Bachelor Degree Project

THE RELATIONSHIP BETWEEN DURATION OF SMARTPHONE USAGE AND INHIBITORY CONTROL

A Stroop and stop-signal task investigation

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Abstract

The smartphone has quickly become the most used device to access the internet. Academic and public concern has been raised if overuse of smartphone technology can have detrimental effects on brain and behavior. Preliminary results suggest that excessive smartphone usage may be linked to impaired inhibitory control. The present study investigates whether such a relationship is present in a sample of healthy individuals with varying degrees of usage. To investigate the proposed relationship, the Stroop color and word task and the stop-signal task was utilized to measure inhibitory control, while screen time was utilized to measure duration of smartphone usage. A Pearson's correlation analysis and an independent t-test/Mann Whitney-U test analyzed the results, which did not yield statistical significance.

Keywords: smartphone usage, inhibitory control, Stroop task, stop-signal task,

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Introduction

The smartphone has brought immense utility and convenience to our hands by allowing instant connection to the internet through a wide range of applications. There are approximately 3.5 billion smartphones users across the world today (Statista, 2020). The usefulness of the smartphone cannot be denied; nevertheless, overuse of smartphones has resulted in problems for individuals. Excessive smartphone usage has reached epidemic proportions and has been linked to several detrimental effects on physical and mental health (Elhai, Levine, Dvorak, & Hall, 2016; Gezgin, 2018)

One essential cognitive function for controlling one's usage is inhibitory control (IC). IC helps regulate behavior and emotions when the behavioral response is inappropriate and not serving a goal-directed motive (Cohen, 2017). IC dysfunction is a key characteristic in a range of psychiatric conditions such as attention-deficit hyperactivity disorder (ADHD), obsessive-compulsive disorder (OCD), impulse-control disorders and addictive disorders (Chambers, Garavan, & Bellgrove, 2009; Verbruggen & Logan, 2008).

Preliminary results (Chen, Liang, Mai, Zhong, & Qu, 2016) suggest that there may be a relationship between excessive smartphone usage and IC function. However, controversies and limited research in the field challenge consensus. This study evaluates the notion of IC impairments in excessive smartphone users. This is an important question to address as it may have implications in preventative strategies, regulatory policies and clinical domains.

The aim of this thesis is (1) to supply information to the literature through an empirical investigation of the relationship between smartphone usage and IC and (2) to present relevant evidence related to excessive usage, smartphone addiction (SPA) and its relationship to IC.

This thesis will begin with presenting relevant background information regarding conceptualization and controversies in the literature of excessive smartphone usage and move on to discuss impairments associated with excessive use. Onward, a brief background will be provided on cognitive control (CC), the mechanisms necessary for exerting control and then narrowing down to the focus of this study; IC. From there on, an overview of the neurobiological correlates of IC will be presented in reference to the task paradigms used in this study. This is followed by the research paradigm in the empirical investigation, the results from the analysis and data collected, and finally, a discussion about the results, limitations and parallels to relevant research.

Concepts, Distinctions and Definitions

Excessive smartphone usage refers to an overuse/abuse of smartphone technology. It is conceptualized in a variety of terms in the literature, which is often not clearly distinguished and agreed upon (Montag, Wegmann, Sariyska, Demetrovics, & Brand, 2021; Panova & Carbonell, 2018). Excessive smartphone usage is in its essence, a subtype of internet use disorder as it requires internet to function as intended (Montag et al., 2021). In the literature, excessive smartphone usage is conceptualized by the terms: SPA, smartphone dependence, problematic smartphone use, mobile phone dependence and pathological smartphone use. This study will make use of research from the whole spectrum of these conceptualizations.

The problematic nature behind excessive smartphone use is not clearly defined. Instead, there are various factors to which the excessive use is attributed, including contents engaged, duration and frequency of usage, pathological behavioral patterns or addiction to the phone itself (Billieux, 2012; Panova & Carbonell, 2018). There is not yet an overarching framework that holds these pieces together, and much disagreement is found throughout the literature. Another aspect that brings discord into the literature is the exclusion of SPA in the DSM-5 or the ICD-11(American Psychiatric Association, 2013; World Health Organization, 2018). Additionally, a variety of different measures and methodologies is used for studying SPA. This lead to difficulty in generalizing and making inferences between research, as it is difficult to understand how the results and conceptualizations relate to one another (Montag et al., 2021; Yu & Sussman, 2020). The great majority of research is also conducted with adolescent and young adult samples, which may not reflect other age groups and further challenges generalizability.

