	0.00	.981
Music	-0.03	1	81.8	0.47	.495
Block*Music	----	1	64.6	0.25	.621
Condition*Music	----	2	103.1	0.16	.850
Block*Condition*Music	----	2	64.6	1.65	.196
Modality*Music	----	1	81.8	0.00	.966
ADHD	-0.03	1	64.6	0.37	.543
Block*ADHD	----	1	66.9	0.05	.819
Condition*ADHD	----	2	103.1	0.14	.868
Block*Condition*ADHD	----	2	64.6	0.72	.490
Modality*ADHD	----	1	81.8	0.02	.884
Parents' education	----	1	81.8	0.43	.515
Household income	----	1	64.6	15.75	<.001*

Note. Condition = entrainment condition (Sham RSS, RSS, or rhythm task); ADHD = ADHD symptom severity according to Adult ADHD Self-Report Scale; *= significant at the .05 level; d = Cohen's d. Cohen's d is reported for effects with only two levels.

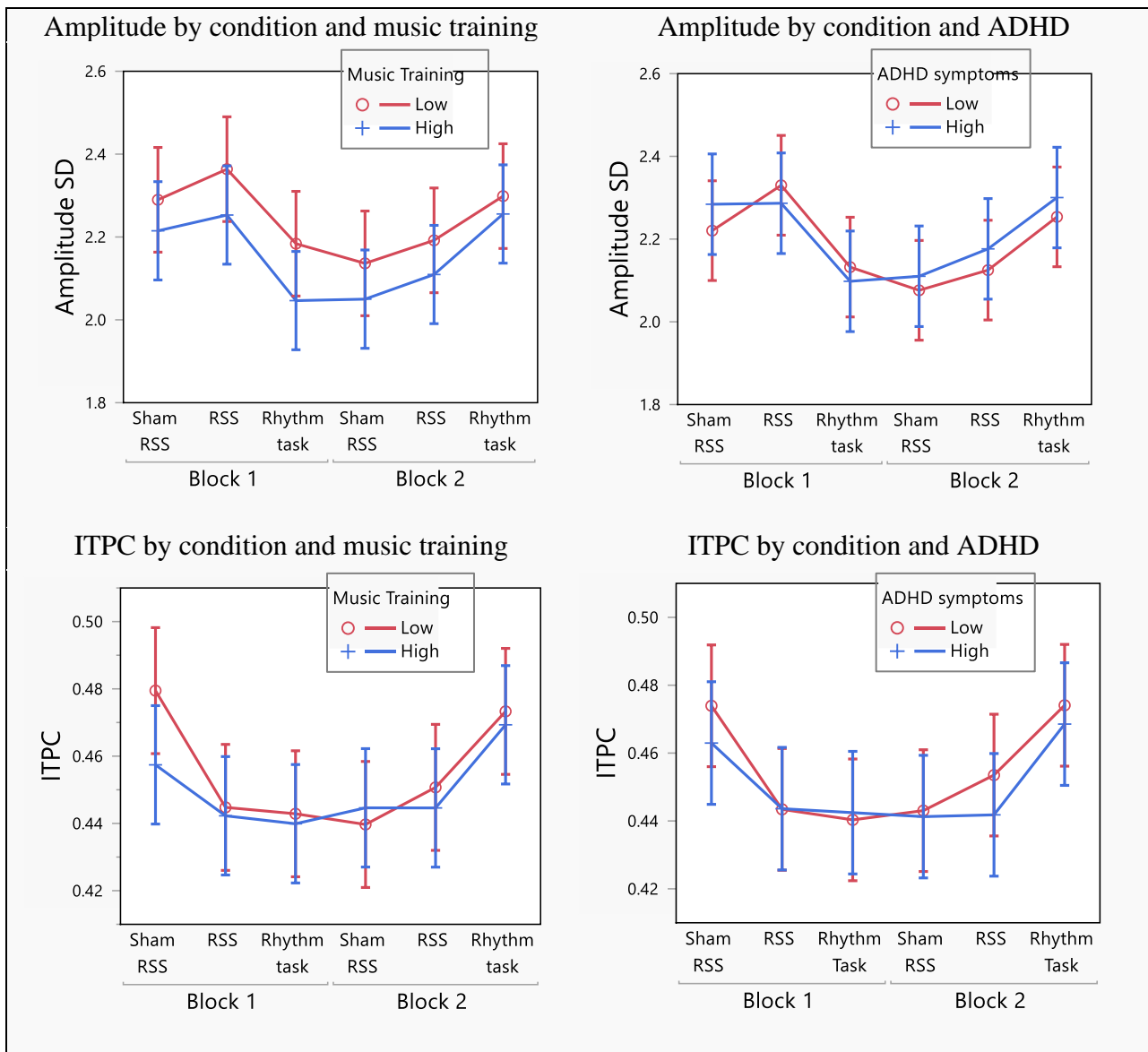
Effects of entrainment condition are shown in Table 5 and Figure 5. In block 1, entrainment did not improve from rhythmic stimulation (amplitude Cohen's $d = -0.07$, $t(105) = -0.96$, $p = .170$; ITPC Cohen's $d = -0.14$, $t(162) = -4.11$, $p < .001$) or task engagement (amplitude Cohen's $d = -0.33$, $t(105) = -4.57$, $p < .001$; ITPC Cohen's $d = -0.01$, $t(162) = -0.34$, $p = .367$). However, block 2 effects were significant and in the hypothesized direction for both rhythm (amplitude Cohen's $d = 0.21$, $t(105) = 2.85$, $p = .001$; ITPC Cohen's $d = 0.09$, $t(162) = 2.74$, $p = .003$) and task engagement (amplitude Cohen's $d = 0.22$, $t(105) = 2.99$, $p = .002$; ITPC Cohen's $d = 0.12$, $t(162) = 3.74$, $p < .001$).

Table 5. Contrasts testing effects of stimulus rhythm and task engagement on entrainment

Contrast	SSEP amplitude					SSEP ITPC				
	<u>L</u>	<u>d</u>	<u>t</u>	<u>df</u>	<u>sig</u>	<u>L</u>	<u>d</u>	<u>t</u>	<u>df</u>	<u>sig</u>
Block 1 rhythm	-0.04	-0.21	-0.96	105.1	.170	-0.03	-0.14	-4.11	162.0	<.001*
Block 1 task	-0.19	-1.02	-4.57	105.1	<.001*	-0.00	-0.01	-0.34	162.0	.367
Block 2 rhythm	0.12	0.64	2.85	105.1	.003*	0.02	0.09	2.74	162.0	.003*
Block 2 task	0.13	0.67	2.99	105.1	.002*	0.02	0.12	3.74	162.0	<.001*

Note. *L* = contrast value. *d* = Cohen's *d*. *= significant at the .05 level.

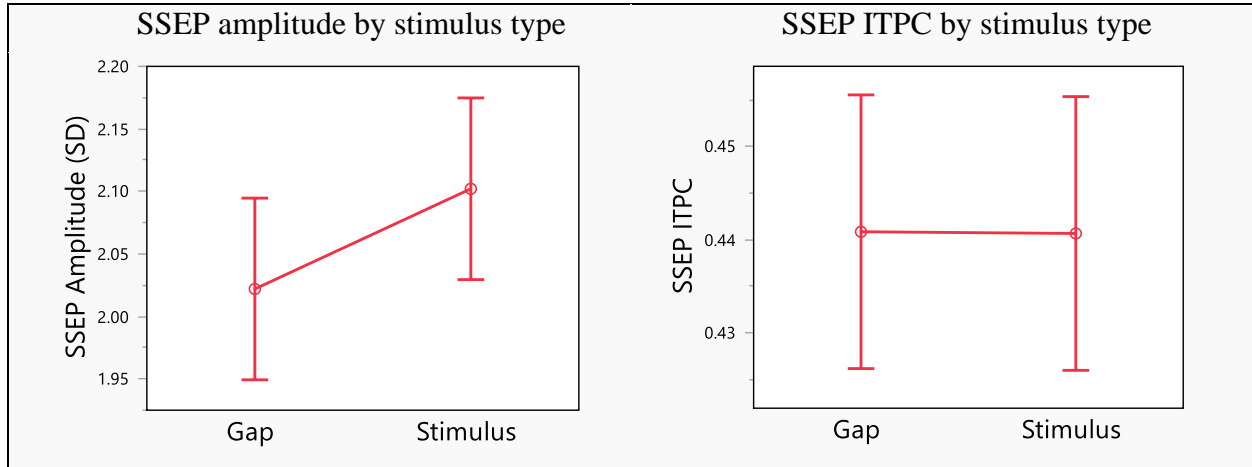
Figure 5. Effects of study variables on entrainment



Note. ADHD symptom severity is calculated according to Adult ADHD Self-Report Scale. Values displayed are least squares means. Error bars represent 95% confidence intervals.

