NEUROCOGNITIVE INVESTIGATION OF EXECUTIVE FUNCTION AFTER SMARTPHONE SEPARATION

By

Kaitlin Michelle Lewin

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Information and Media —Doctor of Philosophy

2024

ABSTRACT

In the United States, almost 312 million individuals own a smartphone device, with the number of users projected to rise each year (Statista, 2023). Throughout their life, these individuals may be separated from their smartphones for a variety of reasons. During these instances of separation, individuals often experience a state of heightened anxiety, termed nomophobia. This smartphone separation induced nomophobia is associated with impairment on a variety of cognitive tasks, specifically those requiring executive function skills such as inhibitory control and cognitive flexibility. While prior research establishes a pattern of behavioral impairments during these tasks, no research has investigated the neurocognitive changes that underlie these behavioral impairments. This dissertation uses electroencephalography (EEG) to examine the potential neurocognitive changes underlying smartphone separation, hypothesizing that separation will affect four distinct neural markers (P2, P3, N2, ERN). To test these hypotheses, 40 undergraduate students completed two executive function tasks– an inhibitory control (Stroop) task and a cognitive flexibility (color-shape switching) task– on separate days of smartphone separation and smartphone possession, all while undergoing EEG recording. Results indicated that the tasks functioned as expected, however there was no effect of smartphone separation on either behavioral performance or neural markers. Rationales behind why the separation manipulation within this dissertation failed are discussed alongside limitations and future directions. Overall, this dissertation is the first to investigate smartphone separation on a neuroimaging level, providing insights for researchers exploring the neurocognitive implications of smartphone separation and guidance for educational policies on smartphone bans.

ACKNOWLEDGEMENTS

Completion of this dissertation, and my PhD, would not have been possible without the support of so many people:

First and foremost, my advisor, Dr. Dar Meshi. Thank you for your time and diligence in mentoring me through the entire research and doctoral process. You have always advocated for me, supported me, and believed in me, even during times when I couldn't myself. I also want to thank my committee members– Dr. Ralf Schmälzle, Dr. Wei Peng, and Dr. Morgan Ellithorpe– thank you for sticking with me from my very first year and for all your thoughtful feedback on this dissertation. Second, I would like to acknowledge the research assistants who volunteered their time to help me run this study– Cattie Jensen, Sarah Hoogstraten, Nia Kepes, and Zijie Mei. Without them, the study and EEG capping process would have taken significantly longer. In addition, I would have gone slightly crazy sitting so many hours alone in the basement lab room of Oyer without their company.

Third, I would like to acknowledge all that people who helped troubleshoot and solve the various issues that came up during this dissertation. In setting up the EEG and MATLAB computer setup– the College of Communication Arts and Sciences department IT team was extremely helpful, in addition to Ava Francesca Battocchio, and staff members at Neurospec. In writing my EEG analysis code– Ardaman Kaur and Matt Pontifex were integral in helping design the order and flow of this code to create clear findings. Fourth, I would like to acknowledge the people and places that helped fund this dissertation. Part of this research was funded by the Graduate School Dissertation Completion Fellowship. In addition, a portion of this research has been supported by the Sandi Smith Research Fellowship awarded through the Michigan State University, ComArtSci Health and Risk Communication Center.

Most importantly, I couldn't have done this without my friends and family. I am a better person and researcher because of you. To my family– you have all supported me and believed in me, even if you didn't understand exactly what I was doing. Your willingness to listen and be my sounding board was invaluable. To my friends, especially Lauren Bullard, thank you for keeping me sane, taking care of me, and listening to my anxieties and rants throughout these past years.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

PSMU	Problematic Social Media Use
EEG	Electroencephalography
ERP	Event-Related Potentials
SAS-SV	Smartphone Addiction Scale – Short Version
STAI	State-Trait Anxiety Inventory
NMP-Q	Nomophobia Questionnaire
YAPS	Young Adult Attachment to Phone Scale
BSMAS	Bergen Social Media Addiction Scale
FOMO	Fear of Missing Out
ANOVA	Analysis of Variance

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

In the United States, over 300 million individuals own a smartphone device, with the number of users projected to rise each year (Statista, 2023). Since the first iPhone was released in 2007, smartphones have rapidly evolved in their capabilities. These devices now offer a multitude of seemingly endless features: streaming (e.g., music, videos), messaging (e.g., texting, calling), social (e.g., social media platforms), entertainment (e.g., games), and a variety of others. Smartphones differ from other communication devices for multiple reasons. The capabilities of smartphones exceed those of mobile phones, with an advanced capability for not only basic calls and messaging, but also internet access, health and fitness metrics, gaming, social media, and a variety of other apps (Park & Lee, 2015). Smartphones differ from other communicative devices such as computers due to their portability and transition across multiple different environmental contexts without need for an external connection. As a result of the numerous capabilities of these devices, scholars often conceptualize smartphones as a *metamedium* (Humphreys et al., 2018; Jensen, 2016), which considers the convergence of all features and mediums within it and its flexibility across a variety of environmental contexts. Smartphones are often at the forefront of innovation and are strong drivers of everyday behaviors and attitudes (Fortunati, 2022), which makes these devices important objects of study for researchers. One important area central to the current dissertation proposal is smartphone separation, or investigating smartphones by examining the various effects when users are *separated* from these devices.

Smartphone separation and nomophobia

Researchers have explored what happens when individuals are separated from their smartphones. Individuals may be separated from these devices for a variety of reasons throughout their daily life. There are accidental incidents of separation in which individuals may forget or lose these

devices in homes, cars, places of business, etc. There are also intentional incidents of separation in which individuals are purposefully instructed to leave their devices behind, for example during academic exams or in places of worship. Furthermore, these are situations in which a sudden loss of service or signal renders an unexpected separation from most smartphones' features or functions. These areas and moments of separation are useful to scholars who are interested in whether this separation parallels psychological, behavioral, and/or cognitive consequences.

One common negative outcome often associated with smartphone separation is anxiety. While anxiety has been conceptualized differently by researchers throughout history, there is a consistent differentiation between state and trait anxiety, both multidimensional concepts (Endler & Kocovski, 2001). State, or acute, anxiety is a transient emotional condition which changes based on the specific situation (Endler et al., 1976; Spielberger, 1972). Levels of state anxiety depend on both the situation and trait anxiety of the person (Endler & Kocovski, 2001). Trait anxiety is considered a generalized predisposition to react to situations consistently, or a stable characteristic of individuals towards anxiety (Allport, 1937; Endler et al., 1976; Endler & Kocovski, 2001; Spielberger, 1972). Research demonstrates high trait anxiety individuals to also display greater state anxiety in threatening situations (Spielberger, 1972). Overall, individuals often report high state anxiety if they are abruptly separated from their smartphones, termed "nomophobia".

Nomophobia stands for "NO MObile PHOne phoBIA" and was first coined by the UK Post Office (León-Mejía et al., 2021). In 2008, the UK Post Office hired a research group to examine whether phone users experienced symptoms of anxiety regarding their devices. They found that over half of the people surveyed reported anxiety regarding scenarios of separation from their devices, including forgetting their phones, running out of battery, or losing service

(see original article: "Nomophobia Is the Fear of Being out of Mobile Phone Contact - and It's the Plague of Our 24/7 Age | Daily Mail Online," 2008). After this initial survey of UK phone users, one of the first research teams to investigate nomophobia were King and colleagues, who defined nomophobia as an anxiety or discomfort caused by the non-availability of virtual communication devices (2010, 2013). In separate case studies, these researchers observed that patients with anxiety disorders reduced their anxiety through a dependency on virtual communication, and used these devices to feel safer, more confident, and less nervous (King et al., 2010, 2013). Overall, nomophobia is considered a state of anxiety evoked by the unavailability of a smartphone, or even the thought of losing access to it (Yildirim & Correia, 2015). Important to note is that nomophobia is a situational phobia resulting from smartphone separation, or the anticipation of separation, not a dependency or addiction to these objects (e.g., not smartphone addiction). Researchers posit four dimensions, or main fears, behind nomophobia: (1) fear of not being able to communicate (loss of communication), (2) fear of losing connectedness (loss of connection), (3) fear of not being able to access information (loss of information access), and (4) fear of giving up convenience (loss of convenience).

Scholars often view smartphones and theorize the rationale behind the potential consequences and fears of smartphone separation and nomophobia through the lens of Belks' Extended Self Theory (Belk, 1988, 2013). Important possessions (e.g., smartphones) are often seen as central to an individual's sense of self, therefore loss or separation from these objects can result in negative effects. Researchers who investigated smartphone use through this theoretical framework interviewed heavy smartphone users and demonstrated a blurred boundary between these smartphone users and their devices (Park & Kaye, 2019). In this study, heavy smartphone users viewed their smartphones as a seamless extension of their sense of self in multiple different

aspects, even attributing a unique personality and identity to their devices. Furthermore, researchers have investigated how smartphones modify the body schema, which is an individual's imagined representation of their body in its external environment. During a mental hand rotation task, participants were both faster and more accurate when they viewed a hand holding a smartphone compared to images of hands holding non-smartphone mobile devices or empty hands (Liu et al., 2022). These behavioral results also translated to electrophysiological differences, with different neural markers for hands with smartphones compared to without. Overall, existing literature demonstrates the significance of smartphone devices to their users, with individuals often viewing these devices as an extension of their selves and their physical bodies. Therefore, there is something unique and specific about smartphone devices wherein a temporary separation from these salient devices acts as a separation from an extension of oneself, resulting in high state anxiety, or nomophobia.

Many researchers have investigated the relationships between nomophobia and smartphones in conjunction with mental health variables such as anxiety, depression, and sleep quality. Overall, a multitude of survey research supports direct positive links between nomophobia and these mental health variables (Ayar et al., 2018; Kara et al., 2021; Mir & Akhtar, 2020; Sharma et al., 2019), with greater nomophobia associated with greater self-reported levels of anxiety, depression, and sleep quality. These results suggest that nomophobia is a distinct concept due to smartphone separation that has negative relationships with mental health. In addition, anxiety from smartphone separation is not alleviated through a replacement by other communication devices (e.g., laptops; Nie et al., 2020). Kara and colleagues (2021) investigated daily smartphone use as an environmental factor in the relationship between nomophobia and broader anxiety. Duration of daily smartphone use was significantly positively

related with both nomophobia and trait anxiety. In addition, trait anxiety mediated the relationship between daily smartphone use and nomophobia (Kara et al., 2021). Therefore, extant research establishes significant links between nomophobia, anxiety, and smartphone use.

As nomophobia is a situational state of anxiety resulting from loss of access to a smartphone, researchers have employed experimental designs to intentionally separate participants from their smartphones across three different studies. Cheever and colleagues (2014) separated participants from their smartphones before having them fill out a survey measure of state anxiety at three different time points. Participants reported higher anxiety when separated from their smartphones, and this anxiety increased over time. Furthermore, these researchers demonstrated that anxiety levels varied amongst different categories of smartphone users– high daily smartphone users reported greater anxiety over the three time points when separated from their smartphones compared to moderate or low daily smartphone users. A second study replicated these findings, as participants who sat in a waiting room for seven minutes without their smartphones reported significantly greater anxiety than participants who were permitted to keep their smartphones (Schmidt et al., 2018). Third, Clayton and colleagues (2015) conducted a smartphone separation experiment in which they not only assessed self-report measures of anxiety, but also physiological indices often associated with anxiety, during two-word search puzzle tasks. Unlike prior studies, these researchers separated participants from their smartphones at two different time points (either beginning or middle of task), and returned these devices to participants during the middle or end of the experiment. Participants reported greater state anxiety after separation from their smartphones, regardless of the timepoint they were separated. Furthermore, their self-reported anxiety decreased once their smartphones were returned to them. Physiological results paralleled self-reported anxiety, with both heart rate and

blood pressure increasing during moments of separation (Clayton et al., 2015). In addition, smartphone separation was significantly related with decreased performance on the word search tasks. Overall, research across survey and experimental research demonstrates significant, positive, associations between smartphone separation, nomophobia, and anxiety.

Relationships with executive function

Aforementioned literature demonstrates that smartphone separation is related with greater state anxiety and nomophobia across both survey and experimental studies. However, researchers are not only interested in these relationships, but also whether this relationship between smartphone separation and nomophobia result in subsequent behavioral or cognitive task performance deficits. For example, in the above experiment by Clayton and colleagues (2015), participants who were separated from their smartphone performed worse on cognitive word search puzzles than participants who were not separated. Therefore, these researchers demonstrated that smartphone separation and anxiety induced task/ performance costs for individuals. Researchers often investigate these same relationships with regard to impaired executive function.

Executive functions are a set of top-down cognitive processes needed for everyday actions and behaviors and extend over multiple domains of human performance including cognitive, social, emotional, and behavioral (Baggetta & Alexander, 2016; Diamond, 2013). According to Diamond (2013), the core executive functions are inhibition (or inhibitory control), working memory, and cognitive flexibility, and all other executive functions can be built upon these three. Other researchers have posited similar "core" executive functions such as shifting (similar to cognitive flexibility), updating (similar to working memory) and inhibition (Miyake et al., 2000). Of these three core executive functions, current theories on anxiety dictate that anxiety most primarily disrupts inhibitory control and cognitive flexibility abilities (Eysenck et al.,

2007). A recent meta-analysis of over 58 studies confirms that anxiety negatively impacts inhibitory control and cognitive flexibility tasks, but not working memory (or "updating") tasks (Shi et al., 2019).

Inhibitory control is defined as the ability to control behaviors, thoughts, emotions, attitudes, attention, etc. when needed, especially when needed to override a prepotent response (Diamond, 2013). Common assessments of inhibitory control include the Stroop task, Go/No-Go task, and antisaccade task. In these tasks, participants must often override a more 'automatic' thought or behavior with a different one (Miyake et al., 2000). For example, the Stroop task presents participants with a color word, which is colored in either a congruent ink color (e.g., the word 'red' in red ink) or incongruent ink color (e.g., the word 'red' in blue ink). Here, participants must respond to the color of the ink, overriding the automatic comprehension of the word. The "Stroop effect" is calculated as the difference in response time or accuracy between incongruent and congruent trials (Stroop, 1935).

Cognitive flexibility (also called "shifting"; Miyake et al., 2000) is the ability to adjust fluidly between demands, tasks, instructions, and perspectives (Dajani & Uddin, 2015; Diamond, 2013). Common assessments of cognitive flexibility are the Wisconsin Card Sorting Task (WCST) and task-switching paradigms, in which participants must switch between two sets of instructions. For example, a common task switching paradigm is the color-shape switching task, where participants are given two sets of instructions (e.g., respond to the color or shape of stimuli) and must switch behind instructions dependent on a certain cue, which randomly changes. Task switching paradigms involve two types of cognitive flexibility– switch costs and mixing costs. Switch costs refer to performance differences associating with a switch between instructions within a sequential task, whereas mixing costs refer to performance differences

associated with a shift between two tasks with the same instruction (Strobach et al., 2012). Overall, both cognitive flexibility and inhibitory control are related in that people must inhibit prior behaviors when needing to switch between tasks or instructions (Dajani & Uddin, 2015), and tasks which disrupt these executive functions often display lower accuracy rates and longer response times.

Researchers investigate how anxiety disrupts inhibitory control and cognitive flexibility. Attentional control theory posits that anxiety occupies a portion of our cognitive resources, limiting the ability to allocate attention and resources to other important processes, such as task performance and executive function (Eysenck et al., 2007). As a result, anxiety often is associated with adverse effects on cognitive tasks (for review see Eysenck, 1992). Furthermore, information processing theory suggests that our cognitive resources are allocated for personally motivating, goal-directed behaviors (Lang, 2000, 2017). The saliency of a valuable personal object (e.g., smartphones) may heighten through temporary separation, making individuals even more motivated to direct resources and attention to the loss of this object, leaving less for processes such as executive function or relevant tasks at hand. Therefore, if individuals are separated from their smartphones, subsequent feelings of nomophobia (a state-based anxiety) can reduce their ability to fully attend to, and perform efficiently, certain types of cognition.

