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Electrophysiological effects of smartphone notifications on cognitive control following a brief mindfulness induction

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ABSTRACT

Smartphone use is nearly ubiquitous, with 93% of adults among economically developed countries, including the United States, Canada, Israel, and South Korea owning a smartphone (Taylor & Silver, 2019). Multiple studies have demonstrated the distracting effects of smartphone notifications on behavioral measures of cognition. Fewer studies have examined the effects of notifications on neural activity underlying higher-level cognitive processes or behavioral inductions to reduce smartphone-related distraction. Using EEG spectral frequency power densities, we assessed the effects of smartphone notifications (vs. control trials) on engagement of attentional shifting processes involved in cognitive control during a Navon Letter visual oddball task. Participants were randomly assigned to a brief mindfulness induction (N = 44) or a neutral narration control condition (N = 43). Overall, participants had lower theta-band power, but higher alpha- and beta-band power densities on target letter trials preceded by smartphone notifications. Additionally, participants in the mindfulness (vs. control) condition had a larger attention shifting oddball assessed via theta power density and theta/beta ratio (TBR) values—reflecting increased engagement of cognitive control—particularly on smartphone notification (vs. control) trials. Altogether, these results provide evidence supporting the idea that smartphone notifications can decrease activity of neural correlates of cognitive control, and offer the promise of a brief mindfulness induction to buffer against the effects of smartphone notifications on cognitive control. The findings indicate a need for further research on mindfulness inductiosn as a means to reduce potential distraction caused by smartphones.

During a time of remote employment and social distancing, the use of smartphones has become more prevalent than ever. Recent global data indicate that 76% of adults own a smartphone (Taylor & Silver, 2019), and 5 billion people are subscribed to mobile internet services (The Mobile Economy, 2020). Smartphone usage data indicate that people spend 2–5 hours on their smartphones and check them 52–84 times per day (Andrews et al., 2015; dscout, 2016; Lee et al., 2019; Rosen et al., 2018). However, use of these devices may come with a cost. People who use their smartphones excessively have reduced attentional capacities (Kushlev et al., 2016), have worse academic performance (Felisoni & Godoi, 2018), and experience negative effects on their real-world interpersonal relationships (Sbarra et al., 2019). These effects may be driven by the effects of smartphones on *cognitive control* - i.e., the capacity to prioritize information for the purpose of maintaining goal-directed behavior (for review, Mackie et al., 2013). To date, little work has examined whether acute smartphone usage or smartphone notifications influence cognitive and neural indices of cognitive control. Even less work has examined how to buffer against the negative effects of smartphones on cognitive control. This study addresses this gap by examining how smartphone notifications influence cognitive and neural indices of cognitive control, as well as how a mindfulness induction may influence these dynamics.

A smartphone notification is, by design, intended to capture the device user's attention and orient it toward the device—no matter the user's current task. The notifications are thus intended to disrupt cognitive control by interfering with ongoing processing and goal-directed behavior (Kim et al., 2016). This goal interference, in turn, could contribute to the problematic outcomes associated with smartphone overuse, including poorer cognitive performance on attention and cognitive control tasks (Ito & Kawahara, 2017; for review, Liebherr et al., 2020; Wilmer et al., 2017). Although findings suggest that smartphone overuse is related to poorer cognitive control, the neurocognitive mechanisms are not well characterized.

Electroencephalography (EEG) signals indicative of cognitive control

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have been well characterized; thus, these signals can help to uncover the neurocognitive mechanisms underpinning potential effects of smartphone notifications on cognitive control (Cavanagh & Shackman, 2015; Klimesch, 2012; Lu et al., 2017). Spectral frequency power density describes the magnitude, or strength, of neural oscillatory fluctuations in EEG signal underlying various cognitive processes (Le Van Quyen & Bragin, 2007; Morales & Bowers, 2022). Power is examined in different frequency bands (e.g., theta, alpha, beta) that have been associated with specific states of mental activity (e.g., Stevens & Zabelina, 2019). Changes in EEG spectral power following experimental stimuli are considered to reflect changes in synchronization of electrical cortical activity across time and space (Makeig, 1993; Pfurtscheller & Lopes da Silva, 1999). Indices of cognitive control are detectable in each EEG spectral frequency band. For example, greater event-related theta-band (4–7 Hz) power is thought to reflect conflict monitoring processes, and it is indicative of increased levels of neural communication across brain regions during goal-directed tasks involving response conflict (e.g., Flanker task; Nigbur et al., 2012). In contrast to theta, lower levels of event-related frontal alpha-band (8–12 Hz) power are associated with enhanced task-relevant attentional control and inhibition during executive function oddball tasks (Klimesch, 1999, 2012; Klimesch et al., 2007). Beta-band oscillations (13–30 Hz) are involved in sensory information maintenance processes, and like theta power, increased non-event related resting state beta power is indicative of greater attentional vigilance (Laufs et al., 2006), and engagement of cognitive control processes reflected by a narrowed attentional breadth during a Navon letter task (Pitchford & Arnell, 2019). Even high frequency gamma-band (30–80 Hz) power has been found to be modulated by cognitive control processes (ElShafei et al., 2019).

In addition to the individual spectral power bands, a growing body of EEG literature suggests that a frontal theta/beta ratio (TBR) may offer a robust electrophysiological index of cognitive control. TBR measured at frontocentral scalp locations is considered to reflect communication between top-down cortical activity involved in cognitive control and bottom-up subcortical activity involved in stimulus reward and motivation responses (Schutter & Van Honk, 2005). Higher frontal midline resting state TBR is associated with increased ADHD symptoms (Zhang et al., 2017), increased distraction and emotion regulation difficulties (Kobayashi et al., 2020), greater levels of mind wandering with lower executive control network activity (van Son et al., 2019), and lower levels of cognitive control of attention (Angelidis, 2018; Angelidis et al., 2016). Mindfulness-based inductions have been found to reduce resting TBR in people with ADHD (Sibalis et al., 2017) and bipolar disorder (Howells et al., 2012), and these effects were also accompanied by improvements in behavioral indices of attention. Using task-based EEG measures, Sibalis and colleagues (2017) found that youth with ADHD demonstrated decreased TBR following a mindfulness induction (vs. control), reflecting greater attentional control abilities on a Go/No-Go task. See supplemental materials for a summarized table of these findings (Table S1).

Despite growing evidence of spectral measures as markers of cognitive control, little work, and none to our knowledge in the case of TBR specifically, has examined these well-validated indices in relation to smartphone use and cognitive control. Other EEG work, however, has examined frontal theta/posterior alpha band (TAR) power ratios as an index of top-down cognitive processes while people use smartphones in different ways, such as listening to podcast audio or producing voice messages (Cabañero et al., 2020). While actively producing (vs. passively consuming) content on a smartphone, people had increased TAR, reflecting greater cognitive load. One study found that when smartphones were placed near sleeping participants, they demonstrated increased low frequency delta band power in combination with delayed sleep onset latency (Hung et al., 2007).

A separate study documented that exposure to auditory distraction enhances neural responses to auditory stimuli, and subsequently reduces available neural resources for effectively engaging cognitive control indexed via theta band power (Ponjavic-Conte et al., 2012). Other work still, has found modulatory effects of smartphone use levels on neural excitability in pre-frontal cortical regions, such that heavier smartphone users showed reduced evoked potential activation and increased impulsivity and hyperactivity (Hadar et al., 2017). Furthermore, there is evidence that greater frontocentral cortical activation provides an index of increased pre-attentive neural activation involved in processing auditory stimuli (i.e., mismatch negativity) and likely reflects involuntary attentional switching processes when exposed to smartphone notification sounds (Lee et al., 2014). Together, these results suggest that temporary decrements in cognitive control induced by smartphone notification sounds, if they exist, should be detectable in EEG spectral power.

If smartphones reduce cognitive control, determining practices that could prevent such cognitive effects would be important. One potential practice that may reduce the cognitive costs associated with smartphone use is mindfulness, which prior work has suggested may help to improve cognitive control and related EEG spectral power indices (Berkovich-Ohana et al., 2012; Bing-Canar et al., 2016; Bishop et al., 2004; Cahn et al., 2013; Cahn & Polich, 2006; Howells et al., 2012; Lomas et al., 2015; Sibalis et al., 2017; Xue et al., 2014). Abundant empirical evidence suggests beneficial effects of multiple and long-term mindfulness practices on higher level cognitive processing (for review, Lin et al., 2022). Importantly, however, even brief one-time mindfulness inductions completed prior to starting a cognitive task can reduce neural activity associated with mind-wandering and automatic reactivity. For example, participants who completed a 14-minute mindful breathing (vs. control) exercise showed greater suppression of frontal error-related alpha power during a Stroop task (Bing-Canar et al., 2016). The same mindfulness induction protocol was originally employed in earlier work demonstrating a reduction in error related neural activation during a Flanker task (Larson et al., 2013). Similarly, completing a 25-minute mindfulness (vs. control) practice reduced late (500 ms post stimulus) and increased early (0–250 ms) event-related alpha power and increased theta phase synchrony at frontal midline regions during an auditory oddball task (Cahn et al., 2013). This suggests that inducing a mindfulness state increases neural activity associated with self-monitoring and attentional focus during the completion of subsequent tasks requiring cognitive control. In addition, inducing mindfulness may decrease neural signal linked to autonomic arousal while completing cognitive control tasks. In turn, inducing a less reactive mental state may increase efficient recruitment of task related neural resources necessary for efficient engagement of cognitive control processes.

Based on evidence that brief, one-time mindfulness-based inductions can affect neural markers indexing enhanced cognitive control along frontal midline cortical locations, it is possible that mindfulness could buffer against detrimental effects of smartphones on cognitive control processes. To date, no study has examined the effects of a one-time, brief mindfulness induction on smartphone-induced modulation of EEG indices underlying cognitive control processes.

1. The current study

To evaluate the neurocognitive effects of smartphone notifications and potential buffering by mindfulness, the current study examined event-related EEG spectral frequency dynamics during a visual Navon Letter attentional shifting oddball task after participants completed either a one-time mindfulness-based induction or control induction task. During the oddball task, target stimuli were preceded by smartphone notifications, control sounds, or silence. This paradigm involves high perceptual homogeneity across visual stimuli (Becker et al., 2013) that require similar motor responses, reducing concerns of stimulus orienting contingencies (Folk et al., 1992) and motor activity (Luck, 2014) confounds for frontal midline neural measures indexing higher level cognitive processes. In addition, we assessed the degree to which a mindfulness intervention influenced the attentional switching, or shifting, component of cognitive control as opposed to the inhibition or updating components (Miyake et al., 2000). Prior work suggests that mindfulness may enhance one's capacity to flexibly shift attention efficiently from one point of concentrated focus to another depending on perceptual task demands (Lutz et al., 2008). Thus, we expected the effects of mindfulness on cognitive control to be most robust for a paradigm requiring attention shifting with little variation across stimuli perceptual features.