In terms of neural entrainment and stimulus type, stimuli caused greater neural entrainment relative to gap periods, but only for SSEP amplitude (amplitude Cohen’s $d = .08$; $t(73) = 1.33$, p ; ITPC Cohen’s $d < .001$, $t(98) = .02$, $p = .98$). These effects are shown in Figure 6.

Figure 6. *Neural entrainment during rhythm task, by stimulus type*



Note. SSEP = steady state evoked potential; ITPC = intertrial phase coherence
 Values displayed are least squares means. Error bars represent 95% confidence intervals.

Flanker Task Performance

Overall performance in Flanker showed high accuracy (99%). The initial mixed model analyzing random effects of within-person variables on individual Flanker stimulus reaction times showed significant variance components for block ($R^2 = .05$, Wald $\chi^2 = 4.40$, $p < .001$), entrainment condition ($R^2 = .02$, Wald $\chi^2 = 4.98$, $p < .001$), congruency ($R^2 = .16$, Wald $\chi^2 = 5.03$, $p < .001$), Flanker position before or after entrainment stimuli ($R^2 = .01$, Wald $\chi^2 = 2.94$, $p = .003$), and stimulus pair order ($R^2 = .20$, Wald $\chi^2 = 5.21$, $p < .001$), but not stimulus offset (negative variance component). Variables with significant and non-negative random effects were added as fixed effects along with the individual difference variables for the full model.

Results from the full model and a priori contrasts are presented in Tables 6 and 7 and Figures 6 and 7. Reaction times were faster in block 2 (28 ms difference, Cohen's $d = .21$, $t(135) = 2.81$, $p = .001$), between nonrhythmic stimuli and rhythmic stimuli (21 ms difference, Cohen's $d = .15$, $t(128) = 3.04$, $p = .001$) congruency ($F(1,34) = 262.93$, $p < .001$), and stimulus order ($F(1,21) = 77.28$, $p < .001$). The pre-post differences were in the opposite direction as expected, with both overall Flanker reaction times and Flanker effects increasing overall after stimulation (Flanker RT Cohen's $d = 0.10$, $t(102) = 1.98$, $p = .025$; Flanker effect Cohen's $d = 0.10$, $t(139) = 1.92$, $p = .029$). Additional contrasts showed that block 1 reaction time was faster during periods of rhythmic stimulation than arrhythmic stimulation (Cohen's $d = -0.26$, $t(186) = -4.47$, $p < .001$) but was slower during periods of rhythm task than during RSS (Cohen's $d = 0.10$, $t(185) = 1.73$, $p = .042$). Lastly, a significant and negative three-way interaction between block*condition effects and ADHD symptoms suggested that higher ADHD symptoms predicted more modest improvement in Flanker performance after RSS (Cohen's $d = -0.18$, $t(185) = -2.13$, $p = .017$), and worse performance degradation after the rhythm task (Cohen's $d = -0.21$, $t(191) = -2.51$, $p = .007$).

Table 6. Effect of study variables on Flanker reaction time and Flanker effect

<u>Covariance parameters</u>	<u>R²</u>	<u>Estimate</u>	<u>SE</u>	<u>Wald χ^2</u>	<u>sig</u>
Block	.05	732.22	309.04	2.37	.018*
Condition	.01	85.24	90.56	0.94	.347
Block*Condition	.03	403.02	106.46	3.79	<.001*
Pre-post	.00	0.76	54.32	0.01	.989
Order	.17	2526.18	740.71	3.41	.001*
Congruency	.02	330.53	131.98	2.50	.012*
Congruency*Pre-post	.01	160.28	72.30	2.22	.027*
Residual	.72	10921.26	154.55	70.67	----
<u>Fixed effects (RT)</u>	<u>d</u>	<u>df 1</u>	<u>df 2</u>	<u>F</u>	<u>sig</u>
Block	-0.21	1	21.2	19.82	<.001*
Condition	----	2	75.4	18.48	<.001*
Block*Condition	----	2	85.8	10.92	<.001*
Pre-post	0.10	1	39.8	23.74	<.001*
Order	-0.57	1	28.8	52.23	<.001*
Music	-0.10	1	94.0	0.95	.332
Block*Music	----	1	21.3	0.01	.912
Condition*Music	----	2	76.2	2.47	.092
Block*Condition*Music	----	2	86.6	0.37	.693
Pre-post*Music	----	1	40.1	1.69	.201
Order*Music	----	1	28.9	0.27	.608
ADHD	-0.02	1	94.7	0.04	.850
Block*ADHD	----	1	21.3	0.13	.721
Condition*ADHD	----	2	75.9	1.07	.348
Block*Condition*ADHD	----	2	86.3	3.13	.049*
Pre-post*ADHD	----	1	40.0	0.72	.402
Order*ADHD	----	1	28.9	0.70	.409
Parents' education	----	1	93.0	1.31	.256
Household income	----	1	93.4	2.53	.115
<u>Fixed effects (Flanker)</u>	<u>d</u>	<u>df 1</u>	<u>df 2</u>	<u>F</u>	<u>Sig</u>
Congruency	-0.54	1	32.8	262.77	<.001*
Congruency*Pre-post	----	1	48.7	6.33	.015*
Congruency*Music	----	1	32.9	0.67	.418
Congruency*ADHD	----	1	32.9	0.70	.410