Researchers have examined the relationships between anxiety, inhibitory control, and cognitive flexibility. In one of the first studies to investigate attentional control theory, trait anxiety had significant, negative relationships with inhibitory control, with high trait anxious individuals demonstrating performance deficits on an inhibitory control task compared with low anxious individuals (Derakshan, Ansari, et al., 2009). Recently, researchers investigated how state and trait anxiety interact in their relationship with impaired inhibitory control. These

researchers induced state anxiety in participants through a suspenseful video, and demonstrated that high state anxiety significantly impaired performance on an inhibitory control task, especially for individuals with already high trait anxiety (Myles et al., 2020). Researchers have also employed various tasks of cognitive flexibility to assess relationships with anxiety. In one study, high levels of state anxiety was negatively related with performance on a cognitive flexibility task-switching task, with greater switch and mixing costs (Hartanto & Yang, 2022). Other researchers established analogous findings with cognitive flexibility– finding that high state anxiety significantly heightens switch costs and reduces performance compared to low state anxiety. However, this relationship did not exist for high *trait* anxious individuals, and these researchers did not investigate mixing costs (Derakshan, Smyth, et al., 2009). Overall, researchers demonstrate significant relationships between state anxiety and impaired inhibitory control and cognitive flexibility. In addition, attentional control theory posits that anxiety affects efficiency (e.g., response time) more than effectiveness (e.g., accuracy) of a task (for meta-analysis see: Shi et al., 2019). Therefore, broader state anxiety and executive function research often demonstrate differences in response time, but no differences for accuracy rates.

Researchers have taken prior research on anxiety's detrimental relationship with both inhibitory control and cognitive flexibility and applied it specifically to a smartphone separation and nomophobia context. Hartanto and Yang (2016) examined the relationships between smartphone separation, the resulting nomophobia, and executive function. To do this, these researchers separated participants from their smartphones and had them perform three different tasks: an inhibitory control task, a cognitive flexibility task, and a working memory task (Hartanto & Yang, 2016). Smartphone separation was directly related with greater state anxiety, poorer performance on the Stroop task of inhibitory control, and poorer performance on the

color-shape switching task of cognitive flexibility. However, there were no significant differences between smartphone separation and anxiety during the working memory task. These findings support attentional control theory, in that state anxiety disrupts inhibitory control and cognitive flexibility, but not working memory. Furthermore, state anxiety mediated the relationship between smartphone separation and performance costs on the inhibitory control and cognitive flexibility tasks. In addition, problematic smartphone use moderated Stroop task performance, with individuals who reported greater smartphone dependency also demonstrating greater inhibitory control deficits after smartphone separation. Overall, in this study, smartphone separation and nomophobia were significantly related with behavioral deficits in both inhibitory control and cognitive flexibility.

Other researchers further investigated smartphone separation, state anxiety/nomophobia, and inhibitory control across two experiments: (1) a twenty-minute separation with no distraction and (2) a fifteen-minute separation that included a neutral distraction (Reichrath & Pietrowsky, 2022). After both instances of separation, participants completed the Stroop task of inhibitory control. In the first experiment, individuals who demonstrated a greater dependency on, or problematic use of, their smartphones (assessed through the smartphone addiction scale), reported greater state anxiety after separation than individuals with a low smartphone dependency. However, individuals in the second experiment, which involved a neutral distraction during the separation, did not report significantly greater anxiety. In addition, problematic smartphone users demonstrated greater response times Stroop effects (impaired inhibitory control) than non-problematic/non-dependent smartphone users in the second experiment, but not the first. Therefore, this second study partially supports Hartanto and Yang's (2016) findings with inhibitory control (Reichrath & Pietrowsky, 2022), however they did not investigate

cognitive flexibility. In a third study, researchers attempted to investigate a more 'real-world' setting of academic performance and nomophobia, and established that greater nomophobia levels were related with poorer student attention and performance on quizzes (Mendoza et al., 2018). Overall, on a behavioral level, smartphone separation and nomophobia seem to be associated with task performance deficits associated with executive function, most primarily inhibitory control and cognitive flexibility.

Potential neurocognitive relationships with nomophobia

Researchers commonly use electroencephalography (EEG) to detect how various stimuli alters the electrical activity of the brain. Event-related potentials (ERPs) are voltage changes in continuous electrical brain activity time-locked to an event (either internal or external; Kappenman & Luck, 2011). Specifically, these voltage changes result from a synchronized summation of postsynaptic potentials across an area, that can be detected amidst the larger signal. These voltage changes are recorded using EEG with ERP components having a specific peak amplitude, duration/latency, and scalp distribution (Luck, 2005). Overall, ERP components are said to generally reflect specific neural or psychological processes and the same component may differ depending on the modality (e.g., visual or auditory; Kappenman & Luck, 2011).

Currently, no research has examined the neural relationships of smartphone separation, the resulting nomophobia, and executive function. However, as nomophobia is a situational state of anxiety, other literature on state anxiety can provide insights into these potential relationships with nomophobia. The following studies with state anxiety center around three specific stimuli-locked ERPs: P2, P3, and N2, all with their own unique neural signature. The N2 component is a negative deflection typically peaking around 200ms after stimulus onset, with a typically frontocentral scalp distribution (Folstein & Van Petten, 2008; Näätänen & Gaillard, 1983). The

P2 component is a positive deflection peaking around 200ms after stimulus onset, typically with a maximum vertex topography (Crowley & Colrain, 2004; Curran et al., 1993). The P3 component is a positive deflection occurring around 300ms after stimulus onset, with maximum change over midline electrodes from frontal and parietal distributions (Johnson, 1993; Polich, 2007). The visual N2, P2, and P3 are all stimulus-locked components, with their peak in relation to the initial presentation of the stimulus. In other words, these three components occur after the presentation of a stimulus (e.g., the cue for the color-shape task switching task or the word in the Stroop task), not an error or response made by the participant.

Researchers have investigated how anxiety impacts the P2, P3, and N2 components in inhibitory control tasks. For inhibitory control, researchers recruited test anxious individuals and had participants complete two versions of the Stroop task. Test anxiety, like nomophobia, is another situational state of anxiety during performance evaluations such as exams. In this study, high test anxious individuals demonstrated longer response time (aka heightened response time Stroop effects), but not differences in accuracy rates. These results establish support for attentional control theory's assertation that anxiety hinders efficiency (response time) more so than effectiveness (accuracy). When examining ERPs, high test anxious individuals displayed larger P2 amplitudes, larger P3 amplitudes, and smaller N2 amplitudes for test-related words than low test anxious individuals (Zhang et al., 2019). Overall, we may expect similar patterns demonstrated by prior state anxiety research to be present in a nomophobia context as well.

Researchers have also investigated how anxiety impacts the P2, P3, and N2 components in cognitive flexibility tasks. A recent study explored the neural markers of state anxiety, reduced attentional control, and cognitive flexibility. More specifically, whether high math anxious individuals would demonstrate different ERP components and behavioral performance during a

task switching task than low anxious individuals. Similar to test anxiety and nomophobia, math anxiety is a situational state of anxiety during math-related problems or settings. Overall, high math anxious individuals demonstrated longer response times during switch trials on the task switching task (aka greater switch costs), and larger P2 amplitudes during switch trials compared to non-switch trials (González-Gómez et al., 2023). In other words, individuals who are experiencing a higher state of anxiety demonstrate specific neural patterns during cognitive tasks that differ from individuals not in a state of anxiety. If nomophobia is a state of anxiety after smartphone separation, we can hypothesize similar ERP patterns.

The aforementioned N2, P3, and P3 ERP components occur after presentation of the stimulus. However, many cognitive tasks require a response from participants, in which participants either respond correctly (e.g., naming the ink color rather than the word on the Stroop task) or incorrectly (e.g., naming the word). Error-related negativity (ERN) is a response-locked component, with its amplitude peak in relation to a behavioral response, specifically an error. This component is a negative deflection occurring around 50ms after the occurrence of an error with a front-central distribution (Moser et al., 2013; Olvet & Hajcak, 2008). In other words, after participants make an error on task (e.g., responding to the word rather than the ink color on the Stroop task), this component would be present in the EEG recording. Response errors are often key trials to investigate as the errors indicate that something (e.g., anxiety) may have interfered with the participant's ability to respond correctly. In a meta-analysis on anxiety and error-related negativity (ERN), Moser and colleagues distinguish between anxious apprehension and anxious arousal. Anxious apprehension is similar to state anxiety, categorized by a state of worry and rumination surrounding a perceived threat, whereas anxious arousal is characterized by physiological symptoms (e.g., heart rate). Overall, their meta-analysis established an overall

small to medium association between anxious apprehension and ERN amplitude, with high anxious individuals often displaying enhanced ERN amplitudes compared to non-anxious individuals during response errors (Moser et al., 2013). If an anxious state reflects heightened ERN amplitudes, we can hypothesize that a specific state of anxiety such as nomophobia would also result in similar ERN amplitude differences.

Hypotheses

Overall, individuals may be separated from their smartphones for a variety of reasons through daily life. Regardless of the reason for separation, researchers have established a subsequent heightened state of anxiety after separation, termed nomophobia. State anxiety in general induces differences in both behavior and cognition. However, current research on nomophobia has solely focused on the behavioral consequences of task performance (e.g., response time and accuracy rates). While prior research on broader state anxiety, and other specific types of situational anxieties (e.g., test or math anxiety) establish neurocognitive differences, no research has yet investigated the neural mechanisms behind whether smartphone separation and subsequent nomophobia results in similar changes in ERP components during cognitive tasks. The current dissertation explores the potential neurocognitive aberrations associated with smartphone separation and nomophobia on two indices of executive function: inhibitory control and cognitive flexibility.

In this dissertation, I first expect to replicate previous literature which establishes behavioral relationships between smartphone separation, greater nomophobia, and reduced inhibitory control and cognitive flexibility. Furthermore, these behavioral relationships should also result in a mediation through state anxiety/ nomophobia (Hartanto & Yang, 2016). Second, in accordance with attentional control theory, I expect greater state anxiety to impair efficiency (e.g., response

time) over effectiveness (e.g., accuracy rates). In addition, the general simplicity of the tasks combined with the age of proposed participants in this study (college students) also makes it more likely that behavioral differences will manifest in response times but not accuracy for both tasks.

To address whether these behavioral differences due to smartphone separation also manifest in neurocognitive aberrations, I have three hypotheses based on broader state anxiety literature which investigated ERP amplitude differences:

H1: Smartphone separation will lead to greater P2 and P3, reduced N2, and greater ERN amplitudes during an inhibitory control task.

H2: Smartphone separation will lead to greater P2 and greater ERN amplitudes during a cognitive flexibility task.

H3: State anxiety/ nomophobia will mediate the relationships in H1 and H2.

To assess these predictions, participants performed the color-word Stroop task to assess inhibitory control and the color-shape task switching task to assess cognitive flexibility, similar to previous behavioral research (Hartanto & Yang, 2016). Overall, these performance-based behavioral task measurements are particularly advantageous for combining with neuroimaging methods such as EEG. The progress of performance throughout time permitted correlates between specific moments of engagement with an executive function process (e.g., an inhibition or switching trial) with momentary brain activity. To note, these hypotheses focus on ERP amplitude, rather than other characteristics such as latency, due to prior discussed state anxiety and executive function literature which either does not investigate, or reports no significant relationships, with latency (González-Gómez et al., 2023; Moser et al., 2013; Zhang et al., 2019).

This dissertation research is critical to help advance the current understanding of smartphone separation, nomophobia, and executive function. First, this dissertation will allow for a comparison of nomophobia with more generalized state anxiety research. Specifically, while researchers have explored how state anxiety affects neural correlates of cognition and executive function (P2, P3, N2, and ERN amplitudes), it has yet to be assess how nomophobia may impact these same markers. Therefore, this dissertation will elucidate the relationship between anxiety and nomophobia, clarifying if nomophobia is a situational state of anxiety with similar neural and cognitive outcomes as general state anxiety, or if there are different mechanisms at play. These findings will help researchers better understand whether nomophobia is in fact a phobia, or something else. In addition, these findings may help clinicians focused on anxiety surrounding smartphones or other technology use with their patients. Second, by assessing both behavioral task performance and neural activity associated with smartphone separation, this study provides a more holistic understanding of its relationship with cognitive performance. By further explicating the role of smartphone separation on executive function, researchers and clinicians can be better stewards for teachers, parents, policy makers, and individuals, providing evidence-based advice surrounding smartphone use and situations which dictate smartphone separation. Third, despite previously demonstrated relationships between behavioral impairments of smartphone separation, the neural indices have yet to be explored. By assessing neural differences associated with smartphone separation and executive function, this dissertation will help explicate this gap in current literature, affording researchers a more comprehensive understanding of smartphone separation, nomophobia, and cognitive performance from brain to behavior. Important to note, it could also be the case that this dissertation yields results in a different direction, or that there are null results. Even if this situation, this dissertation is still the

first study to investigate these relationships using neuroimaging techniques and can better inform future studies that wish to further investigate smartphone separation. Furthermore, a lack of positive findings would still contribute to scientific knowledge and inform public policy in regard to, for example, smartphone separation in schools. Overall, this dissertation research has the potential to inform multiple different audiences on the behavioral and neurocognitive aberrations of smartphone separation.

CHAPTER 2: METHOD

Participants

Forty undergraduate students were recruited from Michigan State University via the Communication Arts and Sciences online SONA system. This sample size was determined through an a-priori power analysis using G*Power to detect within-subject differences with an effect size of .59, indicating at least 33 participants to achieve a power of .90 and 28 participants to achieve a power of .85. This effect size was identified through prior research which investigated smartphone separation and performance on cognitive task (Clayton et al., 2015). Furthermore, the four ERP components (ERN, P2, P3, N2) hypothesized in this dissertation are all distinct, well-established components, with large effect magnitudes (>.50). Previous researchers ran Monte-Carlo simulations to detect the minimum sample and trial numbers to detect these components and achieve high statistical power (≥ .80)– indicating at least 16 participants and 8 trials each for a within-subjects design (Boudewyn et al., 2018; Jensen & MacDonald, 2023). Overall, as the main purpose of this dissertation is to identify the potential ERP differences, this sample size is more than sufficient to detect these neurocognitive changes, while still yielding enough power to detect and replicate behavioral relationships.

Inclusion criteria included: 1) ownership of a smartphone device (iPhone, Android, etc.) and 2) no pre-existing conditions that impair task performance (color-blindness) or EEG recording (left-handed or cochlear implant). Exclusion criteria included: 1) participants who perform below 2.5 standard deviations for either accuracy or response time (two participants), 2) consumed any major substances beforehand (e.g., alcohol, cannabis, etc.) (no participants), 3) displayed poor electrode connectivity or had more than 50% of trials rejected due to artifacts (four participants) or 4) did not finish all tasks or survey measures (two participants). Overall,

eight participants were excluded during data analysis, for a final sample size of 32 participants. Participants received four total hours of SONA credit (2 hours per day) in addition to $20 for completion of the second day. All procedures were approved by the Institutional Review Board at Michigan State University before testing (Approval # STUDY00009617).

Procedure and Experimental Design

This study employed a within-subjects experimental design across two separate testing days (Figure 1). This study was only visible on SONA to participants who met the inclusion criteria detailed above. To be eligible to sign up for a timeslot for this study on SONA, participants first completed an additional pre-screening survey to confirm inclusion criteria. If eligible, participants received an access code at the end of the pre-screening survey to sign up for time slots. Participants signed up for both testing days of this study via SONA with day 1 and day 2 scheduled 5-7 days apart. After scheduling, participants were randomly assigned to one of two groups. Group 1 (D1Sep/D2Poss) refers to smartphone separation on day 1 and smartphone possession on day 2. Group 2 (D1Poss/D2Sep) refers to smartphone possession on day 1 and smartphone separation on day 2.