Drawing on prior work (e.g., Angelidis, 2018; Angelidis et al., 2016; Arns et al., 2013; Putman et al., 2010, 2014; Snyder & Hall, 2006), we expected to find that smaller TBR would be associated with greater engagement of cognitive control, and that smartphone notifications would negatively affect cognitive control (Kim et al., 2016; Upshaw et al., 2022). We further expected that participants randomly assigned to the mindfulness induction condition would show better cognitive control (both in behavioral and neural indices—namely, lower TBR, greater alpha power) than participants in the control condition, and that experimental condition differences would be more pronounced on trials preceded by smartphone notifications.

2. Method

2.1. Participants

Eligible college students ($N = 101$) participated in the study. Four participants had incomplete EEG data and were removed from the dataset prior to further analyses for a total sample of 97 participants available for EEG data preprocessing. Ages ranged from 18 and 29 ($M = 20.34$, $SD = 2.85$). Sixty-four participants were female; 33 were male. In terms of race, 80% of participants identified as Caucasian, 9% Latino(a), 7% Asian (American), 1% African (American), 1% Native (American), and 1% multi-racial. EEG data for ten participants were excluded from the analyses for excessive signal noise. The final sample used for EEG data analysis was $N = 87$, Mindfulness = 44, Control = 43, Male = 32, Female = 55, age range 18–29, $M_{age} = 20.30$, $SD = 2.82$.

Participants were recruited through the university news email and via the university's psychology research pool. Participants were screened for visual or hearing impairments, tightly curled or braided hair, permanent wigs or hair extensions, moderate to severe claustrophobia symptoms, or regular muscle twitching that causes significant body movements. Participants were compensated with research participation credit ($N = 74$) or a $35 Amazon gift card ($N = 13$). Of the paid participants, approximately half (7/13) were randomly assigned to the mindfulness condition. The study protocol was approved by the local University Institutional Review Board, and all participants provided informed consent prior to participation.

Power analysis was conducted to determine the necessary sample size using the *pwr.f2.test()* function from the pwr package in RStudio (RStudio Team, 2020). We set the function arguments to detect a medium sized effect of $\eta_p^2 = .11$ (Cohen, 1988), with an effect detection power of $\beta = .80$, a significance threshold of $\alpha = .05$, and 2 degrees of freedom for the numerator (experimental condition and sound stimulus condition). Results revealed a required sample size of 31 people per experimental condition (i.e., mindfulness induction and control induction).

3. Materials

3.1. Brief mindfulness induction

As a mindfulness induction we used a three-minute guided audio recording of a "cRaisin-eating" exercise, also known as a mindful eating meditation (Kabat-Zinn, 2003), adapted from Kabat-Zinn and colleagues' (1992) mindfulness-based stress reduction program. Participants were given a craisin and were then asked to close their eyes and take a deep breath ,and were guided through multiple sensory experiences involved in eating a craisin. They were told to feel, smell, visually examine, and reflect on the origins of the craisin. Lastly, they were instructed to mindfully taste the craisin for 10 s before slowly chewing and swallowing it. The recording featured a female voice and was listened to via wired Apple earphones.

3.2. Control induction

A three-minute audio recording providing information about glaciers (i.e., how they form and travel) and the valleys they formed (Wikipedia contributors, 2021). The recording was chosen because such information is considered affectively neutral (Pliner et al., 1974). Participants in the control condition ate a craisin at the end of the audio recording to keep blood sugar level changes consistent between induction conditions. The control audio recording featured the same female voice used in the mindfulness induction recording and was listened to via wired Apple earphones.

3.3. Local-global navon letter task

A modified Navon Letter task (Navon, 1977) was used to assess attentional shifting of cognitive control. During this task, one of a series of 12 hierarchical letter stimuli (i.e., one big letter comprised of smaller letters) were presented pseudo-randomly to participants on a computer monitor (Fig. 1A). Participants were instructed to respond "Yes" (1 key = present) or "No" (2 key = not present) with their right hand to the presence of a target letter provided at the beginning of each block. Letter stimuli were designed so that global and local oriented letters elicit approximately equal target letter response speeds and accuracy (Bultitude et al., 2009).

Participants were positioned 67 cm from their nose to the monitor (1920 ×1200 Pixel Resolution 24" LCD monitor). The task was delivered via Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). The local letters (subtending 0.43 by 0.86 degrees of visual angle) were arranged within a 5 cm × 3 cm rectangular grid forming the boundary of global letter (subtending approximately 2.57 by 4.27 degrees of visual angle).

Each trial began with a 1250 ms auditory stimulus or silence presented concurrently with a visual fixation cross that was randomly jittered between 1400 and 1600 ms (Fig. 1, panel C). The fixation cross was followed by the visual letter stimulus centered on the screen for 700 ms. During this time, participants were to respond to the presence or absence of the target letter. On any of the 16 task blocks, target letters were presented either at the global (large letter) or local (small letters) level of attention 80% of the time (frequent trials, 48 trials per block), at the opposite attentional level 10% of the time (rare, 6 trials per block), or was not present 10% of the time (6 trials per block), for a total of 960 trials (Fig. 1, panel B). Sound and letter stimuli were pseudo-randomly ordered and counterbalanced to ensure equal presentation across experimental blocks.

The auditory stimulus condition was either a smartphone notification vibration, a computer-generated square wave tone (control sound), or no sound (silence). Sounds were presented in a pseudo-random order. The sounds were delivered via wired Apple headphones. Sound volume levels were adjusted to 89db in MP3GainExpress and were played at 70% maximum volume (~62db). The smartphone notification sound was a default iPhone vibration downloaded from freesound.org. The control sound was a computer-generated square wave tone created in Audacity (version 2.2.2, Audacity Team, 2019). The auditory spectrums of the sound stimuli were adjusted to be acoustically matched on amplitude (loudness = 89db) and duration (1250 ms; Fig. 2A). Sound frequencies were manually adjusted and partially matched using Voxengo CurveEQ virtual studio technology plugin in LMMS music editing software to reduce differences in auditory perception preferences and maintaining the uniqueness of each sound's specific timbre (Fig. 2B; De Martino et al., 2015). See supplemental material for more details on

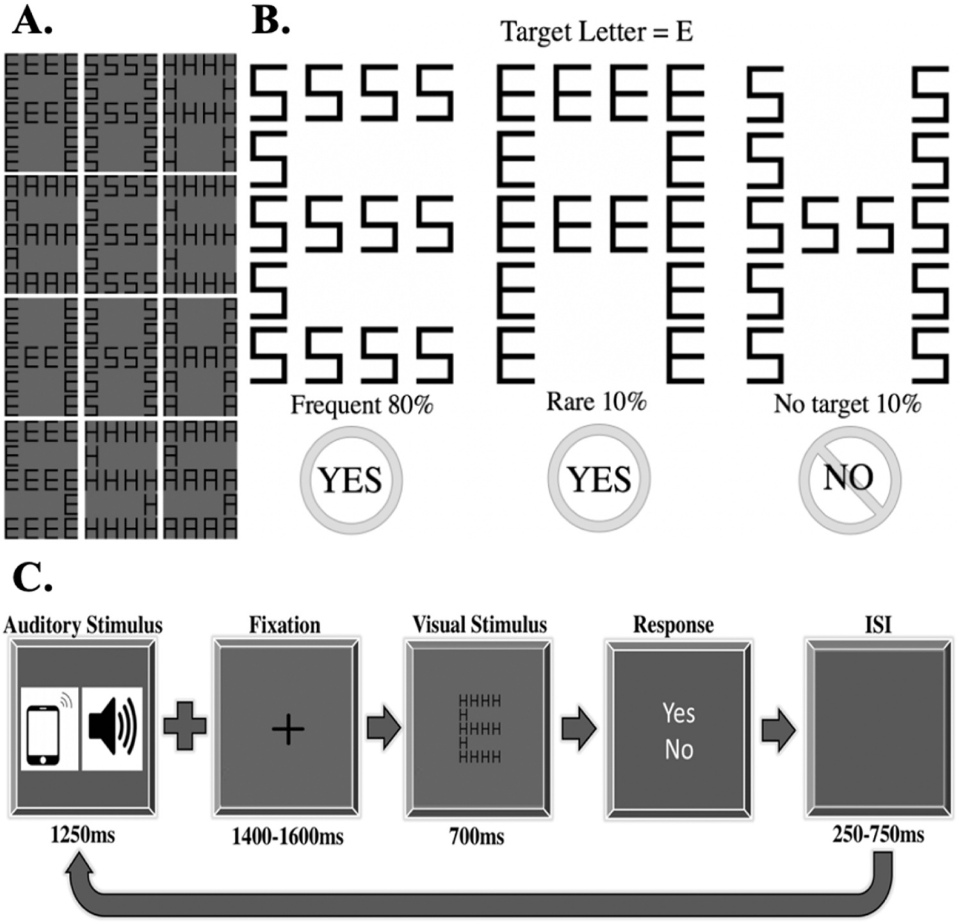

Fig. 1. *Navon Letter Attentional Shifting Oddball Task. Note.* A): Navon Letter task stimuli. B): In this example (white background for example), participants responded if target letter E was present (at the global or local level, 80% and 10% of trials, counterbalanced), or not (10% of trials). C): Single trial task structure. ISI = inter-stimulus interval.