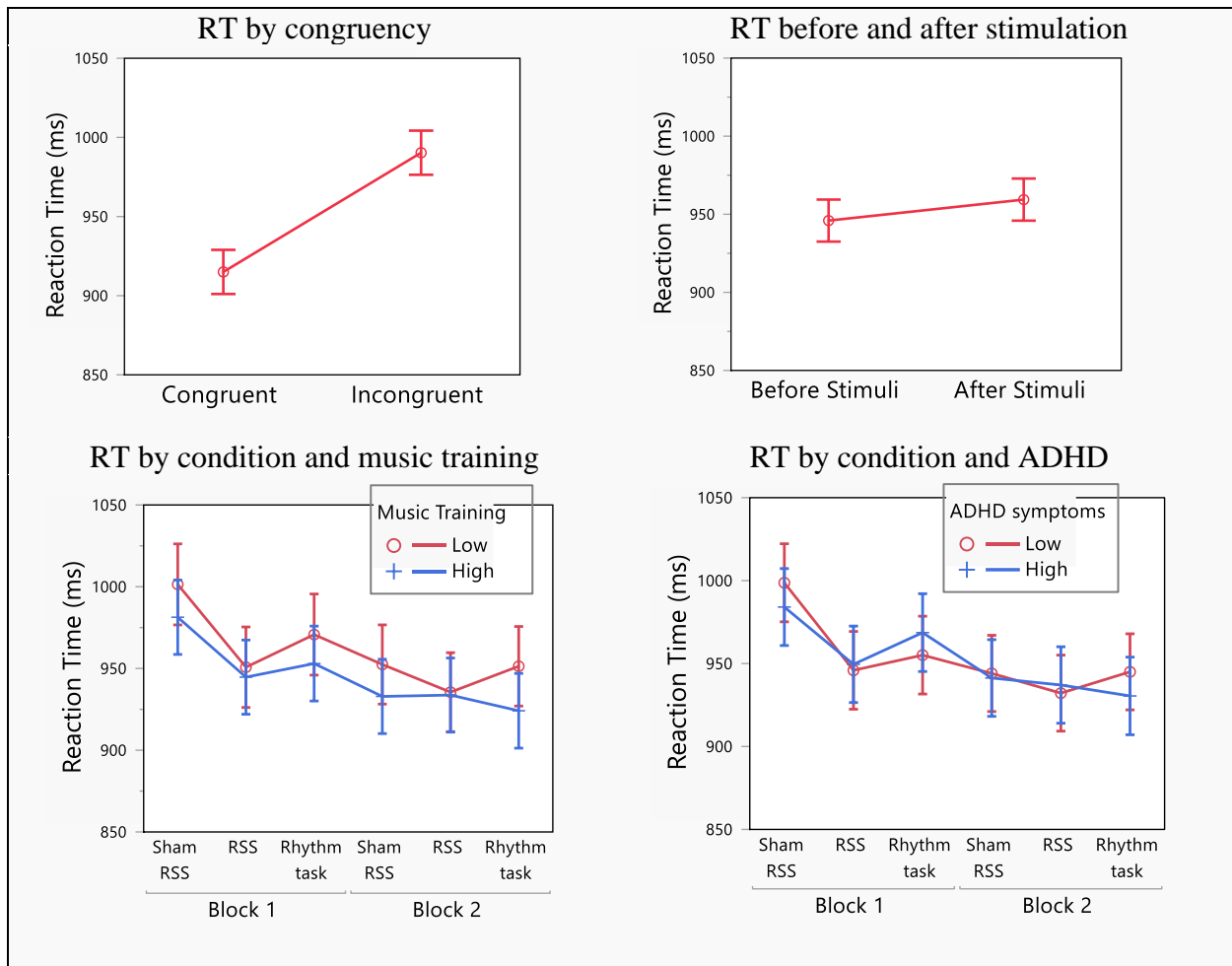
Note. Condition = entrainment condition (Sham RSS, RSS, or rhythm task); Pre-post = change in Flanker performance after trains of entrainment stimuli. ADHD = ADHD symptom severity according to Adult ADHD Self-Report Scale; *= significant at the .05 level. d = Cohen's d. Cohen's d is reported for effects with only two levels

Table 7. Contrasts testing effects of stimulus rhythm and task engagement on Flanker reaction time

Contrast	<u>L</u>	<u>d</u>	<u>df</u>	<u>t</u>	<u>sig</u>
Block 1 rhythm	-36.63	-0.26	185.6	-4.47	<.001*
Block 1 task	14.22	0.10	185.0	1.73	.042*
Block 2 rhythm	-6.53	-0.05	183.8	-0.81	.211
Block 2 task	3.16	0.02	183.8	0.39	.389
Block * Rhythm * Music	-3.17	-0.02	181.7	-0.26	.396
Block * Task * Music	-13.65	-0.10	188.1	-1.14	.128
Block * Rhythm * ADHD	-25.05	-0.18	184.6	-2.13	.017*
Block * Task * ADHD	-29.53	-0.21	190.5	-2.51	.007*

Note. L = contrast value. d = Cohen's d. *= significant at the .05 level. ADHD = ADHD symptom severity according to Adult ADHD Self-Report Scale.

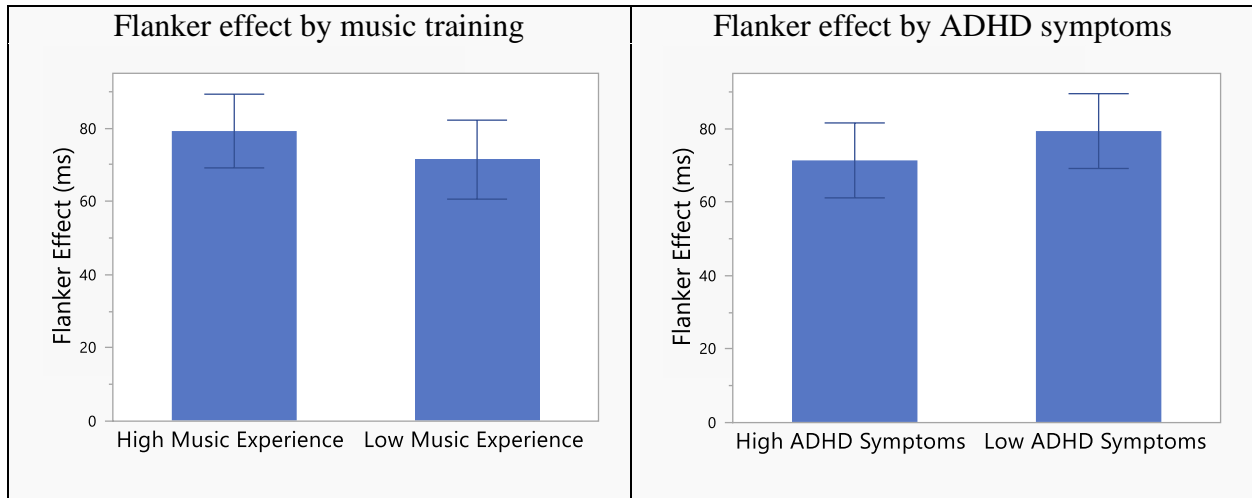
Figure 7. Effects of study variables on Flanker reaction time



Note. RT = reaction time. ADHD symptom severity is calculated according to Adult ADHD Self-Report Scale. Values displayed are least squares means. Error bars represent 95% confidence intervals.

Flanker effects were not impacted by music training (Cohen’s $d < 0.01$, $t(122) < .01$, $p = .500$) or by ADHD symptoms (Cohen’s $d = 0.01$, $t(124) < .01$, $p = .499$), as illustrated in Figure 8.

Figure 8. *Effects of study variables on Flanker effect*



Note. ADHD symptom severity is according to Adult ADHD Self-Report Scale. Values displayed are least squares means. Error bars represent standard error.

Rhythm Task Performance

In initial model building with tapping accuracy and tapping variance during the rhythm task as dependent variables, significant variance components included those of block (accuracy $R^2 = 0.32$, Wald $\chi^2 = 5.43$, $p < .001$; variance $R^2 = .20$, Wald $\chi^2 = 1.93$, $p < .001$), replicate (accuracy $R^2 = 0.06$, Wald $\chi^2 = 4.21$, $p < .001$; variance $R^2 = 0.05$, Wald $\chi^2 = 2.69$, $p = .007$), and stimulus type (accuracy $R^2 = 0.03$, Wald $\chi^2 = 2.00$, $p = .046$; variance $R^2 = 0.06$, Wald $\chi^2 = 2.11$, $p = .035$). These variables were retained along with hypothesis variables for the full analyses.

In the full model analyzing beat-keeping accuracy and variance for both stimulus and gap periods, none of the variables of interest had significant effects. These statistics are presented in Tables 8 and 9.

Table 8. *Effects of study variables on beat-keeping accuracy*

<u>Covariance parameters</u>	<u>R²</u>	<u>Estimate</u>	<u>SE</u>	<u>Wald χ^2</u>	<u>Sig</u>
Block	.31	0.02	0.01	5.10	<.001*
Replicate	.07	0.01	0.00	4.18	<.001*
Stimulus type	.02	0.00	0.00	1.69	.091
Amplitude	.01	0.00	0.00	0.79	.431
ITPC	.02	0.00	0.00	1.79	.073
Residual	.56	0.04	0.00	24.26	----

<u>Fixed effects</u>	<u>d</u>	<u>df 1</u>	<u>df 2</u>	<u>F</u>	<u>Sig</u>
Block	-0.23	1	62.5	2.39	.128
Stimulus type	-0.11	1	31.3	3.73	.063
Amplitude	0.03	1	31.5	0.27	.608
ITPC	0.01	1	39.5	0.01	.917
Music		1	98.3	0.77	.382
Block*Music	----	1	62.3	0.03	.855
Stimulus type*Music	----	1	30.7	0.15	.699
Amplitude*Music	----	1	31.4	1.95	.172
Music*ITPC	----	1	38.8	0.08	.783
ADHD	0.15	1	98.6	2.82	.096
Block*ADHD	----	1	62.3	2.11	.152
Stimulus type*ADHD	----	1	30.7	3.86	.058
Amplitude*ADHD	----	1	31.4	0.02	.881
ITPC *ADHD	----	1	39.0	0.01	.919
Parents' education	----	1	97.8	0.08	.776
Household income	----	1	98.0	0.83	.365

Note. ITPC = intertrial phase coherence; ADHD = ADHD symptom severity according to Adult ADHD Self-Report Scale; *= significant at the .05 level. d = Cohen's d. Cohen's d is reported for effects with only two levels.