On both testing days, participants met a researcher at the Communication Arts and Sciences building in a research-dedicated space. All participants signed an informed consent document on day 1 regardless of their group. Afterward, D1Sep/D2Poss participants were informed that a prior participant's smartphone caused signal interference with the EEG recording, so they must leave it behind in the ComArtSci locked room as a precaution. D1Poss/D2Sep participants were not informed anything differently. On Day 2, D1Sep/D2Poss participants were instructed that we retested the EEG equipment since their last session and resolved the issue, so they do not need to leave their smartphone behind. D2Poss/D2Sep

participants were informed the same rationale as D1Poss/D2Sep participants. Please see the Appendix for full participant script.

On day 1 after finishing the above procedures in the ComArtSci research space, the researcher and participant walked across the street (Red Cedar Road) to the Oyer Building, room 10, where EEG recording and testing took place. Regardless of group (D1Sep/D2Poss or D1Poss/D2Sep), the procedure for all participants was the same in Oyer 10. First, participants were measured and fitted with an elastic cap embedded with 32 electrodes. After capping, participants sat in an adjacent, private, testing room fitted with a comfortable chair, desk, computer at eye level, and a keyboard. At this point, researchers checked the EEG conductance and connectivity between all electrodes and adjusted where needed. Afterwards, participants completed the 20-item state anxiety portion of the STAI scale. After the state anxiety scale, participants completing two executive function tasks (stroop & color-shape switching), with task order counterbalanced across participants. After both tasks, a researcher removed the EEG cap and returned with them to the ComArtSci research space. D1Sep/D2Poss participants were returned their smartphone.

Day 2 followed almost identical procedures as day 1. Participants met in the ComArtSci research space, were instructed according to their group (D1Sep/D2Poss or D1Poss/D2Sep), and walked over to Oyer 10. Participants completed the same EEG recording and task protocol as described above for day 1. After removing the EEG cap and returning to the ComArtSci researcher space, D1Poss/D2Sep participants were returned their smartphone. Day 2 differed from day 1 in that all participants completed the remaining survey measures (apart from the state anxiety scale) at the end of this day in the Communication Arts and Sciences research-dedicated

space. After completing the survey, participants were debriefed, thanked for their participation, and provided appropriate compensation.

Task Measures

Both tasks were coded in MATLAB (The MathWorks Inc., 2021) using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). All stimuli for both tasks were presented via MATLAB on a monitor directly in front of the participant.

Stroop Task

The classic word-color Stroop task (Stroop, 1935) is a measure of inhibitory control. The stimuli for this task are the words "red", "green", and "blue". The words are either presented in the congruent color as the meaning of the word (e.g., the word red in red ink), or an incongruent color (e.g., the word red in blue ink). Participants were instructed to place their index, middle finger, and ring finger of the number pad of the keyboard, where colored circular stickers were placed to represent each color. A red circle on the '4' number pad, a green circle on the '5' number pad, and a blue circle on the '6' number pad. Participants were instructed to respond to the ink color of the word and ignore the word meaning.

Participants first completed a practice block of 15 trials, five for each color-to-key mapping (5 for red, 5 for green, 5 for blue). After the practice block, participants completed three experimental blocks of 100 trials each, for a total of 300 experimental trials. For each experimental blocks, 70% of the trials were congruent and 30% of the trials were incongruent. Overall, participants viewed 210 congruent and 90 incongruent trials. Each experimental block was interspaced with a 15 second break. Every trial began with a fixation cross jittered between 1500ms ± 150ms and then the presentation of the stimulus word (either congruent or incongruent) presented for 200ms (Tillman & Wiens, 2011). The shorter stimulus presentation

time ensured a small/negligible stimulus offset ERP response that would not occur during the timing of the ERPs of interest (Luck, 2014). Responses via key press with the right hand were recorded while the stimuli are presented or during the subsequent intertrial interval. See Figure 2 for visualization of this task.

For the Stroop task, accuracy (% correct) and response time (in milliseconds) were averaged separately for congruent and incongruent trials of each participant on both separation and possession days. The Stroop effect for response time and accuracy were calculated as the performance difference between incongruent and congruent trials.

Color-Shape Switching Task

The color-shape switching task is a measure of cognitive flexibility (Monsell, 2003). In this task, participants must switch between two sets of instructions, responding to either the color or shape of stimuli. The stimuli for this task were similar to previous task-switching experiments: two shapes (circle and triangle), two colors (red and green), and two cues (color gradient and row of small black shapes) (Hartanto & Yang, 2016, 2022). Simple imaged-based cues matched for size were used to avoid the effect that cue complexity can have on response time, as previous research suggests that complex cues can introduce unnecessary and additional processing burden on participants beyond the task itself (Monsell & Mizon, 2006). Participants were instructed to place their two index fingers on the "J" and "F" key on the keyboard, with one key for "red" and "circle" and one key for "green" and "triangle". Key assignments were counterbalanced across participants and stickers depicting either a red circle or a green triangle were placed on these keys to represent this assignment. Participants were instructed to respond to either the color or shape of the stimuli, depending on the instructions of the cue presented above it.

Participants completed a total of five experimental blocks in the following order: two pure blocks, one mixed block, two pure blocks. During pure blocks, participants only responded to one aspect (either shape OR color) the entire time, without switching between them. Each pure block consisted of 32 experimental trials, and the first two pure blocks also began with 8 practice trials. Overall, participants viewed two pure *color* blocks and two pure *shape* blocks by the end of this task. During the mixed block, participants must respond to both aspects (shape AND color), depending upon the cue presented simultaneously above the stimuli. The mixed block consisted of 16 practice trials and 256 experimental trials. For the mixed block, 50% (128) of trials were switch trials and 50% (128) were repeat (non-switch) trials. Switch trials are trials in which the cue differed from the prior trial cue. Repeat trials were trials in which the cue was identical to the prior trial cue. Overall, participants viewed a total of 384 experimental trials (256 mixed block, 128 pure blocks).

Each experimental block was interspaced with a 15 second break. Every trial began with a fixation cross jittered between 1500ms ± 150ms, then the stimulus and cue presented together for 250ms (Jackson et al., 2001). The shorter stimulus presentation time ensured a small or negligible stimulus offset ERP response that will not occur during the timing of the ERPs of interest (Luck, 2014). Responses via key press were recorded while the stimuli were presented or during the subsequent intertrial interval. See Figure 3 for visualization of this task.

For the Color-Shape switching task, accuracy (% correct) and response time (in milliseconds) were averaged separately for switch and repeat trials during the mixed task block and for pure trials in the pure blocks on both separation and possession days. Response time and accuracy switch costs were calculated as the difference in performance between switch and

repeat trials during the mixed block. Response time and accuracy mixing costs were calculated as the difference in performance between pure blocks and repeat trials in the mixed block.

Survey Measures

All survey measures (apart from the state anxiety scale) were given at the end of day 2 to ensure that all participants were exposed to the separation condition before completion.

Smartphone Use

Smartphone use was assessed via three separate measures: self-reported time, built-in device metrics time, and smartphone "addiction." First, participants self-reported the average hours and minutes they spend on their smartphone each day. Second, participants reported built-in screentime metrics measured by their device. For Apple products, the iOS Screentime Function, and for Android products, the Digital Wellbeing function in settings.

In addition to the two screentime metrics, participants completed the Smartphone Addiction Scale-Short Version (SAS-SV; Kwon et al., 2013). As "addiction" as it refers to social media use and therefore smartphones is a debated term (Panova & Carbonell, 2018), I will avoid using the term "addiction" when describing the results of this scale and use the term problematic use. The SAS-SV is a 10-item self-report scale which asks participants to indicate their agreement with each statement on a scale from 1 ("Strongly Disagree") to 6 ("Strongly Agree"). An example statement includes "I will never give up using my smartphone even when my daily life is already greatly affected by it". Scores were averaged to create a single score for each participant, with higher scores indicating a higher degree of problematic smartphone use.

Anxiety

I measured three separate types of anxiety: state anxiety, trait anxiety, and nomophobia. State and trait anxiety were measured with the Spielberger State-Trait Anxiety Inventory (STAI;

Spielberger, 1983; Spielberger et al., 1971). The STAI is 40-item self-report scale which assesses both types of anxiety, with 20-items for state anxiety and 20-items for trait anxiety. The state anxiety subscale asked participants the indicate the extent to which they feel certain emotions *right now*, on a scale from 1 ("Not at all") to 4 ("Very much so"), with statements such as "I feel calm" or "I feel nervous". The trait anxiety subscale asked participants to indicate the extent to which they *generally* feel, on a scale from 1 ("Almost Never") to 4 ("Almost Always"), with statements such as "I worry too much over something that really doesn't matter" or "I am content". Appropriate items were reverse coded, and scores were summed to create a composite score separately for state and trait anxiety, with higher scores indicating greater anxiety.

To assess nomophobia, I used the Nomophobia Questionnaire (NMP-Q; Yildirim & Correia, 2015). The NMP-Q is a 20-item scale which assesses agreement with statements from 1 ("Strongly Disagree") to 7 ("Strongly Agree"). Statements assess four general themes: (1) "If I did not have my smartphone with me, I would be worried because my family and/or friends could not reach me"(loss of communication) (2) "If I did not have my smartphone with me, I would be nervous because I would be disconnected from my online identity" (loss of connection), (3) "I would feel uncomfortable without constant access to information through my smartphone" (loss of information access), and (4) "If I could not use my smartphone, I would be afraid of getting stranded somewhere" (loss of convenience). Scores were summed to create a composite score between 1-140, with higher scores indicating more severe levels of nomophobia. Yildrim and Correia (2015) also proposed a four-level classification system in their development of the NMP-Q: absent (≤20), mild (21-59), moderate (60-99), and severe (≥100) nomophobia, and participants were categorized as such.

Covariates

In addition to the main variables of interest (smartphone use & anxiety), I assessed several other variables. First, I assessed a participant's attitude towards their smartphone with the Young Adults Attachment to Phone Scale (YAPS; Trub & Barbot, 2016). The YAPS is a 6-item scale which assesses an individual's orientation to their smartphone. There are two subscales on this survey: refuge and burden. One item which assesses refuge is "Having my phone makes me feel safer" and an item which assesses burden is "Being without my phone gives me a sense of relief". Second, I assessed participant's social media use with the Bergen Social Media Addiction Scale (BSMAS; (Andreassen et al., 2012). The BSMAS is a 6-item scale, and each item assesses a different core aspect of addiction outlined by Griffiths (2014). Third, I assessed a participant's Fear Of Missing Out (FOMO), with the FoMOs scale (Przybylski et al., 2013). The FoMOs is a 10-item scale which assesses an individuals' fear of missing out on everyday experiences. In addition to these three scales, participants completed several demographic measurements: age, gender, race, and ethnicity.

Electrophysiological Data Acquisition

EEG data was collected with 32 Ag/AgCl electrodes via the Biosemi ActiveTwo system (Amsterdam, Netherlands) at a sampling rate of 512 Hz. Electrode locations were consistent with the International 10–20 System. Additional electrodes were placed over the left and right mastoids for re-reference purposes, as well as the left and right outer canthi and left lateral and supra-ocular area to monitor eye movements. EEG data was recorded unreferenced and unfiltered relative to the common mode sense electrode, as it standard for Biosemi data collection. Impedances were all kept under ±40mV, as is recommended by Biosemi, and the majority were kept under ±20mV.

Statistical Analyses

Behavioral Data

All behavioral analyses were performed using SPSS (version 29). First, I assessed whether I replicated previous behavioral relationships between smartphone separation, nomophobia, inhibitory control, and cognitive flexibility. I performed separate repeated measures ANOVAs to assess differences between smartphone separation and possession days. To assess inhibitory control during the Stroop task, I conducted a 2 (day: separation x possession) x 2 (trial type: incongruent x congruent) repeated measures ANOVA for response time and accuracy. To assess cognitive flexibility during the Switching task, I conducted a 2 (day: separation x possession) x 3 (trial type: switch x repeat x pure) repeated measures ANOVA for response time and accuracy. For any significant findings, I tested whether state anxiety (nomophobia) mediates the relationship between smartphone separation and executive function using Hayes PROCESS model 4.

Electrophysiological Data

EEG data was processed using MATLAB-based EEG Lab (Delorme & Makeig, 2004) and ERP Lab (Lopez-Calderon & Luck, 2014) programs. First, EEG data was re-referenced to the average of the mastoid processes offline. Second, bad channels were removed, and data was high-pass filtered at 0.5Hz via a finite impulse response (FIR) filter. Third, ICA was performed and eyeblink components were removed using icablinkmetrics (Pontifex, 2015). Fourth, any removed bad channels were interpolated, and continuous data was epoched into 1200ms segments, ranging from 200ms before the stimuli to 1000ms after the stimulus event. Epochs were then baseline corrected by subtracting the average signal of the 200ms baseline period from the entire epoch length. At this point, data was low-pass filtered at 30Hz via a FIR filter. Fifth, noisy

epochs were removed via a moving window peak-to-peak threshold, which flags voltage changes exceeding 200 μV across a 200ms window, moving through epochs in increments of 100ms.

After the EEG data was processed, single trial EEG epochs were averaged to create average waveforms within each subject for incongruent trials, congruent trials, switch trials, repeat trials, pure trials, correct responses, and error responses on both separation and possession days. Regions of interest for each ERP component were selected based on prior literature and visual inspection of scalp topographies to select the most prominent distribution of the component within the current dataset. The N2, P2, and ERN components had a predominately frontocentral distribution and were averaged across seven frontocentral electrode sites (*F3, F4, FC1, FC2, Fz, AF3, AF4*; Crowley & Colrain, 2004; Folstein & Van Petten, 2008; Moser et al., 2013; Näätänen & Gaillard, 1983; Olvet & Hajcak, 2008). The P3 component had a predominately centroparietal distribution and was averaged across five centroparietal electrode sites (*P3, P4, Pz, PO3, PO4;* Johnson, 1993; Polich, 2007).

The time window to extract each component amplitude was also determined based on previous literature (Crowley & Colrain, 2004; Folstein & Van Petten, 2008; Moser et al., 2013; Polich, 2007) and visual inspection of the grand average waveform. Amplitudes were calculated as the mean amplitude across a specified time window centered on the peak of the component, which was determined by where it occurred in the grand averaged waveform. Given the narrow peaks for N2, P3, and the ERN, mean amplitudes were extracted across a 60ms time window for these components (N2: 280-340ms, P3: 325-385ms, ERN: 25-85ms) for the Stroop task. The P2 component had a slightly broader peak, therefore mean amplitude was extracted across an 80ms time window between 150-230ms for the Stroop task and 160-240ms for the Switch task. Each ERP amplitude was calculated for each condition, on each day, for each participant. Grand

average ERP waveforms across subjects for each condition were computed for visualization purposes.

After computing ERP amplitudes via MATLAB, all future statistical analyses were performed using SPSS (version 29). Boudewyn and colleagues (2018) determined a minimum of 16 trials needed for a within-subjects design, and all participants included in these analyses met this criterion. To address H1, ERP amplitudes were statistically compared to each other through a 2 (day: separation x possession) x 2 (trial type: incongruent x congruent) repeated measures ANOVA for N2 amplitude, P2 amplitude, P3 amplitude and a 2 (day: separation x possession) x 2 (response: error response x correct response) repeated measures ANOVA for ERN amplitude. To address H2, ERP amplitudes were statistically compared to each other through a 2 (day: separation x possession) x 3 (trial type: switch x repeat x pure) repeated measures ANOVA for P2 amplitude, and a 2 (day: separation x possession) x 2 (response: error response x correct response) repeated measures ANOVA for ERN amplitude.