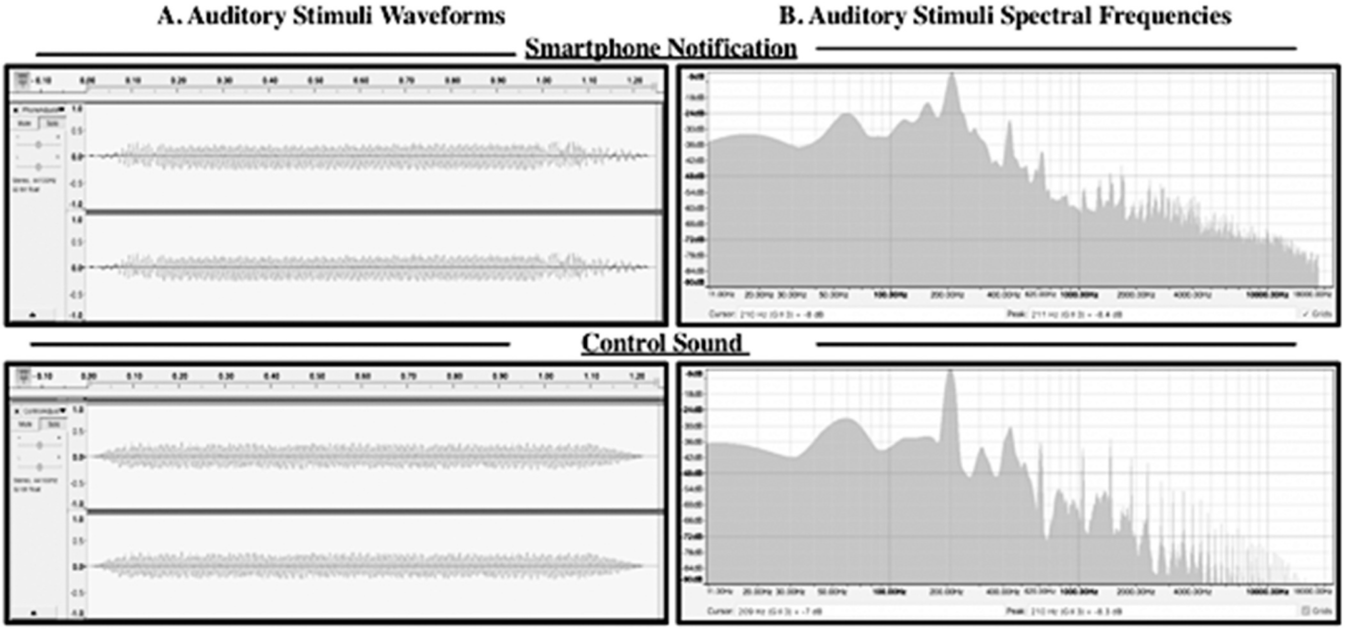

Fig. 2. *Signal Waveforms and Frequency Spectrum Plots of Auditory Stimuli. Note.* A. Sinusoidal waveforms and B. frequency power spectrum plots of auditory stimuli.

Navon Letter task design and validation of the auditory stimuli.

3.4. EEG signal processing

Continuous EEG data were collected from 32 active electrodes arranged according to the 10–20 system with a sampling rate of 512 Hz using an ActiveTwo Biosemi system. Six loose lead Ag/AgCl electrodes were used to differentiate brain vs. non-brain related activity during subsequent EEG data processing. Vertical eye movement was monitored using polarity differences between frontal polar channels above each eye (Fp1,Fp2) and two peri-ocular channels (infra orbital, IO1, IO2) located below each eye, 2 peri-ocular electrodes placed on the outer canthi of the left and right eyes monitored lateral eye movements, and 2 electrodes placed on the left and right mastoids were used for online signal referencing. EEG data were pre-processed offline in MATLAB using the EEGLab plugin (Delorme & Makeig, 2004) and followed Makoto's preprocessing pipeline (n.d.) (see supplemental material for pre-processing MATLAB code). EEG data were down sampled to 256 Hz. Slow wave frequencies (< 1 Hz) were removed from the EEG data using a Hamming windowed sinc finite impulse response (FIR) high-pass filter. Channel locations were imported using the Standard 10–5 montage with electrooculogram (EOG) Besa Spherical montage array in EEGLAB. Sinusoidal line noise artifacts (e.g., 60 Hz AC electrical grid noise) were identified and removed from EEG channel data. Rejected channels were interpolated from the original EEG dataset.

EEG data were re-referenced to the common average to approximate scalp potentials independent from specific reference channel locations. Following re-referencing, high-amplitude, non-stationary signal burst artifacts were cleaned from the data using artifact subspace reconstruction. Data were again re-referenced to the common average to zero-sum the signal across channels, in turn improving ICA decomposition quality. We employed an extended Infomax ICA algorithm to perform EEG data source separation (Bell & Sejnowski, 1995; Makeig et al., 1995) using the *Runica()* function (Makeig, 2000). Individual components were classified using the *ICLabel()* function (Pion-Tonachini et al., 2019). Non-brain identified components with a probability greater than 90% were flagged and later rejected from the data during spectral frequency analysis. Across all participants, an average of 2.73 ($SD = 2.08$) components met were flagged for rejection from participant EEG data. There was no significant difference in the number of components rejected between the mindfulness ($M = 2.80$, $SD = 4.72$) and control ($M = 2.77$, $SD = 4.09$) conditions $t(85) = 0.06$, $p = .951$.

Following ICA decomposition, EEG data were low pass FIR filtered with a high frequency band edge cut-off of 35 Hz, based on processing from Putman et al. (2010). After filtering, 9 time-locked stimulus event labels were added to the EEG data files. 3 events for “frequent” target letter trials preceded by each sound condition stimulus, 3 for “rare” target letter trials preceded by sound conditions, and 3 for “no target” letter trials preceded by sound conditions (not discussed in this paper). EEG data were epoched across the 9 different trial event labels for a total latency window of 3000 ms with a pre-stimulus baseline of − 1000 ms and a post-stimulus onset length of 2000 ms. Epoch latency values were chosen to create an adequate buffer zone (i.e., at least 3 cycles of lowest frequency measured) to avoid edge artifacts from transforming signal data from the time domain to the power domain (Cohen, 2014).

Following EEG data preprocessing, we employed a three-part assessment to quantify the number of trials contaminated with noise artifacts in the processed EEG data (e.g., eye movement, muscle activity, sweat bridging, line noise, etc.). We used a moving window peak to peak threshold detection using two vertical eye channels (IO1/IO2), a step-like artifact detection using two lateral eye channels (LO1/LO2), and a moving window peak to peak threshold using all channels. An artifact summary file for each participant was created (see supplementary material). Preprocessed EEG data from ten participants were excluded from analyses due to an excess of 25% of trials for a given event condition marked as contaminated with artifacts (Luck, 2014). See supplemental material for additional EEG preprocessing information.

3.5. Spectral frequency power density processing

Based on prior work investigating relationships between TBR and executive functions (Angelidis, 2018; Angelidis et al., 2016; Arns et al., 2013; Putman et al., 2010, 2014; Snyder & Hall, 2006), frontocentral electrode channels F3, Fz, and F4 were used for spectral power decompositions. Mean spectral power values were computed for all 12 event epochs described above for each participant using the *std_precompute()* function (Delorme, 2006) which utilizes the *newtimef()* function. Artifactual components flagged using ICA were removed prior to spectral power computations.

Spectral power computations produced a time x frequency matrix with average log power (dB) values with the measurement criteria of 60 output frequencies (between 3 and 30 Hz), 200 output times, and a zero-padded cycle of 3 gaussian shaped Morlet wavelet tapers increasing by a factor of 0.8. Spectral powers were computed for each event epoch using time windows of − 1000 pre-stimulus to 2000 ms post-stimulus onset. Separate spectral power values from frequent and rare letter trials were used to compute an attentional shifting oddball power measure indexing cognitive control. Based on previous research (Bonnefond & Jensen, 2012; Putman et al., 2010), spectral power density (mV^2) was calculated for theta (4–7 Hz), alpha (8–12 Hz), and beta (13–30 Hz) frequency bands. The frequency bands were natural log-normalized (Ln) based on prior reports of skewed distributions (Angelidis, 2018; Angelidis et al., 2016; Putman et al., 2010, 2014). We calculated decibels from Hz using the formula $10 * \log_{10}(mV^2/\text{Hz})$. TBR was calculated by dividing theta power by beta band power density values. Higher TBR (worse attentional control) is reflected by greater frontal theta relative to beta power and vice versa for lower TBR. That is, as frontal beta increases relative to theta power, TBR decreases, reflecting better attentional control.

3.6. Behavioral data processing

For behavioral data analyses, we excluded incorrect response trials, which included responses made outside of the 700 ms stimulus onset window. Within subject letter trials with RTs greater than + /- 2.5 *SD*s from individual participant mean RT were excluded from behavioral analyses. In addition, behavioral data from participants with + /- 2.5 *SD*s of total number of trials excluded for fast or slow RTs relative to the sample mean aggregated RT were excluded from behavioral analyses. Behavioral data were further excluded from analyses if the participants' response error rate was greater than + /- 2.5 *SD* from the sample mean aggregated error rate. Behavioral data from 3 participants were excluded from behavioral analyses due to excessive RTs and error rates. The final sample size for behavioral data analysis was $N = 95$, Mindfulness = 47, Control = 48, Male = 32, Female = 63, $M_{age} = 20.46$, $SD = 2.87$. A split half reliability analysis found a Spearman-Brown correlation of 1 for odd and even trial average RTs indicating a high degree of internal consistency across behavioral response speeds.

4. Procedure

After providing consent, participants completed a 45-minute online questionnaire battery prior to the in-person EEG session. Participants were instructed to not be under the influence of excessive caffeine, unprescribed medication, or alcohol during the EEG session.

4.1. EEG experimental sessions

Participants were randomly assigned to the mindfulness-based induction (N = 49) or control condition (N = 48) and were not informed about condition assignment. We counterbalanced male and female participants across conditions to avoid potential gender effects, a known confound among similar research (Csibi et al., 2021; Lee et al., 2012;

Twenge & Martin, 2020). Participants silenced their personal smartphones and placed their belongings in a separate room. After connecting the EEG equipment and headphones, participants were centered in front of the computer monitor and were asked to maintain an upright, yet comfortable posture during the study. Participants then listened to the mindful craisin-eating (mindfulness condition) or the glacier information recording (control condition) depending on condition assignment.

Following the experimental manipulation, participants were given instructions for completing the Navon Letter oddball task. They were instructed to minimize blinking and other movement while completing the task, especially when hearing sounds or seeing letters on the monitor. They were instructed to respond as quickly and accurately as possible, and to disregard the sound stimuli. Participants were instructed to use break periods to blink, stretch, and refresh themselves as necessary.

After successfully completing two practice blocks, the researcher began recording continuous EEG data as participants completed 16 blocks of the oddball task. Each block ended with a self-paced break, with a mandatory 1-minute break after every fourth block. Each block lasted approximately 5 min, with a 75-minute approximate task finish time. A full EEG session took up to 2.5 h to complete.