Table 9. *Effects of study variables on beat-keeping variability*

<u>Covariance parameters</u>	<u>R²</u>	<u>Estimate</u>	<u>SE</u>	<u>Wald χ^2</u>	<u>sig</u>
Block	.20	0.01	0.00	3.99	<.001*
Replicate	.05	0.00	0.00	2.74	.006*
Stimulus type	.06	0.00	0.00	2.01	.044*
Amplitude	.01	0.00	0.00	0.60	.549
ITPC	.02	0.04	0.00	1.34	.181
Residual	.67	0.01	0.00	24.20	----

<u>Fixed effects</u>	<u>d</u>	<u>df 1</u>	<u>df 2</u>	<u>F</u>	<u>sig</u>
Block	0.06	1	44.6	0.35	.555
Stimulus type	-0.11	1	22.3	3.31	.082
Amplitude	-0.04	1	33.3	0.52	.474
ITPC	-0.03	1	36.6	0.31	.584
Music	-0.00	1	106.0	0.00	.985
Block*Music	----	1	44.3	0.18	.672
Stimulus type*Music	----	1	21.9	0.03	.854
Amplitude*Music	----	1	32.8	1.56	.221
ITPC*Music	----	1	35.7	0.75	.391
ADHD	-0.21	1	106.3	2.71	.103
Block*ADHD	----	1	44.3	0.60	.442
Stimulus type*ADHD	----	1	21.9	0.55	.464
Amplitude*ADHD	----	1	32.8	0.68	.414
ITPC *ADHD	----	1	35.9	0.00	.960
Parents' education	----	1	104.9	1.03	.311
Household income	----	1	104.7	0.64	.427

Note. ITPC = intertrial phase coherence; ADHD = ADHD symptom severity according to Adult ADHD Self-Report Scale; *= significant at the .05 level. d = Cohen’s d. Cohen’s d is reported for effects with only two levels.

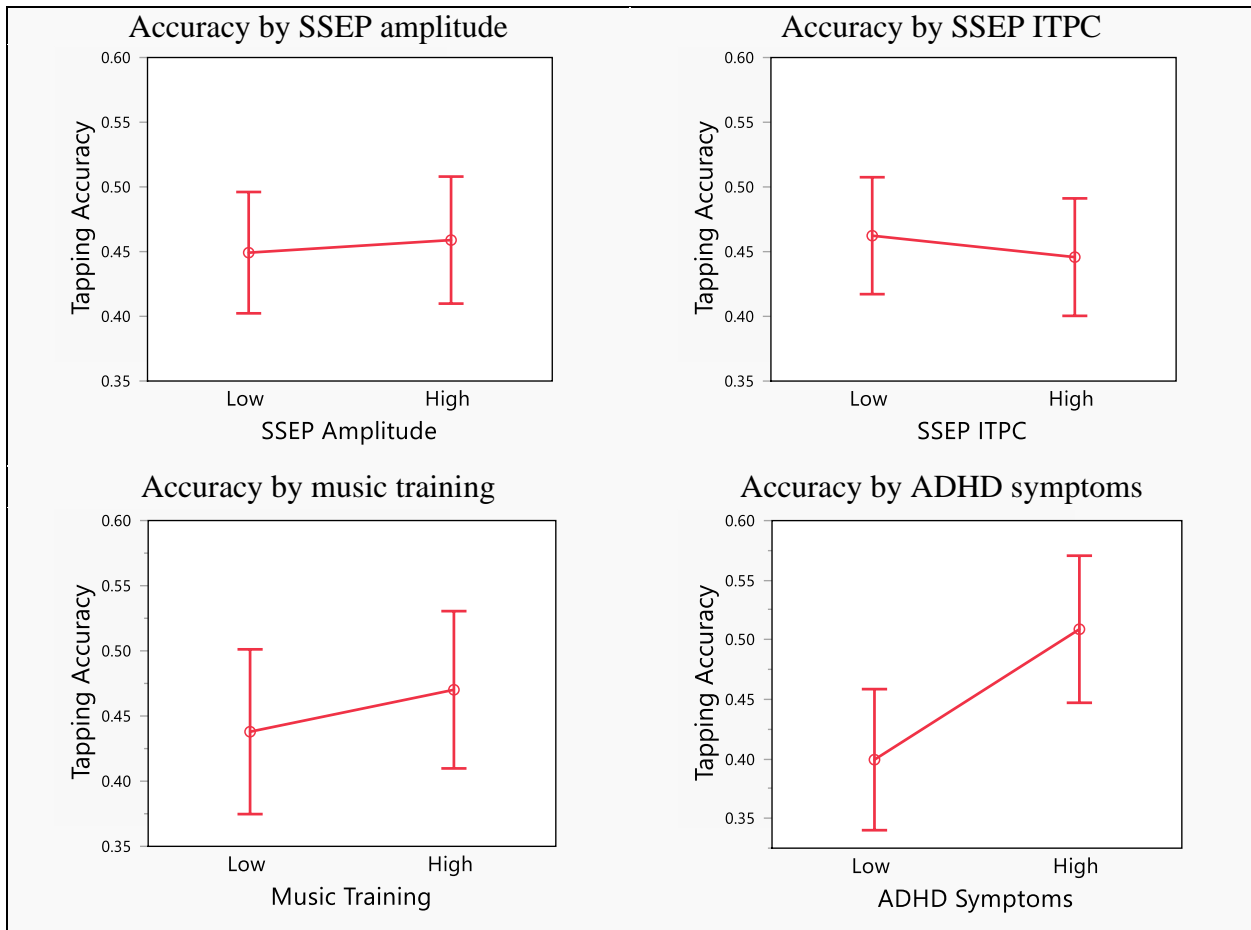
After running the same model analyzing beat-keeping performance during gap periods only and running a priori contrasts, significant effects emerged for ADHD (accuracy Cohen’s d= 0.39, $t(89)= 3.65$; variance Cohen’s d= -0.25, $t(78)= -2.22$, $p=.015$). These effects were in a direction suggesting better beat-keeping accuracy and precision with higher ADHD symptoms. Meanwhile, neither entrainment amplitude nor ITPC predicted beat-keeping performance during gaps. These effects are displayed in Table 10 and Figures 9 and 10.