CHAPTER 3: RESULTS

Behavioral Results

Full demographic information and descriptive statistics for all survey measures can be viewed in Table 1. Participants ranged in age from 19-22 years (*M=20.47, SD=.88)*. Nine participants were males and 23 females. Twenty-six participants identified as White or Caucasian, three identified as Black or African American, two identified as Asian, and one self-identified as Middle-Eastern. Overall, participants were predominately female (71.9%) and white (81.3%). Participants self-reported spending 6.11 (*SD*=2.51) hours daily on their smartphones, and smartphone metrics reported participant daily averages of 6.37 (*SD*=2.38) hours. A dependent samples t-test between self-reported screentime and screentime reported by device metrics was not significant $t_{(31)}$=-.934, p=.358. In other words, participants subjective measures of total screentime were fairly accurate when compared with the objective measures of screentime recorded by their smartphones. Participants self-reported state anxiety levels did not differ between separation (*M*=28.03, *SD*=7.71) and possession days (*M* =28.53, *SD*=8.39), contrary to expectations, $t_{(31)}$=-.655, *p*=.517. When categorizing participants by nomophobia categories (Yildirim & Correia, 2015), the majority (65.6%) of participants fell into a "moderate nomophobia" and 25% of participants fell into the "severe nomophobia" category.

Pearson's bivariate correlations between all demographics and survey measures can be viewed in Table 2. Of relevance, state anxiety on the separation day (but not possession day) was significantly positively correlated with problematic smartphone use, *p=.029*. In other words, participants who reported a greater dependency upon their devices also reported greater anxiety when separated. Nomophobia scores were significantly positively correlated with problematic smartphone use (*p<.001)*, problematic social media use (*p<.001)*, and FOMO (*p<.001)*. In other

words, as participants report greater dependencies upon their smartphones and social media platforms, they also report greater anxiety about being separated from their smartphones. Furthermore, as participants report a greater fear of missing out, they also report greater anxiety about being separated from their smartphones.

Stroop Task

Means and standard deviations for both response time and accuracy rates for the Stroop task are presented in Table 3 below. A 2 (day: separation x possession) x 2 (trial type: incongruent x congruent) repeated measures ANOVA was performed to evaluate the effect of day and trial type on response time and accuracy rates during the Stroop task (Table 4).

Results indicated a significant main effect of trial type for both response time $F_{(1,31)}$ = 161.81, p<.001, η_p^2=.839 and accuracy rates $F_{(1,31)}$ = 61.51, p<.001, η_p^2=.665. Post hoc comparisons with a Bonferroni correction indicated that response times were significantly longer for incongruent trials (M=597*)* compared to congruent trials (M=471*)*, p<.001. See Figure 4 for visualization of response time across both days and trial types. Similarly, accuracy rates were significantly lower for incongruent trials (M=94.8*)* compared to congruent trials (M=98.2*), p<.001*. See Figure 5 for visualization of accuracy rates across both days and trial types. In other words, the Stroop task functioned as expected– participants were slower to respond, and less accurate, for incongruent trials compared to congruent trials.

There was no significant main effect of day for either response time or accuracy rates, all *p's>.05*. There were also no interactions between day and trial type, all *p's>.05*. In other words, smartphone separation did not have any significant effects on Stroop task performance. Finally, the Stroop effect was calculated as the difference in performance between incongruent and congruent trials for response time and accuracy. Paired samples t-tests were performed between

the Stroop effect on separation and possession days. There were no significant differences in the Stroop effect between days for response time, ($t_{(31)}$=-1.40, p=.172) or accuracy, ($t_{(31)}$=1.82, p=.079).

Switch Task

Means and standard deviations for both response time and accuracy rates for the Switch task are presented in Table 5 below. A 2 (day: separation x possession) x 3 (trial type: switch x repeat x pure) repeated measures ANOVA was performed to evaluate the effect of day and trial type on response time and accuracy rates during the Switch task (Table 6). Mauchly's Test of Sphericity indicated that the assumption of sphericity was violated for both response time trial type, ($\chi^2(2)$ =11.62, *p=.003),* accuracy rate trial type ($\chi^2(2)$=20.65, *p<.001),* the response time day x trial type interaction ($\chi^2(2)$=1.93, *p<.001),* and the accuracy rate day x trial type interaction ($\chi^2(2)$ =6.43, *p=.040).* Therefore, Greenhouse-Geisser estimates were used.

Results indicated a significant main effect of trial type for both response time $F_{(1,62)}$ = 405.40, p<.001, η_p^2=.929 and accuracy rates $F_{(1,62)}$ = 86.95, p<.001, η_p^2=.737. Post hoc comparisons with a Bonferroni correction indicated that all three trial types were significantly different from each other for both response times and accuracy rates– response times were significantly longer for switch trials (*M=771)* compared to repeat trials (*M=618)* and pure trials (*M=276),* all *p's<.001*. See Figure 6 for visualization of response time across both days and trial types on the Switch task. Similarly, accuracy rates were significantly lower for switch trials (*M=83.9),* compared to repeat trials (*M=93.1)* and pure trials (*M=97.1)*, all *p's<.001*. See Figure 7 for visualization of accuracy across both days and trial types on the Switch task. In other words, the Switch task functioned as expected– participants were slower to respond, and less

accurate, for switch trials compared to repeat trials. Furthermore, participants were slower to respond to, and less accurate, for repeat trials compared to pure trials.

There was no significant main effect of day for either response time or accuracy rates, all *p's>.05*. There were also no interactions between day and trial type, all *p's>.05*. In other words, smartphone separation did not have any significant effects on Switch task performance. Finally, switch and mixing costs were calculated for response time and accuracy on the Switch task. Switch costs were calculated as the difference in performance between switch and repeat trials, and mixing costs were calculated as the difference in performance between repeat and pure trials. Paired samples t-tests were performed for switch costs and mixing costs between separation and possession days. For switch costs– there were no significant differences between days for response time ($t_{(31)=}$.422, p=.676) or accuracy ($t_{(31)=}$-.241, p=.811). For mixing costs– there were also no significant difference between days for response time ($t_{(31)=}$-1.93, p=.063) or accuracy $t_{(31)=}$.762, p=.452.

Mediation

Pearson's bivariate correlations were performed to examine relationships between state anxiety on the separation day, state anxiety on the possession day, and all behavioral performance measures (response time, accuracy) across both tasks and days. There were no significant relationships between state anxiety and any behavioral performance measure, all *p's>.05.* In addition, separation did not have a significant impact on state anxiety scores, p=.37. Given the lack of a significant relationship between the independent variable (smartphone separation) and the proposed mediator (state anxiety), as well as no significant relationship between the mediator (state anxiety) and any behavioral outcome, no mediation analyses were conducted.

Electrophysiological Results

Means and standard deviations for ERP component amplitudes across all conditions for both the Stroop and Switch task can be viewed in Table 7. Pearson's bivariate correlations were performed between measures of anxiety (trait, state, nomophobia) and all ERP amplitudes, but there were no significant relationships between any variables, all *p's>.05.*

Stroop Task

A 2 (day: separation x possession) x 2 (trial type: incongruent x congruent) repeated measures ANOVA was performed to evaluate the effect of day and trial type on N2 amplitude, P2 amplitude, and P3 amplitudes during the Stroop task.

Results indicated a significant main effect of trial type for N2 ($F_{(1,31)}$=5.86, *p=.022)* and P2 amplitudes ($F_{(1,31)}$=6.57, *p=.015)*. Post hoc comparisons with a Bonferroni correction indicated that N2 amplitudes were significantly *reduced* on incongruent trials (*M*=-4.54), compared to congruent trials (*M*=-5.70), *p=.022* and P2 amplitudes were significantly *larger* on incongruent trials (*M*=2.66) compared to congruent trials (*M*=1.58), *p*=.015 (Figure 8). In other words, N2 and P2 amplitudes were significantly different between incongruent and congruent trials across both days. These finding parallels behavioral response time and accuracy relationships, which demonstrated slower response times and lower accuracy for incongruent trials compared to congruent trials. There was no main effect of trial type on P3 amplitudes.

There was no significant main effect of day for N2 (*p=.616)*, P2 (*p=.784)*, or P3 (*p=.916)* amplitudes. There were also no interactions between day and trial type for N2 (*p=.741)*, P2 (*p=.286)*, or P3 (*p=.391)* amplitudes, which parallels the insignificant behavioral day x trial type interaction for behavioral response time and accuracy on the Stroop task. Overall, N2 and P2 amplitudes were influenced by trial type but not day on the Stroop task.

The Stroop effect for each ERP component were calculated as the difference in amplitude between incongruent and congruent trials, otherwise known as difference waves. Paired samples t-tests were performed between the separation and possession Stroop effect difference waves. There were no significant differences in the Stroop effect difference ways for N2 amplitudes ($t_{(31)}$=.33, p=.741), P2 amplitudes ($t_{(31)}$=1.09, p=.286), or P3 amplitudes ($t_{(31)}$=-.87 p=.391). In other words, the difference waves between the trial types were relatively equal across days.

A 2 (day: separation x possession) x 2 (response: error x correct response) repeated measures ANOVA was performed to evaluate the effect of day and response on ERN amplitudes during the Stroop task. Results indicated a significant main effect of response, $F_{(1,18)} = 31.648$, $p<.001$. Post hoc tests comparisons with a Bonferroni correction indicated a significantly larger ERN amplitude after an error response (M=-6.148) compared to a correct response (M=0.855), $p<.001$, see Figure 9. There was no significant main effect of day or significant day x response interactions for ERN amplitudes. In other words, brain activity was significantly different after an error response, with a larger ERN amplitude, regardless of the day.

Switch Task

A 2 (day: separation x possession) x 2 (trial type: switch x repeat x pure) repeated measures ANOVA was performed to evaluate the effect of separation and trial type on P2 amplitudes for the Switch task.

Results indicated a significant main effect of trial type, $F_{(2,60)} = 29.77$, $p <.001$. Post hoc comparisons with a Bonferroni correction indicated that P2 amplitudes were significantly different between all trials, all p's<.001. P2 amplitudes were largest for switch trials (M=3.71) compared to repeat trials (M=1.14) and pure trials (M=-2.82), see Figure 10. In other words, P2

amplitudes were significantly different between trial types across both days. These finding parallels behavioral response time and accuracy relationships, which demonstrated slower response times and lower accuracy for switch trials compared to repeat trials.

There was no significant main effect of day for P2 amplitudes, $p=.181$. In other words, P2 amplitudes were not significantly different between the separation and possession day. There was also no significant day x trial type interaction for P2 amplitudes during the Switch task ($p=.879$), which parallels the insignificant behavioral day x trial type interaction for behavioral response time and accuracy on the Switch task. Overall, P2 amplitudes were influenced by trial type but not day on the Switch task.

Switch costs were calculated as the difference in amplitude between switch and repeat trials, otherwise known as difference waves. Mixing costs were calculated as the difference in amplitude between repeat and pure trials. Paired samples t-tests were performed between the separation and possession Switch cost difference waves and separation and possession Mixing cost difference waves. There were no significant differences in the Switch cost difference ways ($t_{(31)}$=-.01, p=.990) or the Mixing cost difference waves($t_{(31)}$=.26, p=.799) for P2 amplitudes. In other words, the difference waves between the trial types were relatively equal across days.

A 2 (day: separation x possession) x 2 (response: error x correct response) repeated measures ANOVA was performed to evaluate the effect of day and response on ERN amplitudes during the Switch task. A 2 (day: separation x possession) x 2 (response: error x correct response) repeated measures ANOVA was performed to evaluate the effect of day and response on ERN amplitudes during the Switch task. There were no significant differences for ERN amplitudes during the Switch task.

CHAPTER 4: DISCUSSION

The purpose of this dissertation was to investigate the neural relatsionships between smartphone separation, anxiety, and executive function, with a focus on inhibitory control and cognitive flexibility. Previous research establishes significant behavioral relationships between smartphone separation and greater state anxiety (Cheever et al., 2014; Derakshan, Smyth, et al., 2009; Schmidt et al., 2018). Additionally, smartphone separation induced state anxiety is linked with reduced behavioral performance on tasks of inhibitory control and cognitive flexibility (Hartanto & Yang, 2016; Reichrath & Pietrowsky, 2022). This dissertation aimed to examine the neurocognitive changes that underlie these behavioral relationships during tasks of inhibitory control and cognitive flexibility. Specifically, I focused on four ERP components that are commonly influenced by state anxiety– the N2, P2, P3, and ERN– hypothesizing that smartphone separation will lead to amplitude differences in these components. To evaluate the hypotheses, I assessed behavioral performance and EEG activity during the Stroop task (inhibitory control) and Color-Shape Switching task (cognitive flexibility) on both a smartphone separation and smartphone possession day.

I expected to replicate previous findings which demonstrate a positive relationship between smartphone separation and greater state anxiety, often termed nomophobia. (Cheever et al., 2014; Clayton et al., 2015; Hartanto & Yang, 2016; Schmidt et al., 2018). The current dissertation attempted to maximize feelings of separation and state anxiety by having smartphones separation over a greater amount of time (~2 hours) and distance (separate buildings) during this experiment. Contrary to expectations, there were no significant differences in state anxiety between separation and possession days. In other words, smartphone separation did not induce greater state anxiety within this study.

There are several potential factors that could explain the failure to induce state anxiety. First, most previous studies measured state anxiety immediately after smartphone separation (Clayton et al., 2015; Hartanto & Yang, 2016; Schmidt et al., 2018). While Cheever and colleagues (2014) reported increased state anxiety 35- and 60-minutes post separation, this was only for participants with a high daily use of all electronics (M =25.*19* hours summed across multiple screentime activities). Participants in this dissertation reported an average daily screentime of six hours, which is significantly below the average screentime of all participants in the study by Cheever and colleagues (2014), reported as 13.58 hours. Furthermore, it is even further below the screentime average of the high electronic users in their study, which is the only group that demonstrated anxiety differences after 35 minutes post separation. In the current dissertation, participants completed the state anxiety scale ~40-50 minutes post separation, due the time it took to walk to the testing room in a separate building, measure and cap the participant with the EEG cap, and ensure proper connectivity. Therefore, it could be that any increase in state anxiety due to separation may have diminished over the time and distance taken between the physical moment of separation and measurement of state anxiety.

In the time in between the separation and state anxiety scale, participants and researcher walked from the ComArtSci building to the Oyer research space, set up the EEG equipment, and explained all procedures as they were occurring. During this time, the researcher filled the space with small talk to make the participant more comfortable, as 40-50 minutes of silence may be anxiety-inducing in itself, adding a potential confound to the measurement of state anxiety. Furthermore, as many participants had never experienced EEG or other neuroscience measurements in any capacity, small talk and interaction with the researchers during the capping procedure helped reduce uncertainty due to the unfamiliar equipment and process. For example,

several participants expressed fears that the EEG recording would “hurt”, and it is the ethical responsibility of the researchers to address these concerns and put participants at ease during the capping process. Research demonstrates that a distraction after smartphone separation negates its relationship with greater anxiety, except in high smartphone dependent users (Reichrath & Pietrowsky, 2022). Therefore, it could be that the process of EEG capping and the experiment itself acted as a significant distraction from any anxiety. Third, situational anxiety can be reduced with social interaction (Hudson et al., 2015). Therefore, it could be that interaction with researchers acted as a significant distraction from any potential anxiety. Overall, the time and distance post separation were theorized to *boost* perceptions and effects of separation, however the social interaction and EEG setup as distractors during this time may have unintentionally reduced smartphone separation’s impact on state anxiety in this dissertation.