5. Analytic approach

Data were cleaned and analyzed in RStudio (RStudio Team, 2015). We tested our hypotheses by conducting 2 (experimental condition: brief mindfulness induction vs. control) x 3 (sound stimuli: smartphone, control tone, silent) x 3 (power band: theta, alpha, beta) repeated measures analyses of variance (ANOVAs) with dependent variables (DVs) of spectral power densities time-locked to target letter stimuli for trials overall and for the oddball measure. Follow-up post-hoc comparisons were conducted on significant findings using condition contrasts for estimated marginal means to assess differences between experimental conditions, sound stimuli, and trial types. Partial eta squared effect sizes were calculated from *F*-values and degrees of freedom (Lakens, 2013). The attentional shifting oddball measures were calculated as the absolute value of the difference score for theta, beta, and alpha band power densities, and TBR values between rare and frequent target letter trials. Oddball measures were square root normalized.

For behavioral analyses, we conducted a 2 (experimental condition: brief mindfulness intervention vs. control) x 2 (trial frequency: rare vs. frequent) x 3 (sound condition: smartphone, control tone, silent) repeated measures ANOVAs with RT as the DV and participant identifier as a random effects variable to capture within-subject variance across trials.

See supplemental materials for covariate analyses controlling for dispositional trait mindfulness (MAAS), age, and gender for significant results.

6. Results

6.1. Spectral power findings

Differences in mean spectral power densities for theta (4–7 Hz), alpha (8–12 Hz), and beta (13–30 Hz) power bands time-locked to the letter stimuli were examined between experimental conditions, the auditory stimuli conditions, and letter stimulus presentation frequency We performed a 2x3x2x3 repeated measures ANOVA on power density values as the dependent variable (DV) with experimental condition (mindfulness, control) as a between-subjects factor and within-subjects factors of sound stimuli (smartphone notification, control tone, silence), letter trial type (rare, frequent), and power band (theta, alpha, beta) as the independent variables (IVs). Results revealed a significant three-way interaction of experimental condition, trial type, and power band on spectral power densities, $F(2, 164) = 3.45$, $p = .034$. This result indicates that the difference in overall power density between rare and frequent letter trials varied between the mindfulness and control conditions more for some power bands relative to others.

6.2. Overall spectral power differences

There was a significant two-way interaction between trial type and power band, $F(2, 164) = 141.17$, $p < .001$, and a significant main effect of trial type, $F(1, 82) = 13.72$, $p < .001$. Follow-up tests revealed that compared to frequent trials, rare letter trials had more theta, less alpha, and less beta power, p's $< .001$ (Fig. 3, Table S2), indicating systematic variability in spectral power densities between letter trials presented more or less frequently at opposite levels of attention. Thus, averaging power density values across rare and frequently presented letter trials may inadvertently remove valuable information. As such, we report below additional ANOVA results assessing the attentional shifting oddball as the DV to account for these systematic differences. There were no other significant interactions or main effects of experimental condition on overall power density values, $ps > .227$. These findings fail to support our prediction that overall alpha power would be greater for people in the mindfulness (vs. control) condition.

There was a significant main effect of sound stimuli, $F(2, 164) = 3.93$, $p < .022$, indicating that overall spectral power – i.e., power density values averaged across experimental conditions, target letter trial types, and power bands – varied between trials preceded by smartphone notifications, control tone sounds, and silent trials. Follow-up analyses revealed lower overall spectral power for tone sound (vs. silent) trials, $t(82) = -2.72$, $p = .008$, $\eta_p^2 = .08$. Overall power for smartphone notification trials did not significantly differ from tone sound and silent trials, p's $> .080$. In addition, results of the overall power densities revealed a trending, but non-significant three-way interaction of sound stimuli, trial type, and power band, $F(4, 328) = 2.14$, $p = .076$, and a trending two-way interaction of sound stimuli and power band, $F(4, 328) = 2.02$, $p = .091$. This finding partially suggests that overall power density and to a somewhat greater degree, the attentional shifting oddball varied between the three sound stimuli as a function of the power frequency bands.

Follow-up tests assessed power differences between the three sound stimuli for each power band separately. Results revealed that theta power was marginally lower for smartphone notification (vs. silent) trials, $t(82) = -1.98$, $p = .051$, $\eta_p^2 = .05$ (Table 1, Fig. 4A). Theta did not significantly differ between smartphone and tone trials, $t(82) = -0.46$, $p = .647$, $\eta_p^2 = .003$, or tone and silent trials, $t(82) = -1.53$, $p = .129$, $\eta_p^2 = .03$. Alpha power was significantly lower for tone sound (vs. silent) trials, $t(82) = -2.54$, $p = .013$, $\eta_p^2 = .07$, and marginally higher for smartphone (vs. tone) trials, $t(82) = 1.90$, $p = .061$, $\eta_p^2 = .04$ (Fig. 4B). Alpha did not significantly differ between smartphone and silent trials, $t(82) = -0.69$, $p = .491$, $\eta_p^2 = .01$. Beta power was significantly higher for smartphone (vs. tone) trials, $t(82) = 2.88$, $p = .005$, $\eta_p^2 = .09$. Beta did not significantly differ between smartphone and silent trials, $t(82) = 1.03$, $p = .306$, $\eta_p^2 = .01$, or tone and silent trials, $t(82) = -1.59$, $p = .115$, $\eta_p^2 = .03$ (Fig. 4C).

6.3. Spectral power oddball differences

To account for differential effects of rare and frequent trials on overall power density, a 2x3x3 repeated measures ANOVA was performed on the power density attention shifting oddball as the DV with experimental condition, sound stimuli, and power band as IVs. Results revealed a significant main effect of experimental condition on the power density oddball, $F(1, 82) = 4.71$, $p = .033$, indicating that people in the mindfulness condition ($M = 0.64$, $SD = 0.26$) had a larger overall attentional shifting oddball, reflecting increased engagement of cognitive control, compared to those in the control condition ($M = 0.59$, $SD = 0.26$). There was a marginally significant interaction of experimental condition and power band, $F(2, 164) = 3.01$, $p = .052$, suggesting that differences in the power density oddball between the mindfulness and

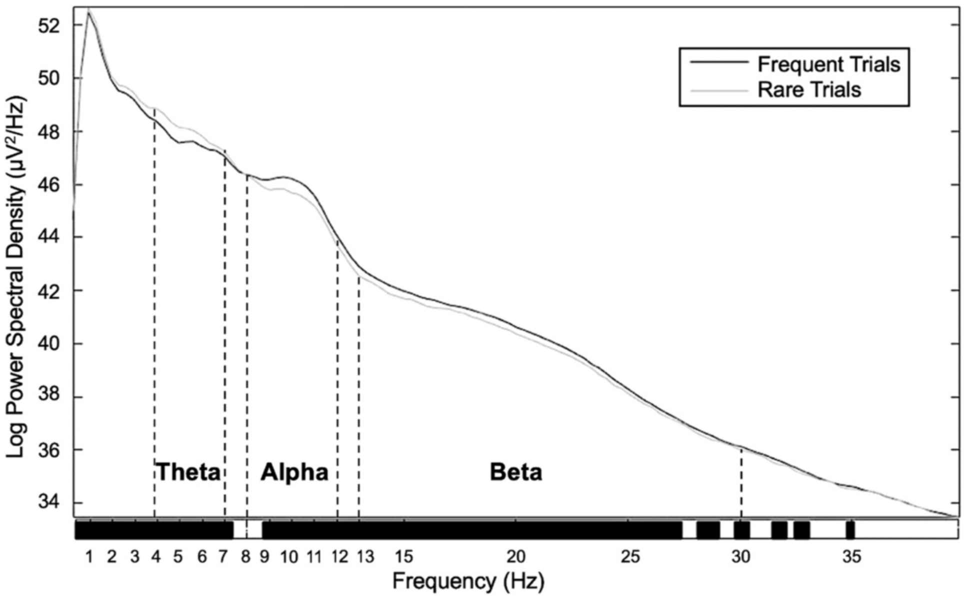

Fig. 3. *Power Density Plots for Rare and Frequent Target Letter Trials. Note*. Spectral power density plots (0–40 Hz) illustrating differences between frequent (black) and rare (gray) target letter trials. Power frequency bands are labeled. The black bar indicates regions of significant difference ($p < .05$).

Table 1
Means and Standard Deviations of Power Densities for Sound Stimuli.

	Theta (db)		Alpha (db)		Beta (db)		TBR	
Auditory Stimuli	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Smartphone Notification	47.64	1.72	45.79	2.90	39.69	2.10	1.202	0.05
Control Tone	47.66	1.72	45.72	2.85	39.65	2.08	1.204	0.05
Silence	47.70	1.71	45.75	2.86	39.65	2.08	1.205	0.05

Note: $N = 87$; TBR = theta/beta ratio.

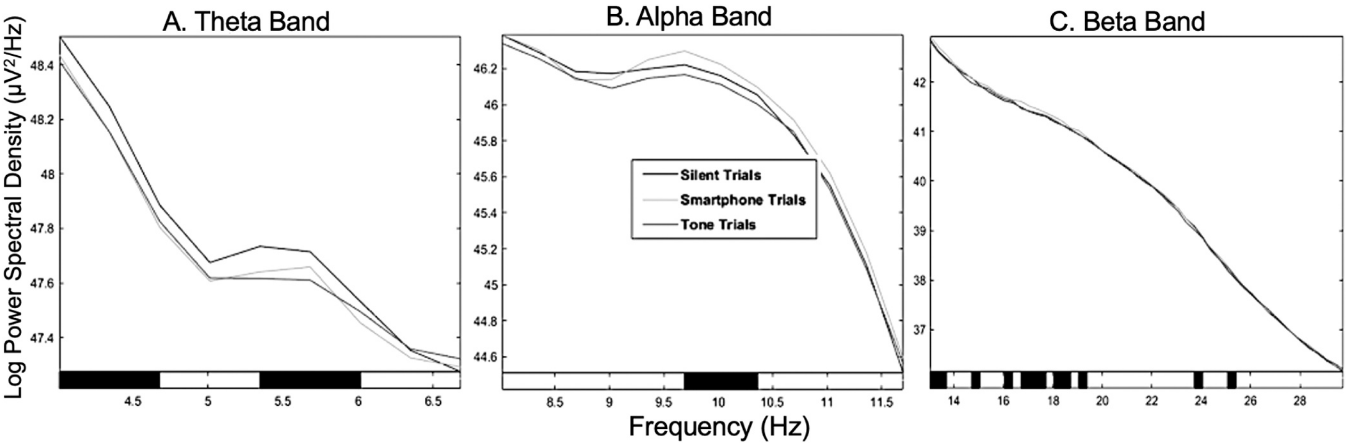

Fig. 4. *Power Density Plots Between Sound Stimuli for Theta, Alpha, and Beta-Bands. Note*. EEG spectral power density plots for theta (4–7 Hz), alpha (8–12 Hz), and beta (13–30 Hz) frequency bands illustrating power differences between target letter trials preceded by smartphone notification sounds (green), control tone sounds (pink), and silence (blue). The black bars indicate regions of significant differences ($p < .05$).

control conditions varied between the three power frequency bands. Follow-up tests revealed a significantly larger theta oddball in the mindfulness (vs. control) condition (Table 2, Fig. 5). There were no significant differences in the oddball for alpha or beta power bands, *ps* > .530 (Table S4), suggesting that experimental condition differences in the overall power density oddball were primarily observed in the theta power band. There were no significant interaction or main effects of sound stimuli on the overall power oddball, *ps* > .180.