Table 10. *Contrasts testing effects of study variables on beat-keeping accuracy and variability*

<u>Accuracy contrasts</u>	<u>L</u>	<u>d</u>	<u>df</u>	<u>t</u>	<u>sig</u>
SSEP amplitude	0.01	0.03	103.3	0.30	.382
SSEP ITPC	-0.01	-0.05	108.5	-0.65	.256
Music training	0.03	0.11	89.2	1.02	.154
ADHD symptoms	0.11	0.39	89.4	3.65	<.001*
<u>Variance contrasts</u>	<u>L</u>	<u>d</u>	<u>df</u>	<u>t</u>	<u>sig</u>
SSEP amplitude	-0.00	-0.02	92.2	-0.17	.432
SSEP ITPC	-0.01	-0.03	94.9	-0.38	.349
Music training	-0.00	-0.01	77.7	-0.39	.462
ADHD symptoms	-0.06	-0.25	77.9	-2.22	.015*

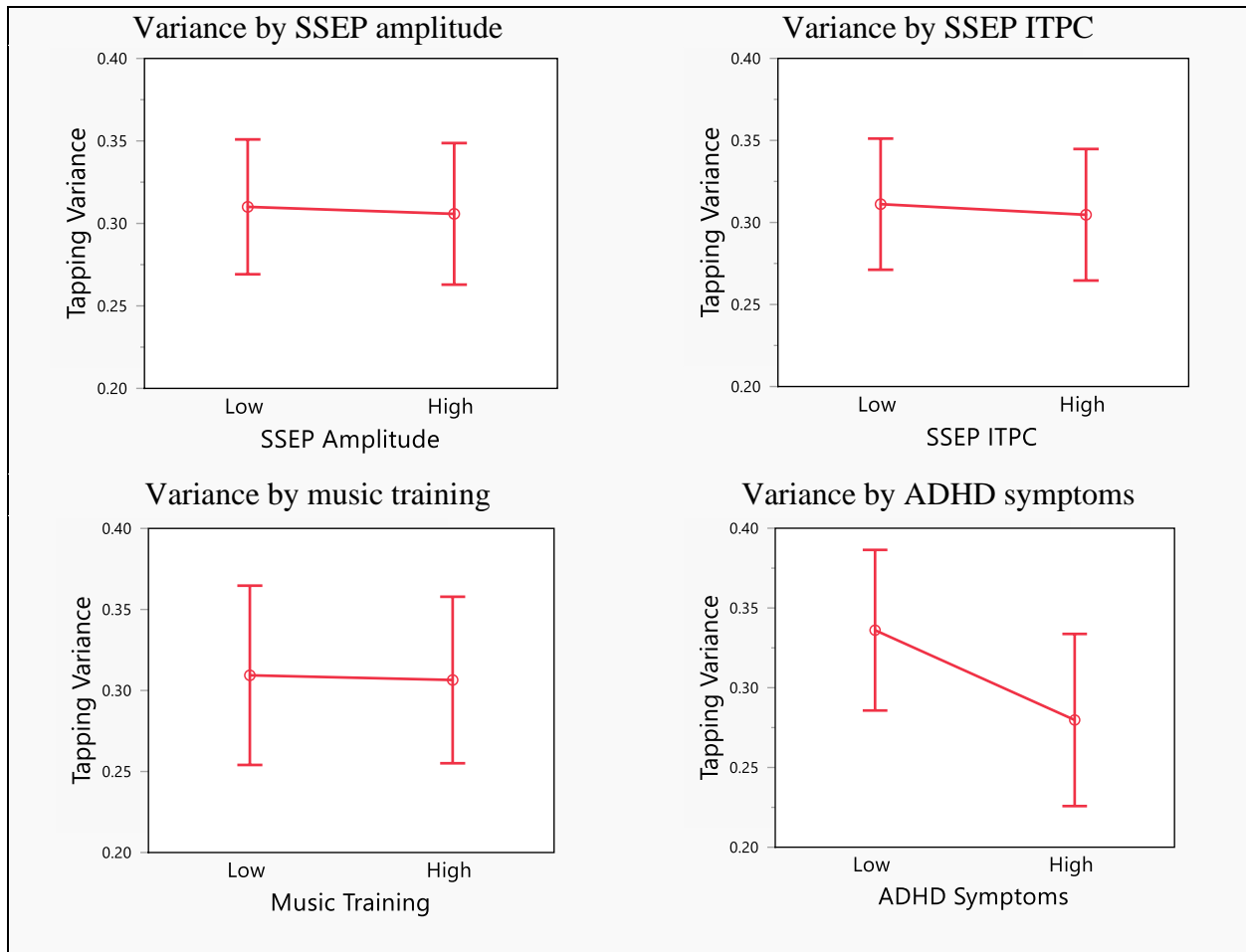
Note. L = contrast value. d = Cohen's d. *= significant at the .05 level.

Figure 9. *Effects of study variables on beat-keeping task accuracy during gaps*



Note. ADHD symptom severity is calculated according to Adult ADHD Self-Report Scale.

Figure 10. *Effects of study variables on beat-keeping task variance during gaps*



Note. ADHD symptom severity is calculated according to Adult ADHD Self-Report Scale

Discussion

The present study investigated the interrelationships between ADHD symptoms, history of music training, sensory entrainment under various stimulus conditions, and motor-cognitive performance in a young adult sample. Results suggest significant variation in sensory entrainment effects across the recording session, depending on the time course, rhythmicity, and task demands of the stimulus period. Some entrainment and performance effects were congruent with findings from prior literature (Albouy et al., 2017; Bugos, 2010; Stefanics et al., 2010), while many other hypotheses regarding entrainment effects were not supported. In terms of individual differences, neither music training nor ADHD symptoms impacted entrainment, but

ADHD did impact the effects of entrainment stimuli on Flanker reaction time, with higher ADHD symptoms predicting worse performance during periods of rhythmic stimulation. Lastly and surprisingly, while neither entrainment, music training, nor ADHD symptoms impacted beat-keeping performance in general, ADHD symptoms predicted better beat-keeping during stimulus gap periods. Results in general paint a complicated picture of acute entrainment effects and individual differences.

Some of the entrainment results were in line with prior research. Entrainment amplitude was greater during periods of stimulation than periods of stimulus gaps, which supports the notion that exogenous entrainment is easier to maintain and thus stronger than endogenous entrainment. However, these effects were only found with amplitude, not ITPC. This could mean that phase effects of stimulation are more robust over time than amplitude effects, but more research is needed to replicate this effect.

Other results were more equivocal. There was better entrainment and Flanker performance during rhythmic stimulation periods than during sham RSS periods, with the caveat that Flanker performance only improved significantly in block 1 and entrainment only improved in block 2. Counter to expectation, both Flanker performance and entrainment tended to be worse during rhythm task periods than during RSS periods. The one exception is block 2 entrainment, which increased from RSS to task. It appears that entrainment may have been vulnerable to fatigue or cognitive load early in the session, and then built back up over the course of the experiment. However, since entrainment did not increase overall between block 1 and block 2, it would not be appropriate to say that the entrainment improved over the course of the experiment. Entrainment also did not wax and wane as individual trains of stimuli were presented and removed, as seen more clearly in prior work (Halbleib et al., 2012; Hanslmayr et al., 2019;

Regan, 1989). It is possible that the gaps between trains of stimuli were not sufficiently long to cause participants to reliably go into and out of states of entrainment.

As for Flanker performance, results point more consistently towards better performance during RSS periods than during sham RSS periods. However, this finding refers to the overall effect of entrainment conditions on Flanker performance. Flanker performance did not improve directly after each train of entrainment stimuli as predicted. Moreover, because all blocks proceeded from sham RSS to RSS and not any other orders, practice effects early in block 1 cannot be ruled out as contributing to these significant Flanker reaction time improvements.

Another finding worth mentioning is the null effects of stimulus onset asynchrony on Flanker performance. If the entrainment procedure is successful, then in theory people should respond faster to stimuli that are delivered at intervals that line up with the entrainment stimulus time points. In this study there was no impact of stimulus onset asynchrony on Flanker effects, which suggests again that entrainment may not have successfully improved short-term attentional performance in similar ways to prior work (Mathewson et al., 2010; Ng et al., 2012; Stefanics et al., 2010).

The last thing to mention is the individual variation in entrainment and performance. ADHD and music experience did not impact neural entrainment at all, despite theoretically being important factors (Albouy et al., 2017; Calderone et al., 2014; Miendlarzewska & Tros, 2014). The interaction effects of ADHD on Flanker imply that ADHD is a detriment to attention performance, which is well in line with theory and prior work (Ziegler et al., 2016). However, the effects of ADHD on beat-keeping were particularly interesting. Participants with higher ADHD symptoms performed better at beat-keeping than participants with lower ADHD symptoms. This may be because people with ADHD, while generally performing poorer on

complex tasks that require task-switching, can hyperfocus on menial repetitive tasks like the rhythm task in this study (Ozel-Kizil et al., 2016).

Future Directions and Limitations

As this project was quite complex, it afforded me the opportunity to use methods and test hypotheses that go beyond even the scope of this dissertation. Issues of time and parsimony kept me from doing all that I wanted to do with these data, but I intend to work with them to test more hypotheses soon.