I also expected to replicate previously established behavioral relationships between smartphone separation, inhibitory control, and cognitive flexibility. In previous research, smartphone separation leads to worsened performance on the Stroop task–with longer response times and lower accuracy, especially on incongruent trials, which are the key trials of inhibitory control (Hartanto & Yang, 2016). These differences resulted in larger Stroop effects on the separation day than possession day. Additionally, smartphone separation leads to worsened performance on the Switch task– with longer response times and lower accuracy, especially on switch trials, which are the key trials of cognitive flexibility (Hartanto & Yang, 2016). These differences resulted in larger Switch costs on the separation day than possession day. In the current dissertation, both tasks functioned as expected, with participants performing worse on the trials that require greater inhibitory control (e.g., incongruent trials) and greater cognitive flexibility (e.g., switch trials). However, there was no relationship with smartphone separation

and task performance. In other words, the smartphone separation manipulation was not significantly related with behavioral task impairments. Overall, this dissertation stands in contrast to previous research on smartphone separation and executive function, as participants demonstrated no difference in performance or anxiety on the separation day compared to the possession day.

Researchers who study nomophobia posit that increased state anxiety is the main mechanism linking smartphone separation with lower performance on cognitive tasks. Along the lines of attentional control theory, anxiety limits our ability to allocate attention and resources to cognitive tasks, resulting in impaired task performance (Eysenck et al., 2007). The absence of induced state anxiety most likely results from the insufficient smartphone separation manipulation. While the sample size within this dissertation was sufficient to detect within-subject differences due to smartphone separation, this manipulation was not affected due to a multitude of aforementioned reasons. Overall, without a significant smartphone separation manipulation, there was no increased in state anxiety and no impairment on task performance.

Hypotheses

The hypotheses of this dissertation focused on the novel neurocognitive relationships between smartphone separation and four ERP components: N2, P2, P3, and ERN. Hypothesis 1 proposed that smartphone separation would lead to greater P2 and P3, reduced N2, and greater ERN amplitudes during the Stroop task. Results did not support this hypothesis– smartphone separation had no effect on any ERP amplitudes. While amplitudes differed based on response and trial type, they did not differ based on the separation or possession day. Previous studies demonstrated reduced N2 and larger P3 amplitudes in test anxious individuals during the Stroop task (Zhang et al., 2019). These patterns were not observed in this dissertation, as there were no

differences in ERP amplitudes due to smartphone separation, and no differences in state anxiety. As discussed above, there are a variety of explanations for why the smartphone separation manipulation within this dissertation was not effective, which affected both the behavioral and neural relationships. Overall, smartphone separation does not disrupt neural markers during an inhibitory control task in the absence of induced state anxiety, or nomophobia.

Both behavioral and EEG results were significant between trial types on the Stroop task– incongruent trials are significantly related with slower response times, lower accuracy, reduced N2 amplitudes, and larger P2 amplitudes. Some literature investigates the P2 component and the Stroop task outside of other relationships (e.g., anxiety), also demonstrating larger P2 amplitudes to be associated with longer response times on inhibitory control trials on the emotional Stroop task (Gootjes et al., 2011). More studies have investigated N2 amplitudes on the Stroop task, finding larger N2 amplitudes on incongruent trials compared to congruent trials, often theorized to reflect increased conflict monitoring (Heidlmayr et al., 2020). The current dissertation established reduced N2 amplitudes on incongruent trials. Prior studies have also demonstrated inconsistencies with the N2 component as an accurate indicator of conflict monitoring on inhibitory control tasks (Bartholow et al., 2005; Tillman & Wiens, 2011). One factor known to impact N2 amplitudes during cognitive tasks is task difficulty. Previous research demonstrates that greater task difficulty is related with a larger N2 amplitudes on inhibition trials compared to easier tasks (Benikos et al., 2013). In other words, low task difficulty does not elicit as large of an N2 on trials which require inhibitory control (e.g., incongruent). The high accuracy rates (>93%) and fast response times (<1 sec) across all trials on the Stroop task could indicate that the task may not have been particularly difficult for college-aged participants. Therefore, incongruent trials in this dissertation may not have elicited as large of an N2. Similarly, prior

research demonstrates that the P3 component is often related with attentional allocation– as individuals pay more attention to tasks, P3 amplitude becomes larger (Polich, 2007). As there was no difference in P3 amplitudes between incongruent and congruent trials in this dissertation, we can further theorize that participants may not have needed to devote significantly more attention to the incongruent trials compare to the congruent trials. However, this rationale is only theoretical– as the current dissertation did not directly measure attention, this is an area for future research.

Hypothesis 2 proposed that smartphone separation would lead to greater P2 and ERN amplitudes during the Switch task. Results did not support this hypothesis– there was no effect of separation on P2 or ERN amplitudes. While previous research established relationships between greater state anxiety and larger P2/ERN amplitudes during a cognitive flexibility task (González-Gómez et al., 2023; Moser et al., 2013), these findings were not replicated within this dissertation. Similar to Hypothesis 1, these findings can be explained due to the lack of induced state anxiety on the separation day.

Both behavioral and EEG results were significant between trial types on the Switch task– switch trials are significantly related with slower response times, lower accuracy, and larger P2 amplitudes. The impact of different trial types on the Switch task on P2 amplitudes is debated and inconsistent in previous literature. Whereas some studies align with this dissertation and report greater P2 amplitudes during switch trials compared to repeat and pure trials, others do not (for review see Gajewski et al., 2018). However, the consensus aligns with this dissertation, in that larger P2 amplitudes are related with worsened switch task performance (Gajewski et al., 2018), but future research is needed to further tease apart this relationship.

Hypothesis 3 proposed that state anxiety would mediate the relationships between separation and ERP amplitudes during the Stroop and Switch task. However, requirements for a successful mediation analysis include an existing significant relationship between the independent and mediating variables, as well as between the mediating and outcome variables. In the current dissertation, this would require a significant relationship between smartphone separation and state anxiety, and between state anxiety and ERP amplitudes. As these conditions were not met, mediation analyses could not be conducted, and this hypothesis could not be tested.

Significance, Limitations, & Future Directions

This dissertation is the first study to investigate neurocognition during smartphone separation using EEG. While the original proposal hoped to explore this through a nomophobia context, results did not find any significant differences with regards to smartphone separation or state anxiety. However, this dissertation suggests that in the absence of increased state anxiety, smartphone separation does not relate with cognitive or executive function impairments on a behavioral or neural level. Future research can use a Bayesian analysis approach to further investigate and confirm this non-significant relationship.

As of October 2024, eight states have passed state-wide bans behind the use of smartphones in school, with more states on the path to follow (Panchal & Zitter, 2024). Opponents to this ban are concerned with the consequences of smartphone separation. This dissertation demonstrates that there are a lot of contextual variables surrounding smartphone separation that may influence its effects. For example, previous research still stands that separating individual from their smartphones immediately before an activity which requires everyday cognitive function skills (e.g., an exam), induces anxiety and leads to lower

performance (Hartanto & Yang, 2016; Mendoza et al., 2018). However, this dissertation aligns with previous studies which suggest that distractions and social interaction can negate anxiety and reduce behavioral consequences associated with smartphone separation (Hudson et al., 2015; Reichrath & Pietrowsky, 2022). Therefore, these results provide guidance and clarification on this ban for policymakers, educators, parents, and students, as smartphone separation may not result in consequences across all contexts.

The main goal behind this dissertation was the investigation into the neurocognitive differences underlying smartphone separation. There were no significant ERP differences due to smartphone separation. As discussed above, this could be due to a variety of factors, but it limits the ability the draw conclusions as to the neurocognitive aberrations associated with specifically nomophobia. Future research should design an EEG research study in which the smartphone separation procedure more closely parallels previous nomophobia literature. For example, it's likely that the time and process of EEG capping acted as a distractor to participants that may have negated any effects with smartphone separation and anxiety. This component of the study is not present in purely behavioral studies, and researchers should be cognizant of how these factors interplay and may affect the separation manipulation when adding neuroscience methodologies. Therefore, setting up and capping the participant with the EEG electrodes *before* smartphone separation may result in a more successful manipulation and induction of state anxiety. To this end, researchers will be able to compare neurocognitive markers of nomophobia with state anxiety markers. Although this dissertation did not identify a neurocognitive marker of smartphone separation or nomophobia, it is still important in paving the way for future studies that wish to explore these relationships on a neurocognitive level.

There are other limitations that deserve mention. First, the sample of this dissertation included college-aged students who displayed average levels of nomophobia, trait anxiety, and problematic smartphone and social media use. Future research should investigate these relationships in a sample of high problematic smartphone users, as previous research demonstrates significant nomophobia and cognitive relationships in this population (Cheever et al., 2014; Reichrath & Pietrowsky, 2022). Additionally, future research could investigate these relationships in a clinically anxious population. Second, the sample of participants in this dissertation does not align with the age of students in schools who are employing smartphone bans. Future research should focus on an adolescent sample rather than college-students, to investigate whether these relationships exist in students who are experiencing smartphone bans.

Conclusion

This dissertation is the first research study to investigate the neurocognitive relationships behind smartphone separation via EEG and ERP markers during two tasks of executive function. Although there were no relationships with smartphone separation or state anxiety, this dissertation is the first step in providing a more *holistic* view on the relationship between brain and behavior of smartphone separation and executive function.

REFERENCES

Allport, G. W. (1937). *Personality: A psychological interpretation* (pp. xiv, 588). Holt.

Andreassen, C. S., Torsheim, T., Brunborg, G. S., & Pallesen, S. (2012). Development of a Facebook Addiction Scale. *Psychological Reports*, *110*(2), 501–517. https://doi.org/10.2466/02.09.18.PR0.110.2.501-517

Ayar, D., Özalp Gerçeker, G., Özdemir, E. Z., & Bektas, M. (2018). The Effect of Problematic Internet Use, Social Appearance Anxiety, and Social Media Use on Nursing Students' Nomophobia Levels. *CIN: Computers, Informatics, Nursing*, *36*(12), 589. https://doi.org/10.1097/CIN.0000000000000458

Baggetta, P., & Alexander, P. A. (2016). Conceptualization and Operationalization of Executive Function. *Mind, Brain, and Education*, *10*(1), 10–33. https://doi.org/10.1111/mbe.12100

Bartholow, B. D., Pearson, M. A., Dickter, C. L., Sher, K. J., Fabiani, M., & Gratton, G. (2005). Strategic control and medial frontal negativity: Beyond errors and response conflict. *Psychophysiology*, *42*(1), 33–42. https://doi.org/10.1111/j.1469-8986.2005.00258.x

Belk, R. W. (1988). Possessions and the Extended Self. *Journal of Consumer Research*, *15*(2), 139–168. https://doi.org/10.1086/209154

Belk, R. W. (2013). Extended Self in a Digital World. *Journal of Consumer Research*, *40*(3), 477–500. https://doi.org/10.1086/671052

Benikos, N., Johnstone, S. J., & Roodenrys, S. J. (2013). Varying task difficulty in the Go/Nogo task: The effects of inhibitory control, arousal, and perceived effort on ERP components. *International Journal of Psychophysiology*, *87*(3), 262–272. https://doi.org/10.1016/j.ijpsycho.2012.08.005

Boudewyn, M. A., Luck, S. J., Farrens, J. L., & Kappenman, E. S. (2018). How many trials does it take to get a significant ERP effect? It depends. *Psychophysiology*, *55*(6), e13049. https://doi.org/10.1111/psyp.13049

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*(4), 433–436. https://doi.org/10.1163/156856897X00357

Cheever, N. A., Rosen, L. D., Carrier, L. M., & Chavez, A. (2014). Out of sight is not out of mind: The impact of restricting wireless mobile device use on anxiety levels among low, moderate and high users. *Computers in Human Behavior*, *37*, 290–297. https://doi.org/10.1016/j.chb.2014.05.002

Clayton, R. B., Leshner, G., & Almond, A. (2015). The Extended iSelf: The Impact of iPhone Separation on Cognition, Emotion, and Physiology. *Journal of Computer-Mediated Communication*, *20*(2), 119–135. https://doi.org/10.1111/jcc4.12109

Crowley, K. E., & Colrain, I. M. (2004). A review of the evidence for P2 being an independent component process: Age, sleep and modality. *Clinical Neurophysiology*, *115*(4), 732–744. https://doi.org/10.1016/j.clinph.2003.11.021

Curran, T., Tucker, D. M., Kutas, M., & Posner, M. I. (1993). Topography of the N400: Brain electrical activity reflecting semantic expectancy. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *88*(3), 188–209. https://doi.org/10.1016/0168-5597(93)90004-9

Dajani, D. R., & Uddin, L. Q. (2015). Demystifying cognitive flexibility: Implications for clinical and developmental neuroscience. *Trends in Neurosciences*, *38*(9), 571–578. https://doi.org/10.1016/j.tins.2015.07.003

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Derakshan, N., Ansari, T. L., Hansard, M., Shoker, L., & Eysenck, M. W. (2009). Anxiety, Inhibition, Efficiency, and Effectiveness. *Experimental Psychology*, *56*(1), 48–55. https://doi.org/10.1027/1618-3169.56.1.48

Derakshan, N., Smyth, S., & Eysenck, M. W. (2009). Effects of state anxiety on performance using a task-switching paradigm: An investigation of attentional control theory. *Psychonomic Bulletin & Review*, *16*(6), 1112–1117. https://doi.org/10.3758/PBR.16.6.1112

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Endler, N. S., & Kocovski, N. L. (2001). State and trait anxiety revisited. *Journal of Anxiety Disorders*, *15*(3), 231–245. https://doi.org/10.1016/S0887-6185(01)00060-3

Endler, N. S., Magnusson, D., Ekehammar, B., & Okada, M. (1976). The multidimensionality of state and trait anxiety. *Scandinavian Journal of Psychology*, *17*(1), 81–96. https://doi.org/10.1111/j.1467-9450.1976.tb00215.x

Eysenck, M. W. (1992). *Anxiety: The Cognitive Perspective*. Psychology Press. https://doi.org/10.4324/9780203775677

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion*, *7*, 336–353. https://doi.org/10.1037/1528-3542.7.2.336

Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: A review. *Psychophysiology*, *45*(1), 152–170. https://doi.org/10.1111/j.1469-8986.2007.00602.x

Fortunati, L. (2022). The smartphone between the present and the future: Five changes. *Mobile Media & Communication*, 20501579221131223. https://doi.org/10.1177/20501579221131223

Gajewski, P. D., Ferdinand, N. K., Kray, J., & Falkenstein, M. (2018). Understanding sources of adult age differences in task switching: Evidence from behavioral and ERP studies. *Neuroscience & Biobehavioral Reviews*, *92*, 255–275. https://doi.org/10.1016/j.neubiorev.2018.05.029

González-Gómez, B., Núñez-Peña, M. I., & Colomé, À. (2023). Math anxiety and the shifting function: An event-related potential study of arithmetic task switching. *European Journal of Neuroscience*, *57*(11), 1848–1869. https://doi.org/10.1111/ejn.15984

Gootjes, L., Coppens, L. C., Zwaan, R. A., Franken, I. H. A., & Van Strien, J. W. (2011). Effects of recent word exposure on emotion-word Stroop interference: An ERP study. *International Journal of Psychophysiology*, *79*(3), 356–363. https://doi.org/10.1016/j.ijpsycho.2010.12.003

Hartanto, A., & Yang, H. (2016). Is the smartphone a smart choice? The effect of smartphone separation on executive functions. *Computers in Human Behavior*, *64*, 329–336. https://doi.org/10.1016/j.chb.2016.07.002

Hartanto, A., & Yang, H. (2022). Testing theoretical assumptions underlying the relation between anxiety, mind wandering, and task-switching: A diffusion model analysis. *Emotion*, *22*, 493–510. https://doi.org/10.1037/emo0000935

Heidlmayr, K., Kihlstedt, M., & Isel, F. (2020). A review on the electroencephalography markers of Stroop executive control processes. *Brain and Cognition*, *146*, 105637. https://doi.org/10.1016/j.bandc.2020.105637

Hudson, B. f., Ogden, J., & Whiteley, M. s. (2015). Randomized controlled trial to compare the effect of simple distraction interventions on pain and anxiety experienced during conscious surgery. *European Journal of Pain*, *19*(10), 1447–1455. https://doi.org/10.1002/ejp.675

Humphreys, L., Karnowski, V., & Pape, T. von. (2018). Smartphones as Metamedia: A Framework for Identifying the Niches Structuring Smartphone Use. *International Journal of Communication*, *12*(0), Article 0.