7. Theta/Beta ratio (TBR) findings

7.1. Overall TBR differences

A 2x3x2 repeated measures ANOVA was performed on the ratio of theta and beta band power (TBR) as the DV with experimental condition as a between-subjects factor and within-subjects factors of sound stimuli and target letter trial type as IVs. Results revealed a significant two-way interaction between experimental condition and trial type on TBR, *F*(1,

Table 2

Post-hoc Tests for Theta Power Densities Between Experimental Conditions.

Measure	Mindfulness		Control						
	M	*SD*	*M*	*SD*	*B*	*SE*	*t* (82)	*p*	η_p^2
Theta (db)									
Overall	47.77	1.81	47.85	1.68	0.07	0.38	0.19	.848	.00
Rare Trials	48.00	1.79	47.98	1.70	-0.01	0.19	-0.05	.957	.00
Frequent Trials	47.55	1.81	47.71	1.66	0.08	0.19	0.44	.665	.00
Oddball	0.72	0.26	0.58	0.26	-0.14	0.04	-3.43	.001	.13

Note: $N = 87$.

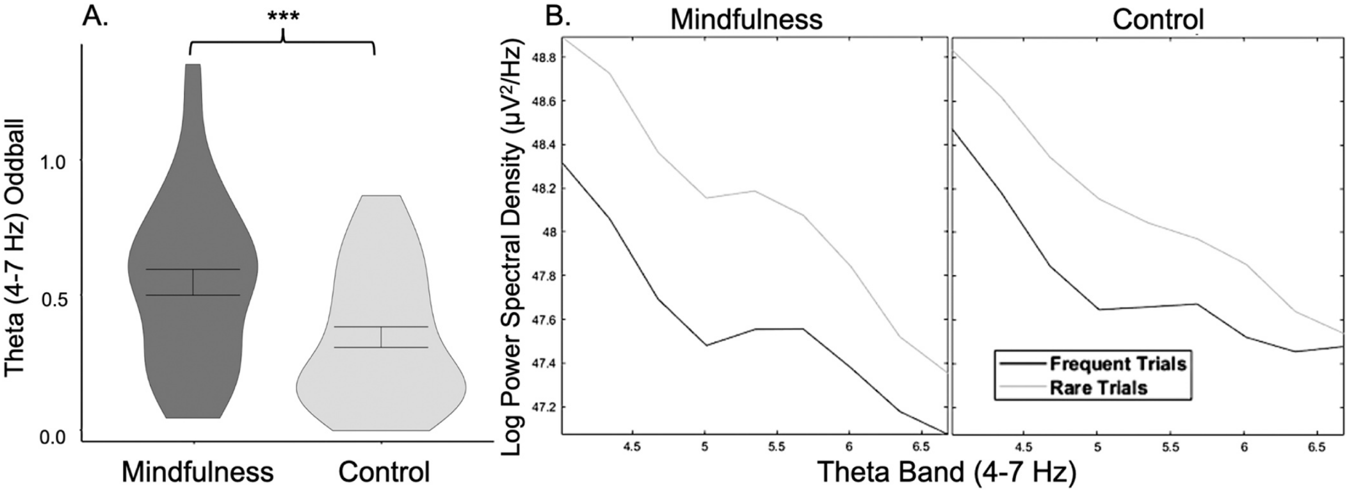

Fig. 5. *Violin and Spectral Power Plots for Theta Oddball Between Experimental Conditions. Note.* Differences in theta band (4–7 Hz) spectral power oddball between experimental conditions. A. Violin plots for mindfulness (dark grey/left) and control (light grey/right) conditions. B. Spectral power density plots of rare (light grey) and frequent (dark grey) trials for mindfulness (left) and control (right) conditions. * ** $p = .001$.

82) = 6.49, $p = .013$, demonstrating that differences in TBR for rare and frequent letter trials (i.e., TBR oddball) varied between the mindfulness and control conditions. In addition, there was a main effect of trial type on TBR, $F(1, 82) = 217.30$, $p < .001$, revealing that TBR was larger for rare ($M = 1.22$, $SD = 0.05$) relative to frequent ($M = 1.20$, $SD = 0.05$) letter trials, $\eta_p^2 = .73$, which would be expected if larger TBR reflects worse cognitive control. This indicates the viability of calculating an attentional shifting oddball from TBR values (see below).

There was a significant main effect of sound stimuli, $F(2, 164) = 3.66$, $p = .028$, indicating that overall TBR differed between the three sound stimuli (Fig. 6). Follow-up tests revealed a smaller TBR for smartphone notification compared to tone sound trials, $t(82) = -2.38$, $p = .020$, $\eta_p^2 = .06$, and silent trials, $t(82) = -2.37$, $p = .020$, $\eta_p^2 = .06$ (Table 1). TBR did not significantly differ on tone (vs. silent) trials, $t(82) = -0.42$, $p = .672$, $\eta_p^2 = .002$. A smaller TBR is considered to reflect better cognitive control, thus, this finding suggests that after hearing smartphone notifications participants had greater engagement of cognitive control processes. The interaction between trial type and sound stimuli was not significant, $F(2, 164) = 1.63$, $p = .199$. Likewise, there was no significant interaction between experimental condition and sound stimuli, $F(2, 164) = 0.78$, $p = .458$, and no significant main effect of experimental condition on TBR overall, $F(1, 82) = 0.11$, $p = .744$. These findings fail to provide support for our hypotheses that overall TBR would be smaller for people in the mindfulness (vs. control) condition in general, and this effect would be strongest on the smartphone notification trials (Fig. 7A). In other words, averaged across rare and frequent letter trials and the three sound stimuli, TBR did not differ between people in the mindfulness and control conditions (Table 3), and there was no significant effect of the sound stimuli on overall TBR between experimental conditions.

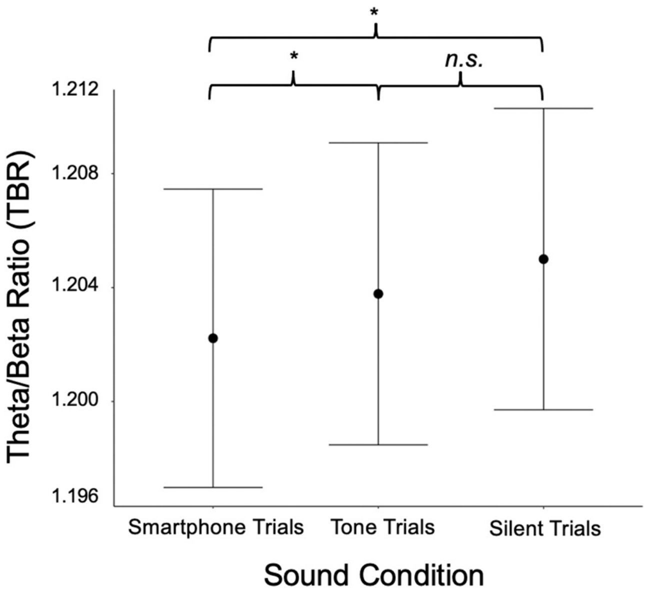

Fig. 6. *Standard Error Plots of TBR Between Sound Stimuli. Note.* Means and standard errors of theta/beta ratios (TBR) between letter trials preceded by smartphone notifications (left), tone sounds (middle), and silence (right). * $p < .05$.

7.2. TBR oddball differences

A 2 × 3 repeated measures ANOVA was performed with the TBR oddball as the DV with experimental condition as a between-subjects

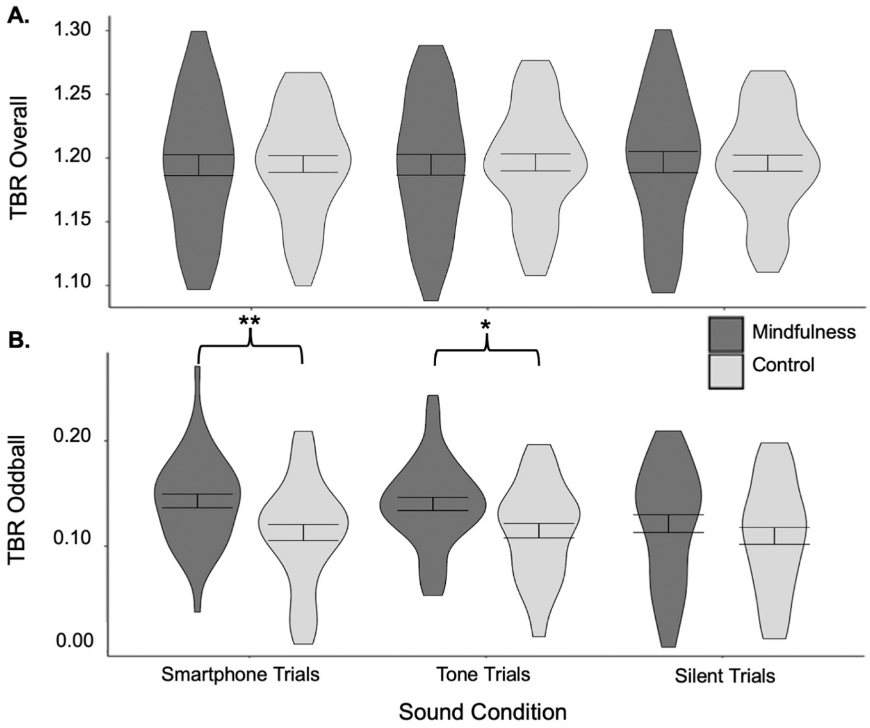

Fig. 7. *Violin Plots for TBR Between Conditions and Sound Stimuli. Note*. Violin plots of theta/beta ratios (TBR) and TBR oddball between the mindfulness (dark grey) and control (light grey) conditions and sound stimuli. * $p = .01$, * * $p < .01$.