One thing I intend to revisit is the imputation method I used to replace missing EEG data. Mean imputation is an acceptable method for EEG data, but it can produce biased estimates if too much information is already missing. It also cannot be used to predict future values based on past values, which is a valuable method for imputing data in sections where data is missing from all channels simultaneously. Other imputation methods, like multivariate autoregressive imputation (Kanemura et al., 2018), may enable me to retain more useable data, enough even that I could include some of the participants that I discounted from the present analyses. I also might be able to salvage more data from the control periods of the experiment, which could give valuable baseline information for comparing neural activity during study conditions.

Another thing to consider is the way in which entrainment effects are quantified. I measured entrainment SSEPs using calculations in the time domain, due to its simplicity and high temporal specificity (Hanslmayr et al., 2019; Nozaradan, et al., 2012a). However, with any fine-grained approach it is possible to miss the forest for the trees. There may be additional benefit to analyzing entrainment effects using spectral decomposition over larger epochs as opposed to the averaged trial-level SSEP variation that I analyzed here. I intend to explore frequency domain properties of the data before publication, both in terms of power spectral density of the

stimulation frequency (Albouy et al., 2017) and in terms of other more nuanced analyses like harmonic effects and cross-frequency coupling, which may give complementary information about cognitive processes during entrainment based on prior work (Gomez-Ramirez et al., 2011; Lakatos et al., 2008; Picton et al., 2003; Wilson & Foxe, 2020).

There are several ways in which the methods of this dissertation could be improved. One of these is selecting participants with more diverse levels of functioning. Cognitive tests can both measure and impact performance, in the case of cognitive load or practice effects (Van Merriënboer, & Sweller, 2005; Wesnes & Pincock, 2002). Future research may prioritize testing attentional performance with a shorter and more elegant procedure than the one used here, as some study participants reported that they found the experiment tedious.

Another detraction to the study concerns limitations of the B-Alert hardware. At its most powerful, the B-alert headset can only record up to 23 channels and at a maximum oscillatory frequency of 128 Hz, which is more limited than most of the entrainment studies cited in this dissertation (Albouy et al., 2017; Boucher et al., 2019; Gomez-Ramirez et al., 2011; Gray et al., 2015; Halbleib et al., 2012; Ng et al., 2012; Nozaradan, 2014; Nozaradan et al., 2012a;). The number of channels limits my ability to localize activity to particular regions of cortex. Better source localization may require recording from more EEG electrodes (e.g. in the more densely packed 10-10 system), or better yet, using magnetoencephalogram (Coffey et al, 2016; Halbleib et al., 2012; Spaak et al., 2014) or the newer functional near-infrared spectroscopy (Guglielmini et al., 2022).

The last limitation is perhaps best described as commentary rather than an actual detraction. The Erikson Flanker Test was chosen for the proposed study due to its widely-accepted validity as a measure of selective attention. The similar measure of Stroop (Stroop,

1935) could have ostensibly been used in this way as well. However, the accepted meaning of Stroop test results has become somewhat more controversial in recent decades, with disagreements about whether the Stroop test effects measure selective attention or top-down cognitive control (Algom & Chajut, 2019; Botvinick et al., 2001). Some of this controversy may be due to the way in which Stroop tests are administered; studies that present back-to-back instructed batteries of congruent trials followed by batteries of incongruent trials may indeed recruit more top-down cognitive control than bottom-up selective attention, as suggested by Algom & Chajut (2019). I chose to use trial-level Flanker test instead of the Stroop test to mitigate concerns about construct validity. However, if Stroop is indeed a measure of top-down control rather than selective attention, this fact may throw the Flanker test into question as well. Therefore, the task performance results from this study should be interpreted with some caution.

Conclusion

Sensory entrainment illustrates the causative role that neural oscillations have in producing and maintaining cognitive states. In addition to this demonstration purpose, rhythmic stimulation and resulting entrainment effects may help coax people into better cognitive functioning. There is evidence that entrainment-promoting rhythmic sensory stimulation improves cognitive performance in dementia, but fewer studies have reported similar performance benefits for mild cognitive impairment like that in adult Attention Deficit Hyperactivity Disorder. The present study showed evidence of successful sensory entrainment to auditory and visual stimuli, but failed to find consistent evidence that this entrainment improved short-term attention and beat-keeping performance. However, the field of sensory entrainment, musicality, and attention is still ripe for exploration.

References

1. Albouy, P., Weiss, A., Baillet, S., & Zatorre, R. J. (2017). Selective entrainment of theta oscillations in the dorsal stream causally enhances auditory working memory performance. *Neuron*, 94(1), 193-206.
2. Algom, D., & Chajut, E. (2019). Reclaiming the stroop effect back from control to input-driven attention and perception. *Frontiers in Psychology*, 10, 1683.
3. Arns, M., Conners, C. K., & Kraemer, H. C. (2013). A decade of EEG Theta/Beta Ratio Research in ADHD: A meta-analysis. *Journal of Attention Disorders*, 17(5), 374–383. <https://doi.org/10.1177/1087054712460087>
4. Bauer, A. K. R., Debener, S., & Nobre, A. C. (2020). Synchronisation of neural oscillations and cross-modal influences. *Trends in Cognitive Sciences*, 24(6), 481-495.
5. Bokde, A. L., Meaney, J. F., Sheehy, N. P., Reilly, R. B., Abrahams, S., & Doherty, C. P. (2011). Advances in diagnostics for neurodegenerative disorders. In *Neurodegenerative Disorders* (pp. 17-42). Springer, London.
6. Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, 108(3), 624.
7. Boucher, V. J., Gilbert, A. C., & Jemel, B. (2019). The role of low-frequency neural oscillations in speech processing: Revisiting delta entrainment. *Journal of Cognitive Neuroscience*, 31(8), 1205-1215.
8. Bradt, J., Magee, W. L., Dileo, C., Wheeler, B. L., & McGilloway, E. (2010). Music therapy for acquired brain injury. *Cochrane Database of Systematic Reviews*, (7).

9. Bugos, J. A. (2010). The benefits of music instruction on processing speed, verbal fluency, and cognitive control in aging. *Music Education Research International*, 4(1), 1-9.
10. Calderone, D. J., Lakatos, P., Butler, P. D., & Castellanos, F. X. (2014). Entrainment of neural oscillations as a modifiable substrate of attention. *Trends in Cognitive Sciences*, 18(6), 300–309. <https://doi.org/10.1016/j.tics.2014.02.005>
11. Canolty, R. T., & Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends in Cognitive Sciences*, 14(11), 506-515.
12. Carr, J. M. (2012). *Re: Development of standards for the collection of socioeconomic status in health surveys conducted by the Department of Health and Human Services*. National Committee on Vital and Health Statistics.
13. Coffey, E. B., Herholz, S. C., Chepesiuk, A. M., Baillet, S., & Zatorre, R. J. (2016). Cortical contributions to the auditory frequency-following response revealed by MEG. *Nature Communications*, 7(1), 1-11.
14. Cohen, Mike X (2014). *Analyzing Neural Time Series Data: Theory and Practice*. MIT Press.
15. Criscuolo, A., Bonetti, L., Särkämö, T., Kliuchko, M., & Brattico, E. (2019). On the association between musical training, intelligence and executive functions in adulthood. *Frontiers in Psychology*, 10, 1704.
16. Driver, J., & Noesselt, T. (2008). Multisensory interplay reveals crossmodal influences on ‘sensory-specific’ brain regions, neural responses, and judgments. *Neuron*, 57(1), 11-23.

17. Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, 16(1), 143-149.
18. Gagol, A., Magnuski, M., Kroczyk, B., Kałamała, P., Ociepka, M., Santarnecchi, E., & Chuderski, A. (2018). Delta-gamma coupling as a potential neurophysiological mechanism of fluid intelligence. *Intelligence*, 66, 54-63.
19. Gevensleben, H., Holl, B., Albrecht, B., Vogel, C., Schlamp, D., Kratz, O., ... & Heinrich, H. (2009). Is neurofeedback an efficacious treatment for ADHD? A randomised controlled clinical trial. *Journal of Child Psychology and Psychiatry*, 50(7), 780-789.
20. Gomez-Ramirez, M., Kelly, S. P., Molholm, S., Sehatpour, P., Schwartz, T. H., & Foxe, J. J. (2011). Oscillatory sensory selection mechanisms during intersensory attention to rhythmic auditory and visual inputs: A human electrocorticographic investigation. *Journal of Neuroscience*, 31(50), 18556–18567.
<https://doi.org/10.1523/JNEUROSCI.2164-11.2011>
21. Gray, M. J., Frey, H. P., Wilson, T. J., & Foxe, J. J. (2015). Oscillatory recruitment of bilateral visual cortex during spatial attention to competing rhythmic inputs. *Journal of Neuroscience*, 35(14), 5489-5503.
22. Guglielmini, S., Bopp, G., Marcar, V. L., Scholkmann, F., & Wolf, M. (2022). Systemic physiology augmented functional near-infrared spectroscopy hyperscanning: A first evaluation investigating entrainment of spontaneous activity of brain and body physiology between subjects. *Neurophotonics*, 9(2), 026601.
23. Halbleib, A., Gratkowski, M., Schwab, K., Ligges, C., Witte, H., & Haueisen, J. (2012). Topographic analysis of engagement and disengagement of neural oscillators in photic

- driving: A combined electroencephalogram/magnetoencephalogram study. *Journal of Clinical Neurophysiology*, 29(1), 33-41.
24. Hanna-Pladdy, B., & MacKay, A. (2011). The relation between instrumental musical activity and cognitive aging. *Neuropsychology*, 25(3), 378.
25. Hanslmayr, S., Axmacher, N., & Inman, C. S. (2019). Modulating human memory via entrainment of brain oscillations. *Trends in Neurosciences*, 42(7), 485–499.
<https://doi.org/10.1016/j.tins.2019.04.004>
26. Harmony, T. (2013). The functional significance of delta oscillations in cognitive processing. *Frontiers in Integrative Neuroscience*, 7, 83.
27. Hartmann, T., & Weisz, N. (2019). Auditory cortical generators of the frequency following response are modulated by intermodal attention. *Neuroimage*, 203, 116185.
28. Herrmann, C. S. (2001). Human EEG responses to 1–100 Hz flicker: Resonance phenomena in visual cortex and their potential correlation to cognitive phenomena. *Experimental Brain Research*, 137(3), 346-353.
29. Herrmann, C. S., Strüber, D., Helfrich, R. F., & Engel, A. K. (2016). EEG oscillations: From correlation to causality. *International Journal of Psychophysiology*, 103, 12-21.
30. Hromádka, T., Zador, A. M., & DeWeese, M. R. (2013). Up states are rare in awake auditory cortex. *Journal of Neurophysiology*, 109(8), 1989-1995.
31. Huster, R. J., Enriquez-Geppert, S., Lavallee, C. F., Falkenstein, M., & Herrmann, C. S. (2013). Electroencephalography of response inhibition tasks: Functional networks and cognitive contributions. *International Journal of Psychophysiology*, 87(3), 217-233.
32. Jensen, O., Kaiser, J., & Lachaux, J. P. (2007). Human gamma-frequency oscillations associated with attention and memory. *Trends in Neurosciences*, 30(7), 317-324.

33. Joyce, M., & Siever, D. (2000). Audio-visual entrainment program as a treatment for behavior disorders in a school setting. *Journal of Neurotherapy*, 4(2), 9-25.
34. Kanemura, A., Cheng, Y., Kaneko, T., Nozawa, K., & Fukunaga, S. (2018). Imputing missing values in EEG with multivariate autoregressive models. *Institute of Electrical and Electronics Engineers Access*, 2018, 2639-2642.
35. Kessler, R. C., Adler, L., Ames, M., Demler, O., Faraone, S., Hiripi, E. V. A., ... & Walters, E. E. (2005). The World Health Organization Adult ADHD Self-Report Scale (ASRS): A short screening scale for use in the general population. *Psychological Medicine*, 35(2), 245-256.
36. Laffere, A., Dick, F., Holt, L. L., & Tierney, A. (2021). Attentional modulation of neural entrainment to sound streams in children with and without ADHD. *NeuroImage*, 224, 117396.
37. Lakatos, P., Karmos, G., Mehta, A. D., Ulbert, I., & Schroeder, C. E. (2008). Entrainment of neuronal oscillations as a mechanism of attentional selection. *Science*, 320(5872), 110-113.
38. Lenz, D., Krauel, K., Flechtner, H. H., Schadow, J., Hinrichs, H., & Herrmann, C. S. (2010). Altered evoked gamma-band responses reveal impaired early visual processing in ADHD children. *Neuropsychologia*, 48(7), 1985-1993.
39. Lofthouse, N., Arnold, L. E., Hersch, S., Hurt, E., & DeBeus, R. (2012). A review of neurofeedback treatment for pediatric ADHD. *Journal of Attention Disorders*, 16(5), 351-372.

40. Mathewson, K. E., Fabiani, M., Gratton, G., Beck, D. M., & Lleras, A. (2010). Rescuing stimuli from invisibility: Inducing a momentary release from visual masking with pre-target entrainment. *Cognition*, 115(1), 186-191.
41. Miendlarzewska, E. A., & Trost, W. J. (2014). How musical training affects cognitive development: Rhythm, reward and other modulating variables. *Frontiers in Neuroscience*, 7, 279.
42. Missonnier, P., Hasler, R., Perroud, N., Herrmann, F. R., Millet, P., Richiardi, J., ... & Baud, P. (2013). EEG anomalies in adult ADHD subjects performing a working memory task. *Neuroscience*, 241, 135-146.
43. Moreno, S., & Bidelman, G. M. (2014). Examining neural plasticity and cognitive benefit through the unique lens of musical training. *Hearing Research*, 308, 84-97.
44. Neuling, T., Rach, S., Wagner, S., Wolters, C. H., & Herrmann, C. S. (2012). Good vibrations: Oscillatory phase shapes perception. *Neuroimage*, 63(2), 771-778.
45. Ng, B. S. W., Schroeder, T., & Kayser, C. (2012). A precluding but not ensuring role of entrained low-frequency oscillations for auditory perception. *Journal of Neuroscience*, 32(35), 12268-12276.
46. Nozaradan, S. (2014). Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369(1658), 20130393.
47. Nozaradan, S., Peretz, I., & Keller, P. E. (2016). Individual differences in rhythmic cortical entrainment correlate with predictive behavior in sensorimotor synchronization. *Scientific Reports*, 6(1), 20612. <https://doi.org/10.1038/srep20612>

48. Nozaradan, S., Peretz, I., & Mouraux, A. (2012a). Steady-state evoked potentials as an index of multisensory temporal binding. *NeuroImage*, 60(1), 21-28.
49. Nozaradan, S., Peretz, I., & Mouraux, A. (2012b). Selective neuronal entrainment to the beat and meter embedded in a musical rhythm. *Journal of Neuroscience*, 32(49), 17572–17581. <https://doi.org/10.1523/JNEUROSCI.3203-12.2012>
50. Okun, M., Naim, A., & Lampl, I. (2010). The subthreshold relation between cortical local field potential and neuronal firing unveiled by intracellular recordings in awake rats. *Journal of Neuroscience*, 30(12), 4440-4448.
51. Ozel-Kizil, E. T., Kokurcan, A., Aksoy, U. M., Kanat, B. B., Sakarya, D., Bastug, G., ... & Oncu, B. (2016). Hyperfocusing as a dimension of adult attention deficit hyperactivity disorder. *Research in Developmental Disabilities*, 59, 351-358.
52. Palva, S., & Palva, J. M. (2007). New vistas for α -frequency band oscillations. *Trends in Neurosciences*, 30(4), 150-158.
53. Picton, T. W., John, M. S., Dimitrijevic, A., & Purcell, D. (2003). Human auditory steady-state responses. *International Journal of Audiology*, 42(4), 177-219.
54. Puyjarinet, F., Bégel, V., Lopez, R., Dellacherie, D., & Dalla Bella, S. (2017). Children and adults with Attention-Deficit/Hyperactivity Disorder cannot move to the beat. *Scientific Reports*, 7(1), 1-11.
55. Rajendran, V. G., & Schnupp, J. W. (2019). Frequency tagging cannot measure neural tracking of beat or meter. *Proceedings of the National Academy of Sciences*, 116(8), 2779-2780.
56. Regan, D. (1977). Steady-state evoked potentials. *Journal of the Optical Society of America*, 67(11), 1475-1489.