Jackson, G. M., Swainson, R., Cunnington, R., & Jackson, S. R. (2001). ERP correlates of executive control during repeated language switching. *Bilingualism: Language and Cognition*, *4*(2), 169–178. https://doi.org/10.1017/S1366728901000268

Jensen, K. B. (2016). Metamedium. In K. B. Jensen & R. T. Craig (Eds.), *THe international encyclopedia of communication theory and philsophy* (pp. 1–4). John Wiley ^ Sons.

Jensen, K. M., & MacDonald, J. A. (2023). Towards thoughtful planning of ERP studies: How participants, trials, and effect magnitude interact to influence statistical power across

seven ERP components. *Psychophysiology*, *60*(7), e14245. https://doi.org/10.1111/psyp.14245

Johnson, R. (1993). On the neural generators of the P300 component of the event-related potential. *Psychophysiology*, *30*(1), 90–97. https://doi.org/10.1111/j.1469-8986.1993.tb03208.x

Kappenman, E. S., & Luck, S. J. (2011). ERP Components: The ups and downs of brainwave recordings. In *The Oxford Handbook of Event-Related Potential Components* (pp. 1–30). Oxford University Press.

Kara, M., Baytemir, K., & Inceman-Kara, F. (2021). Duration of daily smartphone usage as an antecedent of nomophobia: Exploring multiple mediation of loneliness and anxiety. *Behaviour & Information Technology*, *40*(1), 85–98. https://doi.org/10.1080/0144929X.2019.1673485

King, A. L. S., Valença, A. M., & Nardi, A. E. (2010). Nomophobia: The Mobile Phone in Panic Disorder With Agoraphobia: Reducing Phobias or Worsening of Dependence? *Cognitive and Behavioral Neurology*, *23*(1), 52. https://doi.org/10.1097/WNN.0b013e3181b7eabc

King, A. L. S., Valença, A. M., Silva, A. C. O., Baczynski, T., Carvalho, M. R., & Nardi, A. E. (2013). Nomophobia: Dependency on virtual environments or social phobia? *Computers in Human Behavior*, *29*(1), 140–144. https://doi.org/10.1016/j.chb.2012.07.025

Kleiner, M., Brainard, D., & Pelli, D. (2007). *What's new in Psychtoolbox-3?* 14. https://doi.org/10.1177/03010066070360S101

Kwon, M., Lee, J.-Y., Won, W.-Y., Park, J.-W., Min, J.-A., Hahn, C., Gu, X., Choi, J.-H., & Kim, D.-J. (2013). Development and Validation of a Smartphone Addiction Scale (SAS). *PLOS ONE*, *8*(2), e56936. https://doi.org/10.1371/journal.pone.0056936

Lang, A. (2000). The Limited Capacity Model of Mediated Message Processing. *Journal of Communication*, *50*(1), 46–70. https://doi.org/10.1111/j.1460-2466.2000.tb02833.x

Lang, A. (2017). Limited Capacity Model of Motivated Mediated Message Processing (LC4MP). In P. Rössler, C. A. Hoffner, & L. Zoonen (Eds.), *The International Encyclopedia of Media Effects* (1st ed., pp. 1–9). Wiley. https://doi.org/10.1002/9781118783764.wbieme0077

León-Mejía, A. C., Gutiérrez-Ortega, M., Serrano-Pintado, I., & González-Cabrera, J. (2021). A systematic review on nomophobia prevalence: Surfacing results and standard guidelines for future research. *PLOS ONE*, *16*(5), e0250509. https://doi.org/10.1371/journal.pone.0250509

Liu, Q., Wu, J., Zhou, Z., & Wang, W. (2022). Smartphone use can modify the body schema: An ERP study based on hand mental rotation task. *Computers in Human Behavior*, *128*, 107134. https://doi.org/10.1016/j.chb.2021.107134

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: An open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, *8*. https://www.frontiersin.org/articles/10.3389/fnhum.2014.00213

Luck, S. J. (2005). *An introduction to the event-related potential technique* (1st ed.). The MIT Press.

Luck, S. J. (2014). *An Introduction to the Event-Related Potential Technique, second edition*. MIT Press.

Mendoza, J. S., Pody, B. C., Lee, S., Kim, M., & McDonough, I. M. (2018). The effect of cellphones on attention and learning: The influences of time, distraction, and nomophobia. *Computers in Human Behavior*, *86*, 52–60. https://doi.org/10.1016/j.chb.2018.04.027

Mir, R., & Akhtar, M. (2020). Effect of nomophobia on the anxiety levels of undergraduate students. *Journal of the Pakistan Medical Association*, *70*, 1. https://doi.org/10.5455/JPMA.31286

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The Unity and Diversity of Executive Functions and Their Contributions to Complex "Frontal Lobe" Tasks: A Latent Variable Analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134–140. https://doi.org/10.1016/S1364-6613(03)00028-7

Monsell, S., & Mizon, G. A. (2006). Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? *Journal of Experimental Psychology: Human Perception and Performance*, *32*(3), 493–516. https://doi.org/10.1037/0096-1523.32.3.493

Moser, J., Moran, T., Schroder, H., Donnellan, B., & Yeung, N. (2013). On the relationship between anxiety and error monitoring: A meta-analysis and conceptual framework. *Frontiers in Human Neuroscience*, *7*. https://www.frontiersin.org/articles/10.3389/fnhum.2013.00466

Myles, O., Grafton, B., & MacLeod, C. (2020). Anxiety & inhibition: Dissociating the involvement of state and trait anxiety in inhibitory control deficits observed on the anti-saccade task. *Cognition & Emotion*, *34*(8), 1746–1752. https://doi.org/10.1080/02699931.2020.1802229

Näätänen, R., & Gaillard, A. W. K. (1983). 5 The Orienting Reflex and the N2 Deflection of the Event-Related Potential (ERP). In A. W. K. Gaillard & W. Ritter (Eds.), *Advances in Psychology* (Vol. 10, pp. 119–141). North-Holland. https://doi.org/10.1016/S0166-4115(08)62036-1

Nie, J., Wang, P., & Lei, L. (2020). Why can't we be separated from our smartphones? The vital roles of smartphone activity in smartphone separation anxiety. *Computers in Human Behavior*, *109*, 106351. https://doi.org/10.1016/j.chb.2020.106351

Nomophobia is the fear of being out of mobile phone contact—And it's the plague of our 24/7 age | Daily Mail Online. (2008). *Daily Mail.* https://www.dailymail.co.uk/news/article-550610/Nomophobia-fear-mobile-phone-contact--plague-24-7-age.html

Olvet, D. M., & Hajcak, G. (2008). The error-related negativity (ERN) and psychopathology: Toward an endophenotype. *Clinical Psychology Review*, *28*(8), 1343–1354. https://doi.org/10.1016/j.cpr.2008.07.003

Panchal, N., & Zitter, S. (2024, September 5). A Look at State Efforts to Ban Cellphones in Schools and Implications for Youth Mental Health. *KFF*. https://www.kff.org/mental-health/issue-brief/a-look-at-state-efforts-to-ban-cellphones-in-schools-and-implications-for-youth-mental-health/

Panova, T., & Carbonell, X. (2018). Is smartphone addiction really an addiction? *Journal of Behavioral Addictions*, *7*(2), 252–259. https://doi.org/10.1556/2006.7.2018.49

Park, C. S., & Kaye, B. K. (2019). Smartphone and self-extension: Functionally, anthropomorphically, and ontologically extending self via the smartphone. *Mobile Media & Communication*, *7*(2), 215–231. https://doi.org/10.1177/2050157918808327

Park, E.-A., & Lee, S. (2015). Multidimensionality: Redefining the digital divide in the smartphone era. *Info*, *17*(2), 80–96. https://doi.org/10.1108/info-09-2014-0037

Pelli, D. G. (1997). The VideolToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019

Przybylski, A. K., Murayama, K., DeHaan, C. R., & Gladwell, V. (2013). *Fear of Missing Out Scale*. https://doi.org/10.1037/t23568-000

Reichrath, B., & Pietrowsky, R. (2022). Exploring Problematic Mobile Phone Attachment and Associations to Anxiety and Inhibitory Control After a Short-Term Smartphone Separation. *Journal of Cyberspace Studies*, *6*(2), 107–130. https://doi.org/10.22059/jcss.2022.345698.1077

Schmidt, C., Muench, R., Schneider, F., Breitenbach, S., & Carolus, A. (2018). Generation "Always On" Turned Off. Effects of Smartphone Separation on Anxiety Mediated by the Fear of Missing Out. In C. Stephanidis (Ed.), *HCI International 2018 – Posters' Extended Abstracts* (pp. 436–443). Springer International Publishing. https://doi.org/10.1007/978-3-319-92279-9_58

Sharma, M., Amandeep, Mathur, D. M., & Jeenger, J. (2019). Nomophobia and its relationship with depression, anxiety, and quality of life in adolescents. *Industrial Psychiatry Journal*, *28*(2), 231–236. https://doi.org/10.4103/ipj.ipj_60_18

Shi, R., Sharpe, L., & Abbott, M. (2019). A meta-analysis of the relationship between anxiety and attentional control. *Clinical Psychology Review*, *72*, 101754. https://doi.org/10.1016/j.cpr.2019.101754

Spielberger, C. D. (1972). Anxiety as an emotional state. *Anxiety: Trends in Theory and Research*, 23–49.

Spielberger, C. D. (1983). *State-Trait Anxiety Inventory for Adults*. https://doi.org/10.1037/t06496-000

Spielberger, C. D., Gonzalez-Reigosa, F., Martinez-Urrutia, A., Natalicio, L. F., & Natalicio, D. S. (1971). The state-trait anxiety inventory. *Interamerican Journal of Psychology*, *5*(3 & 4). https://journal.sipsych.org/index.php/IJP/article/view/620

Statista. (2023). *Smartphones in the U.S.* https://www-statista-com.proxy2.cl.msu.edu/study/26643/smartphones-in-the-us-statista-dossier/

Strobach, T., Liepelt, R., Schubert, T., & Kiesel, A. (2012). Task switching: Effects of practice on switch and mixing costs. *Psychological Research*, *76*(1), 74–83. https://doi.org/10.1007/s00426-011-0323-x

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662. https://doi.org/10.1037/h0054651

The MathWorks Inc. (2021). *MATLAB version 9.11.0* (Version R2021b) [Computer software]. The MathWorks Inc. https://www.mathworks.com

Tillman, C. M., & Wiens, S. (2011). Behavioral and ERP indices of response conflict in Stroop and flanker tasks. *Psychophysiology*, *48*(10), 1405–1411. https://doi.org/10.1111/j.1469-8986.2011.01203.x

Trub, L., & Barbot, B. (2016). The paradox of phone attachment: Development and validation of the Young Adult Attachment to Phone Scale (YAPS). *Computers in Human Behavior*, *64*, 663–672. https://doi.org/10.1016/j.chb.2016.07.050

Yildirim, C., & Correia, A.-P. (2015). Exploring the dimensions of nomophobia: Development and validation of a self-reported questionnaire. *Computers in Human Behavior*, *49*, 130–137. https://doi.org/10.1016/j.chb.2015.02.059

Zhang, W., De Beuckelaer, A., Chen, L., & Zhou, R. (2019). ERP Evidence for Inhibitory Control Deficits in Test-Anxious Individuals. *Frontiers in Psychiatry*, *10*. https://www.frontiersin.org/articles/10.3389/fpsyt.2019.00645

APPENDIX A: PARTICIPANT SCRIPT

Participant script for smartphone separation and possession days, story for separation deception.

Condition 1 (D1Sep/D2Poss)

Separation Day 1: "Unfortunately, if you have a smartphone or smartwatch, you'll have to leave it here today. One of the other participant's devices interfered with the EEG signal so we're now asking all participants to leave them behind as a precaution until we can retest the equipment and see what's going on."

Possession Day 2: "You don't need to leave any of your devices behind today, we retested the equipment and resolved the interference issue."

Condition 2 (D1Poss/D2Sep)

Possession Day 1: n/a

Separation Day 2: "Unfortunately, if you have a smartphone or smartwatch, you'll have to leave it here today. Since you've were here last, one of the other participant's device interfered with the EEG signal so we're now asking all participants to leave them behind as a precaution until we can retest the equipment and see what's going on."

APPENDIX B: TABLES

Table 1. Descriptive statistics of the sample (N=32).

Variable	**M (*SD*) or N (*%*)**
Age	20.47 *(.88)*
Gender	
Male	9 *(28.1%)*
Female	23 *(71.9%)*
Race	
White	26 *(81.3%)*
Non-White	6 *(18.7%)*
Daily Screentime (hours)	
Self-Report	6.11 *(2.51)*
Device Metric	6.37 *(2.38)*
Nomophobia	87.78 *(20.18)*
Absent	-
Mild	3 *(9.4%)*
Moderate	21 *(65.6%)*
Severe	8 *(25.0%)*
Trait Anxiety	41.41 *(8.95)*
State Anxiety	
Separation Day	28.03 *(7.71)*
Possession Day	28.53 *(8.39)*
Problematic SMU	17.25 (4.65)
Problematic Smartphone Use	25.28 (5.87)
Phone Attachment	
Burden	3.09 (.91)
Refuge	2.76 (.73)
Fear of Missing Out	2.73 (.75)

Note. SMU=Social Media Use.

Table 2. Bivariate correlation matrix of descriptives variables (N=32).

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Age	-	-.22	.32	-.23	-.10	.05	.08	-.28	-.22	-.44*	-.35*
2. Gender		-	-.27	.51**	.15	.10	.09	.37*	.32	.28	.21
3. Race			-	.11	.23	.22	.15	.20	.20	.08	.21
4. Daily Screentime[a]				-	.18	.29	.21	.27	.48**	.33	.29
5. Trait Anxiety					-	.54***	.58***	.40*	.57***	.45**	.58***
6. State Anxiety - Separation						-	.86***	.19	.39*	.29	.28
7. State Anxiety – Possession							-	.25	.33	.21	.20
8. Problematic SMU								-	.64***	.65***	.43*
9. Problematic Smartphone Use									-	.67***	.41*
10. Nomophobia										-	.70***
11. FOMO											-

[a] Subjective self-reported screentime

*p<.05, **p<.01, ***p<.001

Note. Gender was coded as 1=Male, 2=Female, Race was coded as 1= White, 2= Non-White. SMU = social media use, FOMO = fear of missing out.

Table 3. Means and standard deviations for response time and accuracy rates across all conditions during the Stroop Task (N=32).

	Response Time			Accuracy		
	Separation	Possession	*p-value*	Separation	Possession	*p-value*
Incongruent Trials	584 (112)	610 (117)	.121	95.4 (3.7)	94.2 (4.5)	.145
Congruent Trials	466 (83)	476 (89)	.318	98.1 (1.8)	98.3 (1.5)	.576
Stroop Effect	118 (56)	134 (73)	.172	-2.78 (2.8)	-4.16 (3.8)	.079

Note. Significance p-values for the Stroop Effect come from dependent samples t-test. All other p-values come from the Day x Trial Type interaction in repeated measures anova.

Table 4. Repeated measures ANOVA results for response time and accuracy rates during the Stroop task (N=32).

Variable	Sum of Squares	Mean Square	df	F	*p-value*	η_p^2
Response Time						
Trial Type	508909	508909	(1,31)	161.81	<.001	.839
Day	10117	10117	(1,31)	2.21	.147	.067
Day x Trial Type	2141	2141	(1,31)	1.95	.172	.059
Accuracy Rates						
Trial Type	384.684	384.684	(1,31)	61.51	<.001	.665
Day	7.85	7.85	(1,31)	1.05	.314	.033
Day x Trial Type	15.47	15.47	(1,31)	3.31	.079	.096

Note. Type III Sum of Squares, η_p^2 = Partial Eta Squared.