Table 3
Post-hoc Tests for TBR Between Experimental Conditions.

Measure	Mindfulness		Control						
	M	*SD*	*M*	*SD*	*B*	*SE*	*t* (82)	*p*	η_p^2
TBR									
Overall	1.21	0.06	1.21	0.05	-0.004	0.01	-0.33	.744	.00
Rare Trials	1.22	0.06	1.22	0.05	-0.001	0.01	-0.06	.953	.00
Frequent Trials	1.20	0.05	1.20	0.04	-0.01	0.01	-0.61	.545	.00
Smartphone Trials	1.20	0.05	1.20	0.04	-0.00	0.01	-0.37	.716	.00
Tone Trials	1.20	0.06	1.21	0.04	0.00	0.01	0.22	.824	.00
Silent Trials	1.20	0.05	1.21	0.04	0.01	0.01	0.39	.698	.00
Oddball	0.14	0.04	0.11	0.04	-0.02	0.01	-2.69	.009	.09
TBR Oddball									
Smartphone Trials	0.15	0.04	0.12	0.05	-0.03	0.01	-2.80	.006	.09
Tone Trials	0.14	0.04	0.12	0.04	-0.02	0.01	-2.59	.011	.08
Silent Trials	0.12	0.05	0.11	0.05	-0.01	0.01	-0.99	.326	.01

Note: $N = 87$. TBR = Theta/Beta ratio.

factor and sound stimuli as a within-subjects factor as the IVs. Results revealed a significant main effect of experimental condition, $F(1, 82) = 7.24$, $p = .008$, indicating a larger TBR oddball for people in the mindfulness (vs. control) condition (Table 2, Fig. S5), suggesting greater engagement of cognitive control for people in the mindfulness condition. There was also a significant main effect of sound stimuli on the TBR oddball, $F(2, 164) = 3.58$, $p = .030$. Follow-up tests revealed a marginally larger TBR oddball on smartphone notifications ($M = 0.13$, $SD = 0.05$) compared to tone sound trials ($M = 0.12$, $SD = 0.05$), $t(82) = 1.99$, $p = .050$, $\eta_p^2 = .05$. The TBR oddball did not significantly differ between the smartphone and silent ($M = 0.13$, $SD = 0.04$) trials, $t(82) = 0.83$, $p = .408$, $\eta_p^2 = .01$, nor between tone and silent trials, $t(82) = -1.21$, $p = .230$, $\eta_p^2 = .02$. Though marginal, these findings indicate that across all participants, smartphone notification trials were linked to neural indices suggestive of enhanced attentional shifting of cognitive control relative to tone sounds. In contrast, differences were not observed between trials preceded by an auditory stimulus relative to silence.

The two-way interaction of experimental condition and sound stimuli on the TBR oddball was not significant, $F(2, 164) = 1.19$, $p = .308$. Follow-up tests were conducted to determine if the TBR oddball measure differed between experimental conditions separately within any sound stimuli condition. Results revealed that people in the mindfulness (vs. control) condition had a larger TBR oddball, greater engagement of cognitive control) for smartphone notification trials and tone sound trials, while no significant experimental condition differences in the TBR oddball were observed for trials preceded by silence (Table 2, Fig. 7B).

8. Behavioral findings

Means and standard deviations for reaction times (RT) across experimental conditions are reported in Table 4.

Table 4

Means and Standard Deviations for Reaction Times.

Variable	Overall RT ms		Smartphone Trials RT ms		Tone Trials RT ms		Silent Trials RT ms	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Overall	430.56	90.65	426.89	89.86	426.23	90.43	438.63	91.11
Trial Type								
Rare Trials	466.75	110.46	464.44	110.91	461.9	109.06	435.23	88.22
Frequent Trials	427.08	87.72	423.27	86.71	422.8	87.68	473.96	111.08
Oddball	39.67		41.16		39.10		38.73	
Mindfulness	426.89	87.77	423.11	87.03	423.05	86.93	434.54	88.86
Rare Trials	469.06	110.07	466.29	112.01	461.35	106.05	479.57	111.3
Frequent Trials	422.92	84.30	419.02	83.13	419.45	84.03	430.31	85.24
Oddball	46.14		47.27		41.89		49.26	
Control	434.16	93.24	430.59	92.39	429.34	93.63	442.67	93.12
Rare Trials	464.57	110.81	462.68	109.87	462.42	111.86	468.64	110.67
Frequent Trials	431.17	90.78	427.45	89.89	426.09	91.00	440.11	90.82
Oddball	33.39		35.23		36.34		28.53	

Note. RT = reaction time.

8.1. *Overall behavioral (RT) results*

A 2 (experimental condition: brief mindfulness induction vs. control) x 2 (target letter trial type: rare vs. frequent) x 3 (sound stimuli: smartphone, tone, silence) repeated measures ANOVA with RT as the dependent variable revealed a significant three-way interaction, $F(2, 76612) = 3.30$, $p = .037$, $\eta_p^2 = .02$. As expected, there was a main effect of trial type, such that participants responded slower on rare (vs. frequent) letter trials, demonstrating an overall oddball effect of 39.67 ms, $F(1, 76612) = 1157.85$, $p < .001$, $\eta_p^2 = .73$.

There was a main effect of sound stimuli, $F(2, 76612) = 26.41$, $p < .001$, $\eta^2 = .22$. Post-hoc tests revealed that participants responded slower on silent trials compared to smartphone and tone trials (Table 5). Response speed did not significantly differ between smartphone and tone trials. There was no main effect of experimental condition, indicating that overall RT did not significantly differ between the brief mindfulness induction and control conditions, $F(1, 98) = 0.12$, $p = .729$.

8.2. *Behavioral (RT) oddball results*

The two-way interaction of trial type by sound condition was not significant, $F(2, 76612) = 0.45$, $p = .640$, indicating that the RT oddball did not differ as a function of the sound stimuli for RTs averaged across experimental conditions. Similarly, the two-way interaction of experimental condition (mindfulness vs. control) by sound stimuli was not significant, $F(2, 76612) = 1.26$, $p = .282$. Participants in the mindfulness (vs. control) condition did not differ in response speed between the three sound stimuli for RT averaged across frequent and rare trials.

The two-way interaction of experimental condition by trial type was significant, $F(1, 76612) = 29.59$, $p = .003$, $\eta^2 = .05$. This finding indicates that the RT oddball was larger for people in the mindfulness (46.14 ms) compared to the control (33.39 ms) condition (Fig. S4).

Table 5

Post-hoc tests for Reaction Times Between Sound Stimuli.

		95% CI				
Effect	B	*LL*	*UL*	*t* (df)	*p*	η_p^2
Smartphone Trials						
Tone Trials	0.66	-0.90	2.22	0.83 (51321)	.373	.00
Silent Trials	-11.70	-13.31	-10.17	-14.70 (51172)	< .001	.00
Tone Trials						
Silent Trials	-12.40	-13.97	-10.82	-15.42 (50981)	< .001	.00

Note. $N = 95$. N Trials = 76,624. RT = reaction time; M_D = mean difference; CI = confidence interval; *LL* = lower limit; *UL* = upper limit.

Post-hoc tests assessed differences in RT between rare and frequent trials within each experimental condition (i.e., mindfulness vs. control) and preceding sound stimuli. Results revealed that people in the brief mindfulness condition demonstrated an RT oddball of 47.27 ms on smartphone trials, $b = 47.57$, $SE = 2.61$, $t(76612) = 18.24$, $p < .001$, 41.89 ms on tone trials, $b = 42.57$, $SE = 2.63$, $t(76612) = 16.18$, $p < .001$, and 49.26 ms on silent trials, $b = 49.06$, $SE = 2.63$, $t(76612) = 18.66$, $p < .001$. People in the brief mindfulness condition had no significant differences in the RT oddball between smartphone and tone sound trials, $t = -1.35$, $p = .177$, smartphone sound and silent trials, $t = 0.40$, $p = .688$, or tone sound and silent trials, $t = 1.75$, $p = .081$.

People in the control condition demonstrated an RT oddball of 35.23 ms on smartphone trials, $b = 36.54$, $SE = 2.55$, $t(76612) = 14.35$, $p < .001$, 36.34 ms on tone trials, $b = 37.50$, $SE = 2.55$, $t(76612) = 14.69$, $p < .001$, and 28.53 ms on silent trials, $b = 30.66$, $SE = 2.56$, $t(76612) = 11.96$, $p < .001$. People in the control condition had no significant differences in the RT oddball between smartphone and tone sound trials, $t = -0.63$, $p = .531$, or smartphone sound and silent trials, $t = 1.63$, $p = .104$. The control condition had a marginally larger RT oddball on tone sound (vs. silent) trials, $t = -1.89$, $p = .059$. See Fig. 8 for a depiction of RT oddball results by condition and sound.

See supplementary material for behavioral covariate results.

9. Discussion

The current study employed task-based spectral power (theta, alpha, beta), theta/beta ratio (TBR) analysis techniques to examine the effects of smartphone notifications, compared to control tone sounds and

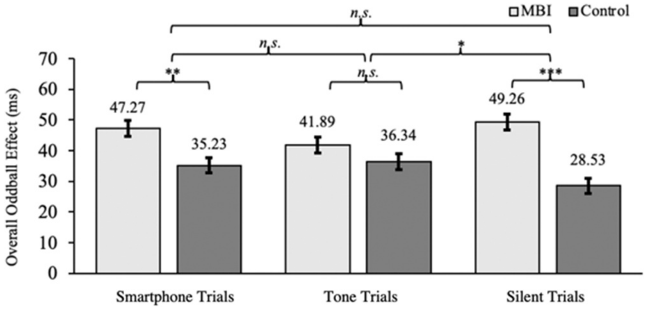

Fig. 8. *Bar Plots for Behavioral Oddball Effect Between Experimental Conditions and Sound Stimuli. Note.* Two and three-way interactions for the RT oddball between experimental conditions (i.e., mindfulness vs. control) and sound stimuli. * $p < .05$. * * $p < .01$. * ** $p < .001$. *n.s.* = not significant. MBI = brief mindfulness induction.

silence, on neural oscillatory activity indexing attentional shifting processes involved in cognitive control. In addition, we tested the efficacy of an experimental manipulation aimed at buffering against any detrimental effects of smartphone notifications on cognitive control—namely a mindfulness-based vs. control induction.