57. Regan, D. (1989). Human brain electrophysiology. *Evoked Potentials and Evoked Magnetic Fields in Science and Medicine*. New York: Elsevier.
58. Rodriguez-Fornells, A., Rojo, N., Amengual, J. L., Ripollés, P., Altenmüller, E., & Münte, T. F. (2012). The involvement of audio–motor coupling in the music-supported therapy applied to stroke patients. *Annals of the New York Academy of Sciences*, 1252(1), 282-293.
59. Rosenblum, M., & Pikovsky, A. (2003). Synchronization: From pendulum clocks to chaotic lasers and chemical oscillators. *Contemporary Physics*, 44(5), 401-416.
60. Schroeder, C. E., & Foxe, J. (2005). Multisensory contributions to low-level, ‘unisensory’ processing. *Current Opinion in Neurobiology*, 15(4), 454-458.
61. Spaak, E., de Lange, F. P., & Jensen, O. (2014). Local entrainment of alpha oscillations by visual stimuli causes cyclic modulation of perception. *Journal of Neuroscience*, 34(10), 3536-3544.
62. Strauß, A., Wöstmann, M., & Obleser, J. (2014). Cortical alpha oscillations as a tool for auditory selective inhibition. *Frontiers in Human Neuroscience*, 8, 350.
<https://doi.org/10.3389/fnhum.2014.00350>.
63. Stefanics, G., Hangya, B., Hernádi, I., Winkler, I., Lakatos, P., & Ulbert, I. (2010). Phase entrainment of human delta oscillations can mediate the effects of expectation on reaction speed. *Journal of Neuroscience*, 30(41), 13578-13585.
64. Steriade, M., Timofeev, I., & Grenier, F. (2001). Natural waking and sleep states: A view from inside neocortical neurons. *Journal of Neurophysiology*, 85(5), 1969-1985.
65. Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18(6), 643.

66. Tal, I., Large, E. W., Rabinovitch, E., Wei, Y., Schroeder, C. E., Poeppel, D., & Golumbic, E. Z. (2017). Neural entrainment to the beat: The “missing-pulse” phenomenon. *Journal of Neuroscience*, 37(26), 6331-6341.
67. Tzounopoulos, T., & Kraus, N. (2009). Learning to encode timing: Mechanisms of plasticity in the auditory brainstem. *Neuron*, 62(4), 463-469.
68. Van Merriënboer, J. J., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review*, 147-177.
69. Vernet, M., Stengel, C., Quentin, R., Amengual, J. L., & Valero-Cabré, A. (2019). Entrainment of local synchrony reveals a causal role for high-beta right frontal oscillations in human visual consciousness. *Scientific Reports*, 9(1), 1-15.
70. Von Stein, A., & Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology*, 38(3), 301-313.
71. Vuust, P., Brattico, E., Seppänen, M., Näätänen, R., & Tervaniemi, M. (2012). Practiced musical style shapes auditory skills. *Annals of the New York Academy of Sciences*, 1252(1), 139-146.
72. Wesnes, K., & Pincock, C. (2002). Practice effects on cognitive tasks: A major problem?. *The Lancet Neurology*, 1(8), 473.
73. Williams, J., Ramaswamy, D., & Oulhaj, A. (2006). 10 Hz flicker improves recognition memory in older people. *BMC Neuroscience*, 7(1), 1-7.
74. Wilson, T. J., & Foxe, J. J. (2020). Cross-frequency coupling of alpha oscillatory power to the entrainment rhythm of a spatially attended input stream. *Cognitive Neuroscience*, 11(1-2), 71-91.

75. Yang, H., Luo, Y., Hu, Q., Tian, X., & Wen, H. (2021). Benefits in Alzheimer's disease of sensory and multisensory stimulation. *Journal of Alzheimer's Disease*, 82(2), 463-484.
76. Zhou, M., Liang, F., Xiong, X. R., Li, L., Li, H., Xiao, Z., ... & Zhang, L. I. (2014). Scaling down of balanced excitation and inhibition by active behavioral states in auditory cortex. *Nature Neuroscience*, 17(6), 841-850.
77. Ziegler, S., Pedersen, M. L., Mowinckel, A. M., & Biele, G. (2016). Modelling ADHD: A review of ADHD theories through their predictions for computational models of decision-making and reinforcement learning. *Neuroscience & Biobehavioral Reviews*, 71, 633-656.

Appendix A: Demographics and Neurological Status Questions

1. What is your age?
2. What is your race?
3. What is your ethnicity?
4. What is your sex assigned at birth?
5. What is your gender?
6. Are you right handed, left handed, or ambidextrous?
7. What is your household income?
8. What is the highest educational attainment of each or your parents?
9. Do you have any musical training experience?
 - a. If yes, what type (instrumental, vocal, both)?
 - b. If yes, how many years did you receive musical training?
10. Are you hypersensitive to stimulation?
 - a. If yes, which sense(s)?
11. Do you ever get right and left confused?
12. Have you ever been diagnosed with ADHD?
13. Are you currently taking stimulant medication for ADHD?
14. Do you have any history of hearing problems?
15. Do you have any history of seizures?

Appendix B: The Adult ADHD Self-Report Scale (ASRS)

<p>Table B1. The WMH-CIDI Adult ADHD Self-Report Scale (ASRS) Questions</p> <p style="text-align: center;">I. Inattention</p> <p>1. How often do you make careless mistakes when you have to work on a boring or difficult project?</p> <p>2. How often do you have difficulty keeping your attention when you are doing boring or repetitive work?</p> <p>3.* How often do you have difficulty concentrating on what people say to you, even when they are speaking to you directly?</p> <p>4.*# How often do you have trouble wrapping up the fine details of a project, once the challenging parts have been done?</p> <p>5.*# How often do you have difficulty getting things in order when you have to do a task that requires organization?</p> <p>6.# When you have a task that requires a lot of thought, how often do you avoid or delay getting started?</p> <p>7. How often do you misplace or have difficulty finding things at home or at work ? 8. How often are you distracted by activity or noise around you?</p> <p>8. How often are you distracted by activity or noise around you?</p> <p>9.*# How often do you have problems remembering appointments or obligations?</p> <p style="text-align: center;">II. Hyperactivity-Impulsivity</p> <p>1.# How often do you fidget or squirm with your hands or your feet when you have to sit down for a long time?</p> <p>2.* How often do you leave your seat in meetings or other situations in which you are expected to remain seated?</p> <p>3. How often do you feel restless or fidgety?</p> <p>4. How often do you have difficulty unwinding and relaxing when you have time to yourself?</p> <p>5.# How often do you feel overly active and compelled to do things, like you were driven by a motor?</p> <p>6. How often do you find yourself talking too much when you are in a social situation?</p> <p>7.* When you're in a conversation, how often do you find yourself finishing the sentences of the people that you are talking to, before they can finish them themselves?</p> <p>8. How often do you have difficulty waiting your turn in situations when turn-taking is required?</p> <p>9.* How often do you interrupt others when they are busy?</p> <p>Response options are: never, rarely, sometimes, often, and very often. Patients were asked to answer the questions using a 6-month recall period.</p> <p>* Clinically significant symptom levels were defined for these seven questions as responses of sometimes, often, and very often. For all remaining 11 questions, often and very often were the clinically significant symptom levels.</p> <p># The six-question ASRS screener.</p>