Table 5. Means and standard deviations for response time and accuracy rates across all conditions during the Switch Task (N=32).

	Response Time			Accuracy		
	Separation	Possession	*p-value*	Separation	Possession	*p-value*
Switch Trials	752 (158)	790 (161)	.174	84.0 (9.8)	83.8 (10.3)	.914
Repeat Trials	597 (116)	640 (140)	.024	93.5 (7.5)	92.9 (7.1)	.698
Pure Trials	272 (75)	279 (81)	.551	97.0 (3.5)	97.3 (3.1)	.683
Switch Costs	155 (86)	150 (78)	.676	-9.4 (6.1)	-9.1 (5.4)	.811
Mixing Costs	325 (113)	361 (112)	.063	-3.5 (5.5)	-4.4 (6.3)	.452

Note. Significance p-values for switch and mixing costs come from dependent samples t-tests. All other p-values come from Day x Trial Type interaction in the repeated measures ANOVA.

Table 6. Repeated measures ANOVA results for response time and accuracy rates during the Switch task (N=32).

Variable	Sum of Squares	Mean Square	df	F	*p-value*	η_p^2
Response Time						
Trial Type	8244222	5445172	(2, 62)	405.40	<.001	.929
Day	42347	42347	(1, 31)	3.34	.077	.097
Day x Trial Type	12080	9997	(2, 62)	1.70	.202	.052
Accuracy Rates						
Trial Type	5871.80	4396.68	(2, 62)	86.95	<.001	.737
Day	.88	.88	(1, 31)	.02	.901	.001
Day x Trial Type	5.48	3.27	(2, 62)	.18	.795	.006

Note. Type III Sum of Squares, η_p^2 = Partial Eta Squared. All values reflect Greenhouse-Geiser corrected values for violations of sphericity.

Table 7. Means and standard deviations for ERP component amplitudes across all conditions and tasks.

Stroop Task		**Mean *(SD)***			
Day	*Trial Type*	**N2**	**P2**	**P3**	**ERN**
Separation	Incongruent Trials	-4.17 *(10.57)*	2.69 *(6.84)*	5.18 *(4.71)*	-
	Congruent Trials	-5.45 *(8.89)*	1.59 *(5.73)*	5.95 *(4.28)*	-
	Stroop Effect	1.28 *(3.84)*	1.09 *(2.44)*	-0.77 *(2.33)*	
	Error Response	-	-	-	-5.06 *(9.32)*
	Correct Response	-	-	-	0.30 *(4.96)*
Possession	Incongruent Trials	-4.92 *(6.56)*	2.63 *(5.30)*	5.30 (*4.16)*	-
	Congruent Trials	-5.95 *(6.36)*	2.03 *(4.77)*	5.71 *(4.69)*	-
	Stroop Effect	1.03 *(2.96)*	.60 *(2.08)*	-0.42 *(1.79)*	
	Error Response	-	-	-	-7.23 *(5.43)*
	Correct Response	-	-	-	1.41 *(4.12)*
Switch Task					
Separation	Switch Trials	-	3.06 *(9.38)*	-	-
	Repeat Trials	-	0.61 *(6.96)*	-	-
	Pure Trials	-	-3.62 *(5.63)*	-	-
	Switch Cost		2.38 *(3.79)*		
	Mixing Cost		4.10 *(5.89)*		
	Error Response	-	-	-	-2.36 *(9.12)*
	Correct Response	-	-	-	2.13 *(4.72)*
Possession	Switch Trials	-	4.36 *(6.25)*	-	-
	Repeat Trials	-	1.97 *(5.55)*	-	-
	Pure Trials	-	-1.84 *(4.34)*	-	-
	Switch Cost	-	2.39 *(3.15)*	-	-
	Mixing Cost	-	3.81 *(5.32)*	-	
	Error Response	-	-	-	-1.82 *(9.28)*
	Correct Response	-	-	-	2.08 *(4.47)*

Note. All values are in μV. Values for the Stroop Effect, Switch Costs, and Mixing Costs reflect difference waves.

APPENDIX C: FIGURES

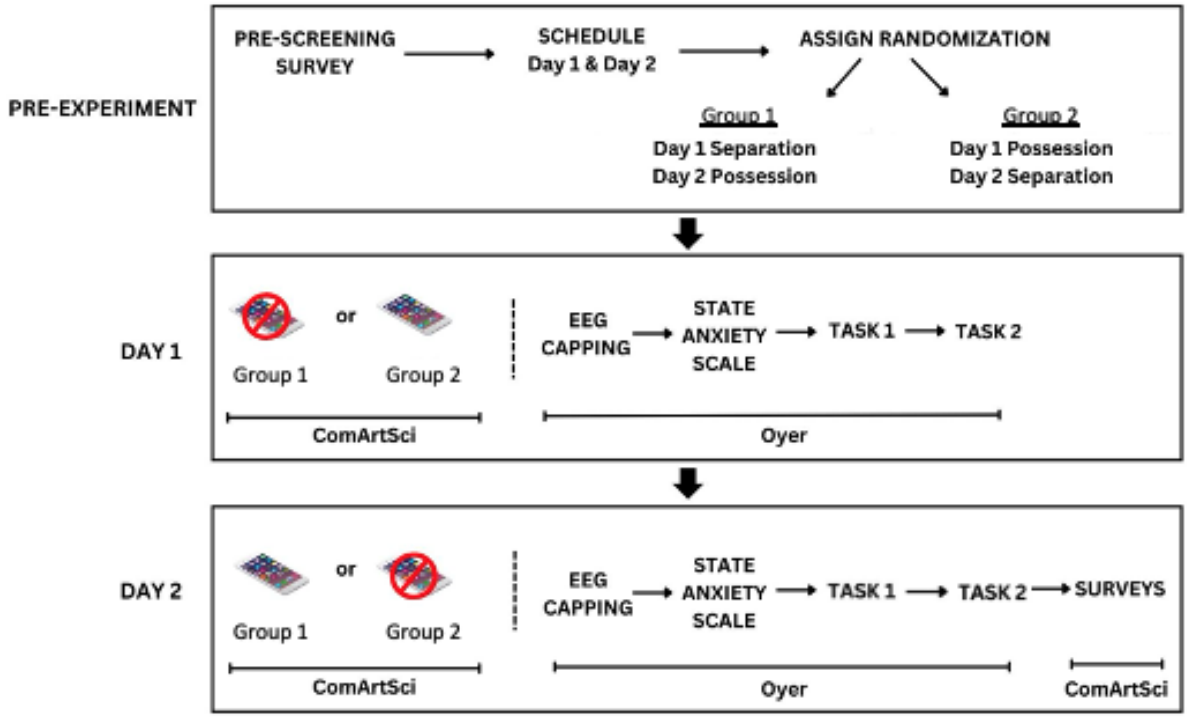

Figure 1. Participant experience flow diagram. Smartphone separation and possession days and task were counterbalanced across participants. *Note.* EEG Capping refers to overall setup including placement of the physical cap, attachment of all 32 electrodes, and checking connectivity & conductance.

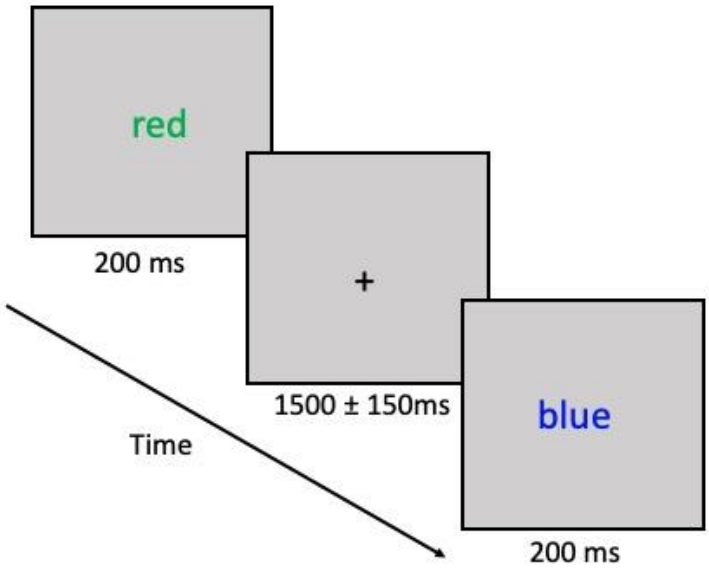

Figure 2. Stroop task, depicting an example of incongruent (top) and congruent (bottom) trials.

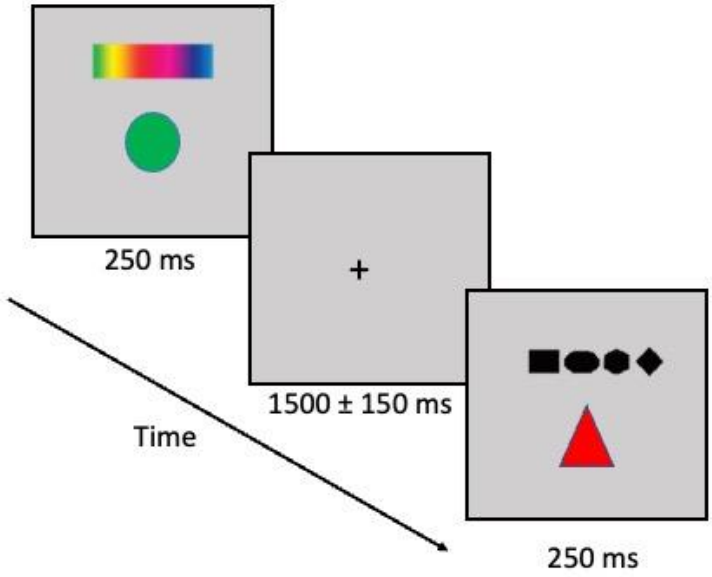

Figure 3. Color-Shape switching task, depicting an example of a switch trial during the mixed block, with participants cued to respond to the color (top) and then to the shape (bottom) of the stimuli.

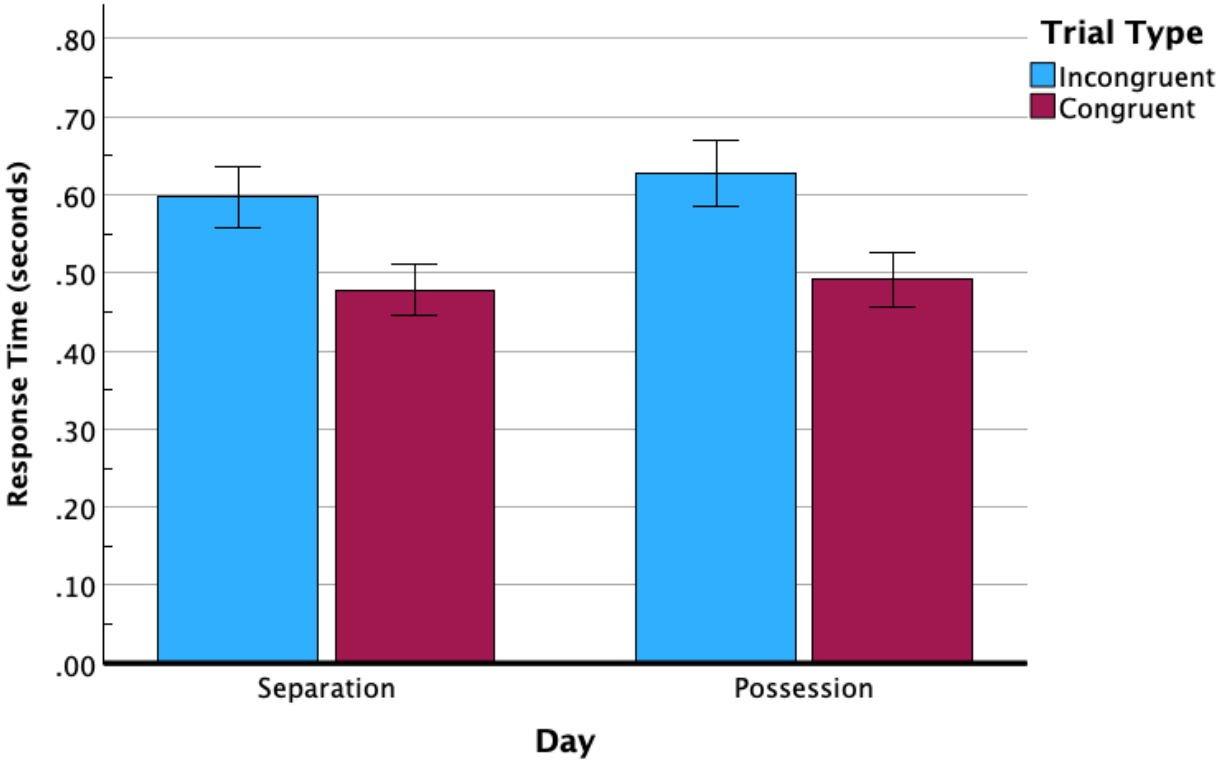

Figure 4. Visualization of the main effect of trial type on response time for the Stroop task. *Note.* Error bars = 95% Confidence Intervals.

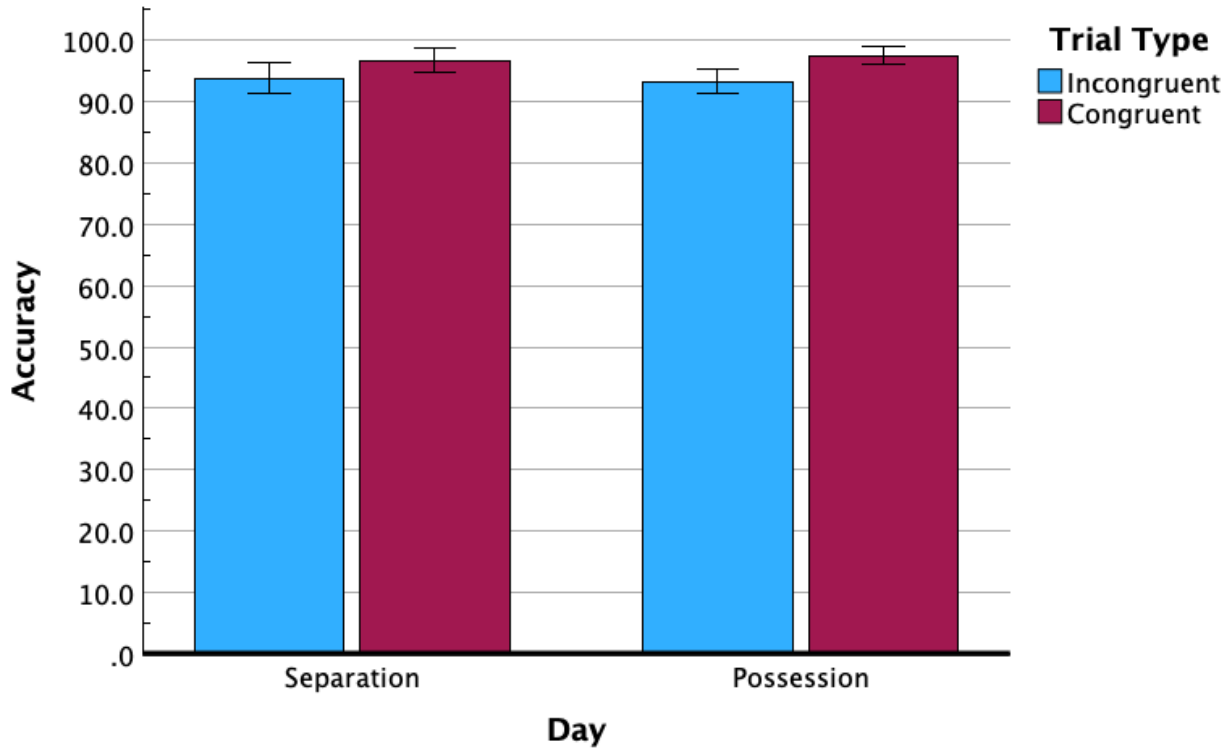

Figure 5. Visualization of the main effect of trial type on accuracy for the Stroop task. *Note.* Error bars = 95% Confidence Intervals.