Averaged across experimental conditions and target letter trial types, we found that smartphone notification (vs. silent) trials had lower frontocentral theta-band, higher alpha-band, and lower beta-band power densities. Between the experimental conditions, we found no differences in power density overall, nor for power density within each power band separately. Importantly however, our results revealed systematic variability in power densities between rare and frequently presented target letter trials, pointing to the value in calculating an oddball effect difference score to glean further insights from analyses comparing the experimental conditions.

In doing so, results indicated that people in the mindfulness (vs. control) condition demonstrated a larger attention shifting oddball (i.e., greater differences between rare and frequent target letter trials) in power density values overall, theta-band power density, and the theta/beta power ratio (TBR). A larger oddball value for neural signal data is considered to reflect greater engagement of attentional shifting processes involved in cognitive control. In addition, this effect was most pronounced on task trials preceded by smartphone notification sounds. These findings provide evidence that hearing smartphone notification sounds can influence neural activity underlying the engagement of cognitive control . Furthermore, the effects of smartphone notifications on cognitive-control-related neural activity were found to be buffered against by a brief one-time mindfulness induction.

A large proportion of prior EEG research linking executive functioning and TBR has measured spectral power during an eyes closed resting state in which attention is directed internally (Angelidis, 2018; Angelidis et al., 2016; Kobayashi et al., 2020; van Son et al., 2019; Zhang et al., 2017). Fewer EEG studies have employed task-based frequency analyses to assess frontal midline TBR during cognitive control tasks. In the current study, EEG data were recorded during a Navon Letter oddball task in which attention was externally oriented while shifting between target stimuli presented at varying levels of attentional focus. Similarly, a considerable amount of prior EEG studies investigating mindfulness-based inductions used resting state neural signal as a control comparison condition. These methodological differences should be considered when comparing our results to prior resting state EEG research. While the current study adds to the mindfulness-based research literature for event-related power density underlying cognitive control processes, little is known regarding the extent to which these forms of EEG data differ. Future work should explore how spectral power density measures differ within and between mindfulness-based inductions as a function of neural activity during resting state and while completing a cognitive task.

10. Spectral power

Our analyses revealed differential patterns of spectral power density between rare and frequent target letter trials both across and within frequency bands. Theta band power was greater for rare relative to frequent letter trials. Increased frontal theta power has been shown to reflect enhanced conflict monitoring processes (Nigbur et al., 2012), and as such, less expected letter stimuli (i.e., rare trials) likely required an upregulation of top-down control of attention to correctly respond on these trials, which involved more conflicting sensory information. This finding is in line with other work demonstrating that greater frontal midline theta serves as a signal for increased engagement of cognitive control (Cavanagh & Shackman, 2015).

In contrast, alpha power was lower on rare relative to frequent letter trials, likely reflecting an event-related desynchronization, or reduction in cortical idling (Pfurtscheller et al., 1996), when participants responded to rare (vs. frequent) target letters. Lower alpha on rare trials could indicate increases in externally directed attention necessary for responding correctly. In fact, prior work has linked lower frontal midline event-related desynchronization of alpha with focal attention on tasks requiring hand responses (Suffczynski et al., 2001). In addition, event-related desynchronization of alpha power has been found to occur during release from inhibitory processes and greater cortical activation (Klimesch, 2012). Our finding is consistent with this cortical activation model, as each event epoch latency extended further beyond the letter stimulus onset (2000 ms) compared to before (−1000 ms). Given this, a release from the inhibition of prepotent "no" responses on rare letter trials resulted in a greater magnitude of alpha event-related desynchronization.

Beta power was also lower on rare compared to frequent target letter trials. This result seems contradictory to findings that increased frontal midline beta power reflects greater levels of engagement with task-relevant stimuli (Laufs et al., 2006; Pitchford & Arnell, 2019), as responding correctly to rare target letters requires heightened on-task engagement. Prior work, however, has also demonstrated an inverse relationship between beta power and the degree of cognitive control demands among visual stimuli during task-switching paradigms (Lu et al., 2017). Given that earlier studies have linked higher resting-state beta power with enhanced cognitive processing, results from the current study provide support that decreases in event-related beta power reflect greater engagement of task-related cognition. Taken together, higher baseline resting state beta power levels may predict greater cognitive control capacity and as task stimulus complexity increases, beta power decreases.

Furthermore, although greater frontal beta power is considered to reflect enhanced task engagement, this effect is most evident when stimuli perceptual features remain unchanging across trials (Engel & Fries, 2010). In other words, when the perceptual qualities of task stimuli remain stable, endogenous top-down attentional control processes recruit fewer neural resources. In comparison, less stable, or more unexpected stimuli are linked to decreases in frontal beta power. This is said to reflect an upregulation of exogenous bottom-up stimulus processing when attending to more unexpected and salient stimuli, which explains the lower beta power on relatively novel rare target letters.

Comparisons between the three sound stimuli conditions revealed that trials preceded by control tone sounds showed the lowest overall power density. Within the theta frequency band, there were no significant differences between the sound stimuli, however results did reveal that smartphone notification trials had marginally lower ($p = .051$) theta power. This finding indicates that after hearing smartphone notification sounds (relative to silence), participants demonstrated a directionally lower magnitude of frontal neural activation underlying enhanced stimulus conflict monitoring and cognitive control processes. While these results were non-significant, smartphone notifications appear to have resulted in the lowest degree of neural activity considered necessary for identifying visual targets, suggesting a reduced preparedness respond correctly after hearing smartphone notifications.

Alpha power was observed to be directionally largest for trials preceded by smartphone sounds. This indicates that the magnitude of neural activity reflecting internally directed attention showed moderate increases after hearing smartphone notifications, and thus available neural resources for focusing on external task demands could have been reduced. In addition, lower alpha reflects increased event-related desynchronization in preparation for responding to stimuli on cognitive tasks. Taken together, lower theta and higher alpha power for smartphone notification trials seems to point to a reduced level of cognitive preparedness for responding to upcoming target letters when they were preceded by notification sounds following notification sounds. Importantly, more work is needed to substantiate these findings before conclusions are drawn regarding the general effects of smartphone notifications on frontocentral theta and alpha power.

Beta power was also found to be largest for smartphone notification trials, demonstrating greater neural activation oriented towards internal cognitive states and away from external task demands after hearing smartphone notifications. Participants may have needed to either recruit greater neural resources after hearing smartphone notifications to maintain task performance, or smartphone notifications may have contributed to a stronger effect on working memory updating and maintenance. Future work should clarify the neural effects of smartphone notifications on executive functioning by comparing EEG indices of neural activity across working memory, sustained attention, and cognitive control tasks assessing various subprocesses, such as inhibition and updating. In addition, further replication studies are needed to substantiate claims about the effects of smartphone notifications on spectral power indices reflecting internal and external cognitive states. Eye-tracking methodologies are one potential direction for this purpose.

Results for experimental condition differences in spectral power densities revealed no significant effects for any power band, thus our hypothesis that alpha power would be higher for people in the mindfulness (vs. control) condition was not supported. This null finding could have been partially explained by power values averaged across multiple task conditions. Other results indicate that task conditions, particularly rare and frequently present target letter trial types demonstrated systematic variable effects on power densities. To account for these differential effects of rare and frequent trials we assessed differences in the attentional shifting power oddball between experimental conditions and sound stimuli.

We hypothesized that participants in the mindfulness condition would demonstrate better cognitive control reflected by a larger spectral power oddball. As expected, participants in the mindfulness (vs. control) condition had a larger overall power density oddball averaged across theta, alpha, and beta-band power densities. Within each power band individually, participants in the mindfulness condition had a larger theta band oddball, however alpha and beta band oddballs did not differ from the participants in the control condition. Separately, we found no significant effects of the sound stimuli for the power oddball overall, nor for the theta, alpha, or beta-band power density oddballs. These findings suggest that the magnitude of neural signal reflecting enhanced conflict monitoring was greater for participants in the mindfulness condition and there were no significant effects of the sound stimuli. We interpreted this finding as suggesting that participants who completed the mindfulness induction were more efficient at recruiting neural resources necessary for successfully monitoring response conflicts between rare and frequent letter stimuli, and experienced little cognitive effects from the sound stimuli on neural activity underlying conflict monitoring processes.

11. Theta/Beta ratio (TBR)

TBR results revealed that, as expected, TBR values were larger on rare compared to frequent target letter trials. Based on prior work demonstrating that a larger TBR reflects worse attentional control (Angelidis, 2018; Angelidis et al., 2016; Putman et al., 2010; 2014), this finding suggests that top-down cognitive control of attention was worse when responding to rare target letters. This makes sense mathematically considering that rare (vs. frequent) letter trials showed higher theta and lower beta power. Interestingly, we found that TBR overall was smallest for trials preceded by smartphone notifications compared to control sounds and silence, indicating that across both experimental conditions, participants demonstrated neural indices of greater engagement of cognitive control after hearing smartphone notifications. Initially, we expected that cognitive control would be worse on smartphone notification trials, yet these results suggest the opposite. Importantly , this result was for TBR values averaged across rare and frequent letter trials, which, as discussed, showed differential effects on the power density measures. Thus, we assessed differences in the TBR oddball between the three sound stimuli conditions to more fully understand how smartphone notification affected the TBR measures underlying cognitive control processes. Results revealed significant differences. Specifically, trials preceded by smartphone notifications had larger TBR oddballs relative to control tone trials, yet TBR oddballs did not differ between silent trials compared to notification and tone trials. In other words, across both experimental conditions, all participants demonstrated spectral power based neural indices of greater engagement of cognitive control after hearing smartphone notifications.

We also hypothesized that people in the mindfulness condition would have smaller TBR overall reflecting better cognitive control. This hypothesis was not supported as TBR averaged across rare and frequent trials did not differ between the experimental conditions. Additional analyses assessing differences in the TBR oddball between experimental conditions revealed a larger TBR oddball for people in the mindfulness (vs. control) condition. This finding indicates that the difference in neural activity between rare and frequent letter trials was more pronounced in the mindfulness condition, which suggests that the mindfulness-based induction increased the efficient recruitment of neural resources underlying attentional shifting processes of cognitive control. The mindfulness-based induction may have improved these individuals' capacity to effectively identify and process visual stimuli presented at contrasting levels of focal attention (i.e., local vs global). In addition, these results offer evidence that future research could benefit from proceeding cautiously when averaging cognitive measures across stimuli presented at varying levels of perceptual focus.

We further hypothesized that people in the mindfulness (vs. control) condition would have the smallest TBR on smartphone notification trials relative to control tone and silent trials. We found no experimental condition differences in average TBR between any sound condition. Analyses for the TBR oddball revealed a non-significant interaction of experimental condition and sound stimuli, suggesting that the TBR oddball index of cognitive control did not vary significantly between people in the mindfulness and control conditions as a function of the sound stimuli condition. To determine if this effect was consistent within each sound stimuli condition, we conducted follow-up tests to examine if experimental condition differences existed separately for trials preceded by smartphone notifications, control tone sounds, and silence. On trials preceded by smartphone notifications and control tone sounds, we found that participants in the mindfulness (vs. control) condition had a larger TBR oddball, but experimental condition differences were not observed on silent trials. This finding suggests that beneficial effects of the mindfulness-based induction on attentional shifting of cognitive control measured as the TBR oddball were seen only on trials preceded by an auditory stimulus and not on silent trials.

Addressing a concern if the chosen mindfulness-based induction induced a mental state of open monitoring, as opposed to focused attention, depends on how we interpret these findings. People in the mindfulness condition demonstrated neural indices of greater efficiency for processing attentional level perceptual differences of letter stimuli reflected by a larger TBR oddball – an effect that was driven primarily by trials without an auditory stimulus. This could mean that participants in the mindfulness condition had an enhanced ability to upregulate cognitive control processes necessary for efficiently shifting single-pointed attentional focus between rare and frequent letters. In contrast, it could have been that participants in the mindfulness condition were more susceptible for having their attention easily captured by less expected, or more unusual letter stimuli. This would imply a reduced ability to maintain a single-pointed focus and would instead be more reflective of an open monitoring mental state.

Taken together, these interpretations both suggest that people in the mindfulness induction condition had an enhanced capacity for attending to novel perceptual features of visual stimuli. Furthermore, participants in the mindfulness (vs. control) condition did not demonstrate evidence of worse cognitive control as indexed by our power density measures. In sum, future work should aim to further explore the differential effects of open monitoring and focused attention mindfulness-based inductions on event-related spectral power density-based indices of top-down executive functions.

12. Behavioral findings

In terms of behavior, participants responded slower on rare vs. frequent trials, indicating that the oddball task operated as designed. That is, rarely presented target letters took longer for people to correctly respond to, as they are designed to be less expected relative to target letter trials presented more frequently. Also as expected, people took longer to respond to target letters preceded by silence, relative to an auditory stimulus. Both the smartphone notification and control tone auditory stimuli likely served as a cue for people to anticipate upcoming letter stimuli.

Results revealed that averaged across experimental conditions (i.e., mindfulness vs. control), the RT oddball effect did not vary between the sound conditions, suggesting that the sound condition alone did not influence cognitive control behaviorally. Analyses further revealed no significant differences in overall response speed on the Navon Letter task between the mindfulness and control conditions. However, we found that people in the mindfulness (vs. control) condition had a larger RT oddball effect, indicating worse cognitive control. We also examined the effect of the sound stimuli on behavior in the mindfulness and control conditions, and discovered no differences in response speed between the sound stimuli when averaged across rare and frequent trials. Again however, we observed condition differences in the RT oddball effect between the sound stimuli. Specifically, people in the mindfulness compared to the control condition had a larger RT oddball effect on trials preceded by smartphone notifications and silence, but not on trials preceded by tone sounds. Interestingly, the largest difference between the mindfulness and control conditions in the RT oddball effect was found on silent trials. This finding indicates that particularly on letter trials which were not preceded by an auditory stimulus, the discrepancy in response speed on rare and frequent trials was larger for people randomly assigned to the brief mindfulness induction. A larger behavioral oddball effect suggests decreased ability to flexibly shift between attentional levels and thus reflects lower engagement of cognitive control in terms of response speed for people in the mindfulness condition.

Evidence from prior work and from the current study indicates that people randomly assigned to the mindfulness-based (vs. control) induction showed worse performance on a task requiring cognitive control particularly on silent trials. Relative to the control induction, perhaps the craisin eating mindfulness induction used in the current study activated an attentional state of open acceptance and monitoring. This open mental state may have promoted a more flexible and less restrictive attentional filtering process for task-irrelevant stimuli (Colzato et al., 2012). In turn, an induced state of open monitoring for people in the mindfulness condition may have led to behavioral deficits to goal-directed focus on task performance. This idea is further supported by our finding that the largest experimental condition (i.e., mindfulness vs. control) differences between rare and frequent letter responses were on trials preceded by silence (vs. sounds). It is possible that without an auditory cue to signal an upcoming response, the open mental state induced from the mindfulness practice could have led to increased recruitment of neural resources for maintaining goal-directed attention to task performance.

13. Limitations and future directions

Although this study has several strengths (e.g., experimental manipulations at both the within- and between-subjects levels, use of a well-validated cognitive task, and multiple levels of analysis for cognitive control outcomes), its limitations should be noted. First, cognitive processes other than attentional shifting of cognitive control (e.g., working memory) may have been involved during the Navon Letter task and thus may have affected the results. (see supplementary materials for additional behavioral results). Future work should replicate and extend these findings with other control tasks and related outcomes. Second, prior work has found variation in terms of the specific peak frequency band range in which the neural oscillatory signal is maximal (Klimesch, 1999). For instance, theta power might be maximal for one person at 6 Hz, whereas another person's theta power could be maximal at 8 Hz. If EEG data processing employs a theta band signal threshold of 4–7 Hz, valuable spectral power data may be unintentionally removed for some individuals and not others. However, these idiosyncrasies should theoretically have washed out at the participant level due to random assignment. Third, while we excluded EEG data from participants with excessive (> 25%) EEG artifact noise (Luck, 2014), we did not remove individual trials in which participants committed a behavioral error prior to analyzing EEG data. For remaining participants, the average trial error rate was 1.7% (0.1–3.5%). While error rate was low in the current study, EEG oscillatory indices of cognitive control (e.g., frontal theta power) can be confounded by error-related EEG signal (Shou & Ding, 2015). This error related confound is particularly concerning for EEG data processed without ICA. It is important that future research considers the influence of behavioral error trials on EEG signal indices of cognitive control and ensure that potential confounds of error-related signal covariance are appropriately mitigated during EEG signal pre-processing.

Fourth, levels of prior meditation experience have been shown to differentially affect neural signal, as experienced (vs. novice) meditators demonstrate greater frontal midline theta-band activity (Lomas et al., 2015) and show the greatest degree of cognitive benefit following mindfulness-based inductions (Allen et al., 2012). In the current study we controlled for self-reported levels of dispositional mindfulness, however we did not exclude individuals with prior meditation experience. Therefore, it is possible that unequal proportion of experienced meditators were assigned to either experimental condition, potentially confounding the results. Future work should ensure equal levels of prior meditation experience between mindfulness-based and control inductions. Along similar lines, we observed several null effects for comparisons between experimental conditions. It may have been the case that completing a one-time mindfulness induction before the cognitive control task led to decreasing differences in cognitive control between the mindfulness (vs. control) conditions over time. Future work should consider examining the effects of regular mindfulness reminders throughout the cognitive task.

Finally, it is likely that other mindfulness or meditative practices (e.g., vipassana, focused attention, open monitoring, loving kindness) would have differential effects on cognitive control (for review, Lippelt et al., 2014; Ng et al., 2021). In the current study, we used a mindful eating mindfulness-based induction in which participants were guided through a multisensory experience of deliberately and slowly eating a craisin in a mental state of non-judgmental acceptance. Prior work has found that this type of meditation, considered open monitoring, can facilitate a broader distribution of recruited neural resources underlying attentional processes, in turn creating a less focused mental state (Colzato et al., 2012).

Future research should disentangle the effects of different types of mindfulness inductions on cognitive processes, such as focused attention meditations, which have demonstrated enhancing effects on cognitive control (Chan et al., 2017). A more thorough understanding of the specific cognitive effects of different mindfulness inductions is necessary to determine which mindfulness induction to use for a given situation or desired cognitive outcome.

14. Conclusion

Little is known about the utility for event-related theta/beta band power density ratio (TBR) to serve as a neural index of attentional shifting subprocesses involved in cognitive control. In addition, no prior work has investigated the neural effects of smartphone notifications on cognitive control and if a brief, one-time mindfulness induction can reduce such effects. Using event-related TBR from EEG data recorded during an attentional shifting Navon Letter oddball paradigm, we provide evidence indicating that people assigned to a mindfulness (vs. control) induction showed indices of greater cognitive control. These effects were stronger on trials preceded by smartphone notifications relative to a control tone, though differences between experimental conditions were most apparent in neural activity averaged across sound stimuli conditions. Essentially, people in the mindfulness condition had neural indices of enhanced processing efficiency for shifting of attention between visual stimuli presented at opposing perceptual levels more or less frequently even after hearing smartphone notifications. Critically, these results point to the importance of accounting for differential neurocognitive effects of stimuli presented at varying levels of attention before interpreting aggregated effects of task stimuli. Before making definitive claims about the benefits of mindfulness inductions on executive functioning, research should seek to clarify how different types of mindfulness inductions influence specific subprocesses for separate executive functions. Further studies should elucidate differences between resting-state and event-related TBR as a measure of cognitive control among clinical and non-clinical samples. In sum, less than five minutes of meditation could help us become more aware of less frequent occurrences in our environment such as a rose in a weed patch or a child's smile amidst a crowd, even in a world of countless distractions.

Research data for this article

Data files and additional materials can be found here: https://github.com/jupshaw/SMARTPHONES-AND-COGNITIVE-CONTROL.

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Declaration of Generative Artificial Intelligence (AI) and AI-Assisted Technologies in the Writing Process.

The author(s) did not use generative AI technologies for preparation of this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.biopsycho.2023.108725.

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