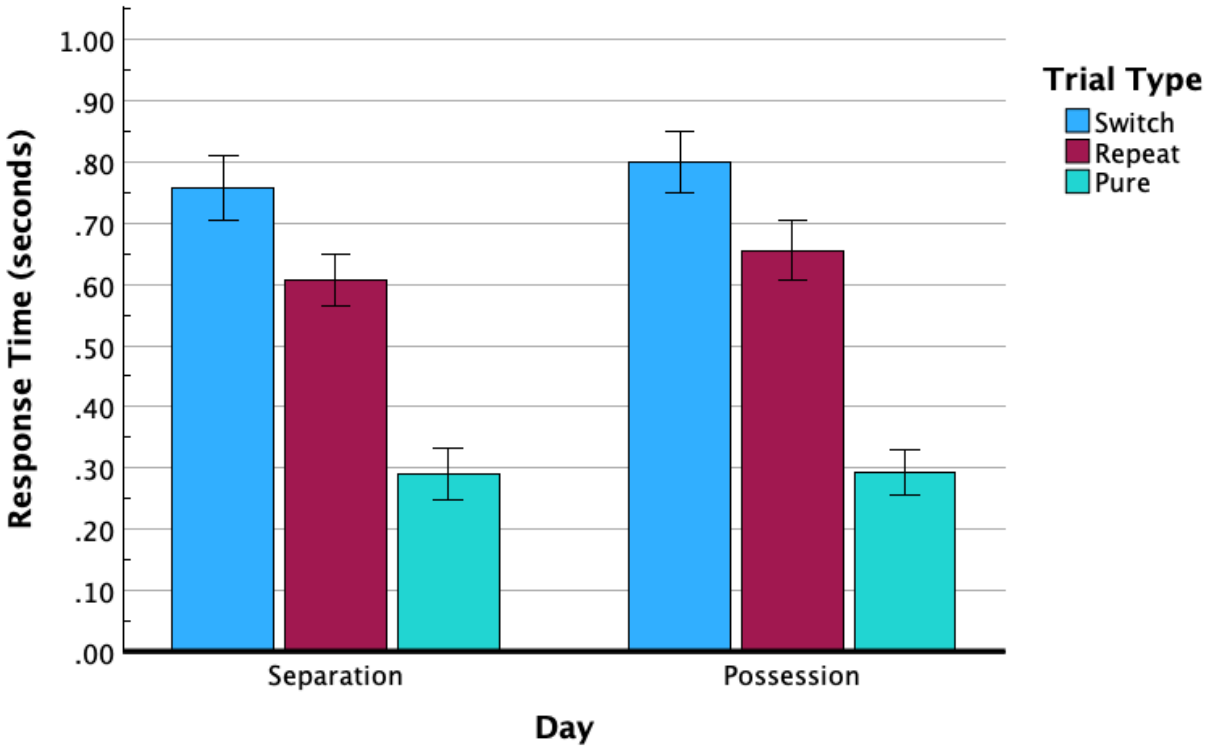

Figure 6. Visualization of the main effect of trial type on response time for the Switch task. *Note.* Error bars = 95% Confidence Intervals.

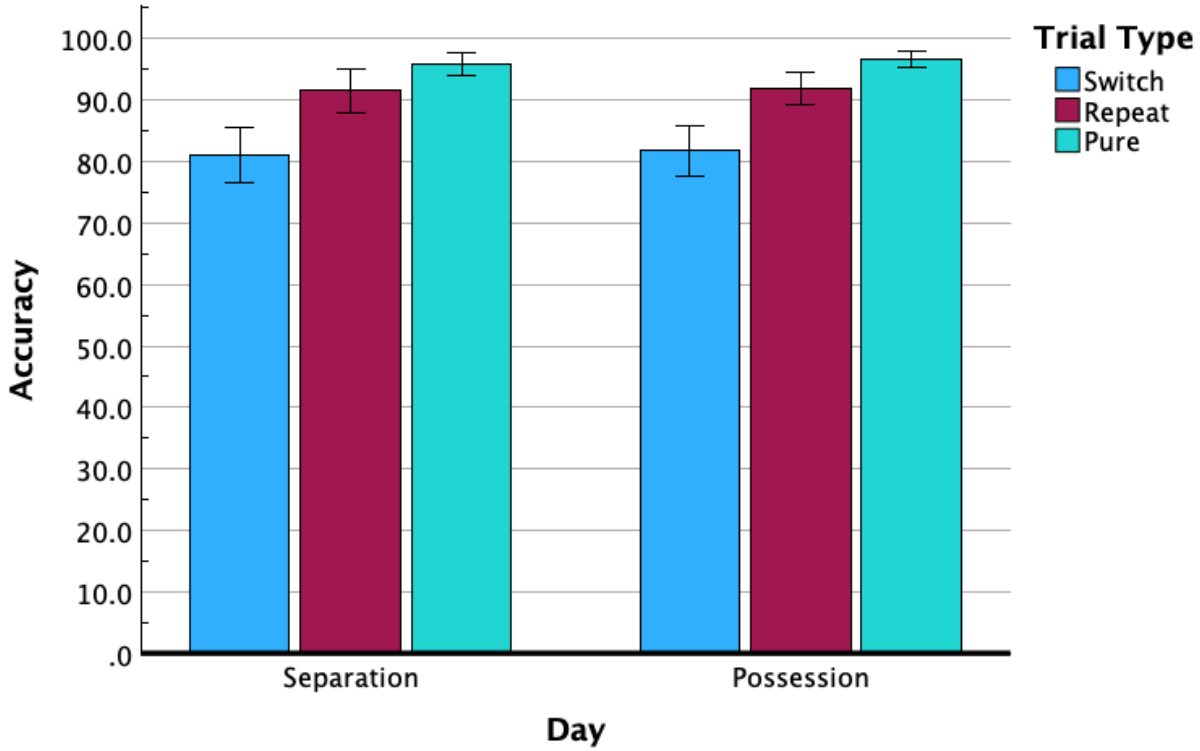

Figure 7. Visualization of the main effect trial type on accuracy for the Switch task. *Note.* Error bars = 95% Confidence Intervals.

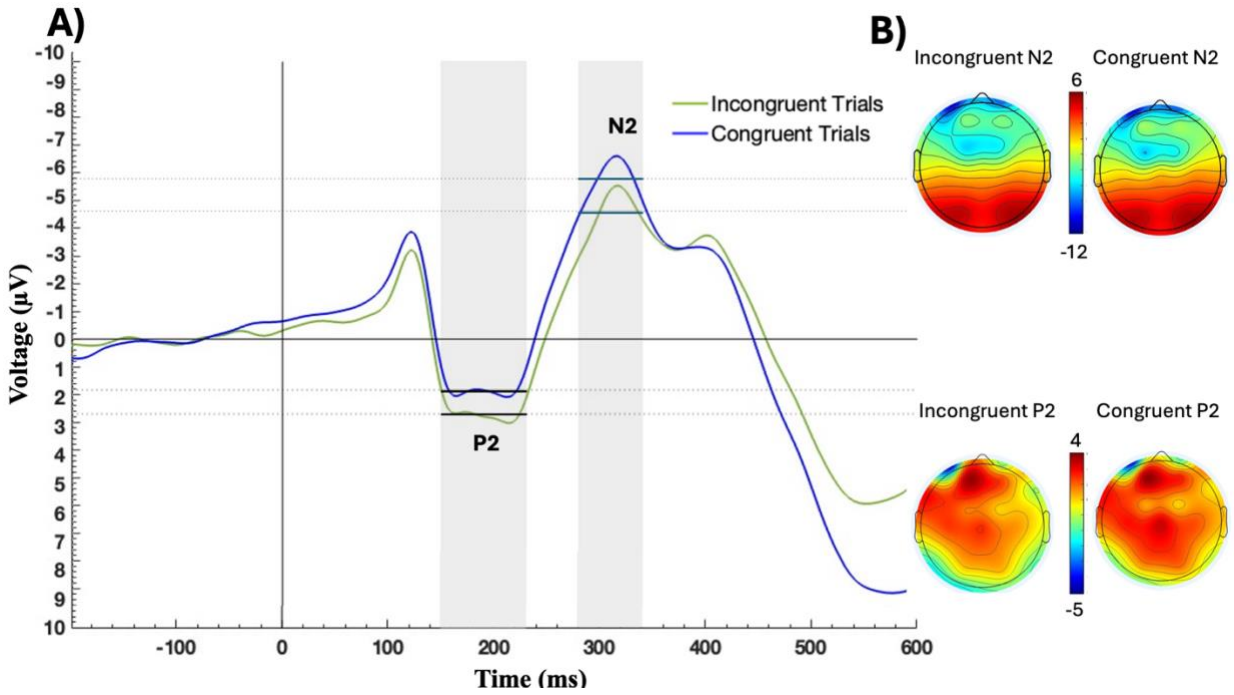

Figure 8. P2 and N2 grand average waveforms and scalp topographies during the Stroop task. (A) Visualization of the main effect of trial type for P2 and N2 amplitudes across frontocentral electrode sites during the Stroop task. Grey shading represents the time window used to calculate the amplitude for each component, and horizontal black lines indicate the mean amplitude for each day. (B) Associated scalp topographies for incongruent and congruent trials for N2 (top) and P2 (bottom).

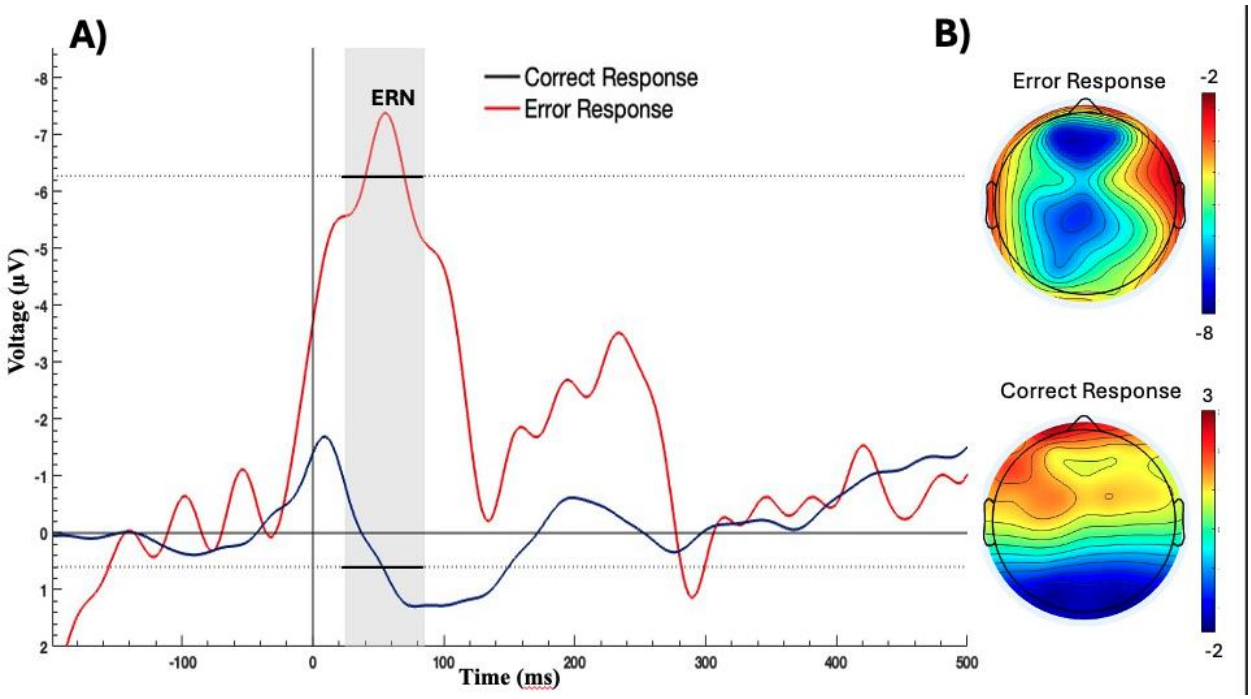

Figure 9. ERN grand average waveform and scalp topography after response error during the Stroop task. (A) Visualization of the main effect of response for ERN amplitudes across frontocentral electrode sites during the Stroop task, collapsed across both separation and possession days. Grey shading represents the time window used to calculate the amplitude for this component, and horizontal black lines indicate the mean amplitude for each response. (B) Associated scalp topography for an error response (top) and correct response (bottom).

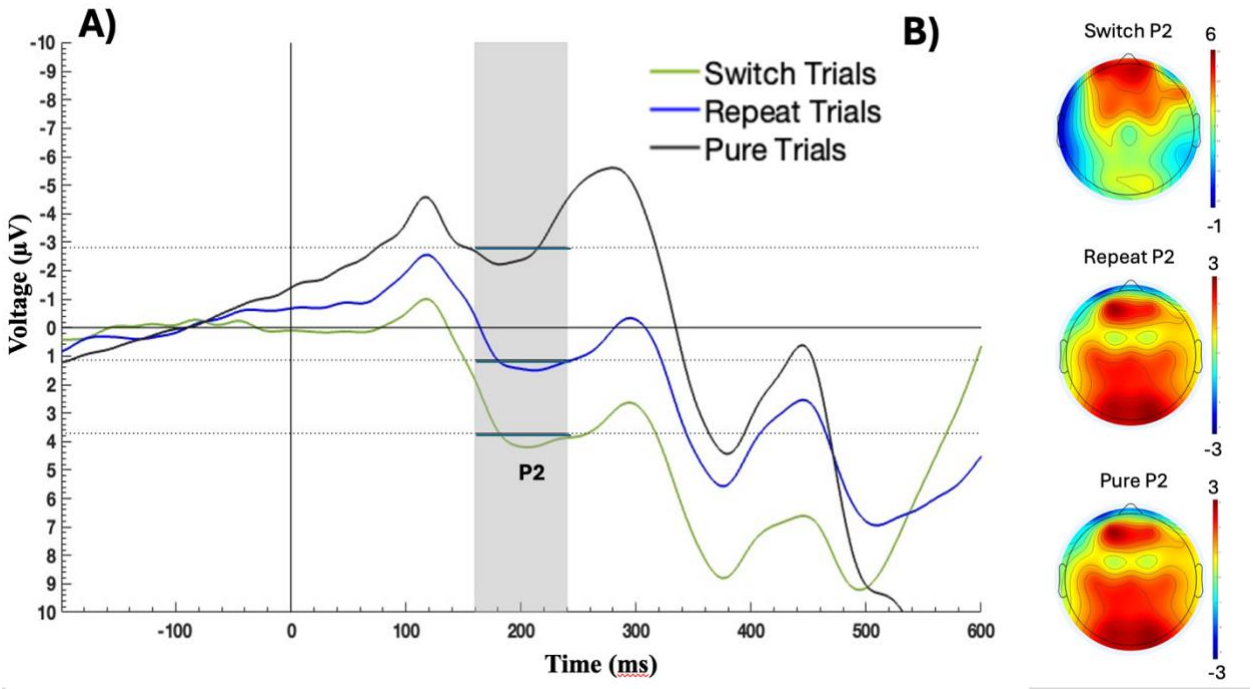

Figure 10. P2 grand average waveform and scalp topography during the Switch task. (A) Visualization of the main effect of trial type for P2 amplitudes across frontocentral electrode sites during the Switch task, collapsed across both separation and possession days. Grey shading represents the time window used to calculate the amplitude for this component, and horizontal black lines indicate the mean amplitude for each trial. (B) Associated scalp topographies for Switch (top), Repeat (middle), and Pure (bottom) trials for P2.