Predictors and Key Factors in Excessive Usage

Key predictors of excessive smartphone usage are commonly associated with duration and frequency of usage (Elhai, Yang, Rozgonjuk, & Montag, 2020; Rozgonjuk, Levine, Hall, & Elhai, 2018), social network use (Gezgin, 2018; Gökçearslan, Mumcu, Haşlaman, & Çevik, 2016; Jeong, Kim, Yum, & Hwang, 2016), fear of missing out (Elhai et al., 2016; Wolniewicz, Tiamiyu, Weeks, & Elhai, 2018) and relieving emotional discomfort (Elhai et al., 2018; Kardefelt-Winther, 2014). In addition, age and gender are also important factors in excessive use (Buctot, Kim & Kim, 2020; Kim et al., 2016).

Duration and frequency have been argued in several studies to be among the strongest predictors of SPA (Haug et al., 2015; Lee, Ahn, Choi, & Choi, 2014; Lin et al., 2015) and can

be consisered a key components in excessive smartphone usage. A link between duration of usage and detrimental effects in the brain is supported in both behavioral and neuroimaging studies (Demirci, Akgönül, & Akpinar, 2015; Gezgin, 2018; Horvath et al., 2020; Hu, Long, Lyu, Zhou, & Chen, 2017; Lee, Namkoong, Lee, Lee, & Jung, 2019).

Excessive Smartphone Usage as an Addiction

Whether excessive smartphone usage can be considered an addiction or not is a debate with a long history in the related field of internet addiction and has been carried into the SPA literature as well (Beard & Wolf, 2001; Panova & Carbonell, 2018; Shapira, Goldsmith, Keck, Khosla, & McElroy, 2000; Yellowlees & Marks, 2007). There are some parallels between behavioral addictions and SPA that make this claim plausible.

The traditional framework of addiction has been in reference to dependence on a chemical of some sort. This has been redefined in recent years, including behavioral addictions that refer to a dependence on an activity (American Psychiatric Association, 2013; Koob & Volkow, 2010). The behavioral addictions include gambling addiction, impulse-control disorders, and internet gaming disorder (American Psychiatric Association, 2013; Grant, Potenza, Weinstein, & Gorelick, 2010). Behavioral addictions display analogous pathological patterns to chemical addictions. They are expressed with behavioral characteristics related to salience, mood modification, tolerance, withdrawal, loss of control, and relapse, following Griffiths component model of addiction (Griffiths, 2005; Koob & Volkow, 2010). In terms of everyday functioning, addiction is commonly associated with decreased work/academic performance, psychosocial functioning, and mental, cognitive and physical health (Grant et al., 2010).

SPA shares many of these behavioral characteristics, which supports the claim of characterizing it as an addiction (Kuem, Ray, Hsu, & Khansa, 2020; Lee, Han, & Pak, 2018; Yu & Sussman, 2020). One example giving support to this parallel is smartphone separation. It refers to the reaction to absence from one's phone. This has been shown to lead to transitory behaviorally measurable impairments in CC, suggested being related to increased anxiety levels caused by withdrawal (Hartanto & Yang, 2016). A recent meta-analysis has inquired into the plausibility of placing SPA under the behavioral addiction spectrum by analyzing 108 studies (Yu & Sussman, 2020). Yu & Sussman's final remarks posit that it seems justified to classify SPA under the addictive behaviors continuum.

Neurobiological correlates in SPA has also been found in neural loci similar to other addictions with abnormal activity and integrity in several parts of the brain, including the

fronto-striatal cortical network (Chun et al., 2018; Horvath et al., 2020; Wang et al., 2016). The fronto-striatal cortical network is critically involved in all forms of addiction (Chun et al., 2018; Feil et al., 2010)

Given the shared behavioral characteristics and similar neural loci to other addictions, it seems plausible that excessive smartphone usage can be placed under the umbrella of behavioral addictions. In this thesis, SPA is defined as excessive smartphone usage that has a negative impact on one's mental and physical health. This definition is based upon Horvath's distinction (Horvath et al., 2020), and for convenience, the term SPA will be used throughout this thesis.

Measuring Smartphone Usage

Another challenge in the field of SPA is how the usage should be measured. A common term found in the literature is screen time (ST). ST refers to the time spent on any type of digital screen. Previously, ST has mainly been evaluated with self-reported questionnaires. However, research has consistently demonstrated that bias for self-reported ST is strong while estimation is poor (Boase & Ling, 2013; Scharkow, 2016). For example, in a sample of 3401 participants, only one-third of the sample provided accurate self-evaluated judgment of ST use (Scharkow, 2016). In another study, only a moderate correlation was found between logged ST and self-reported ST (Boase & Ling, 2013).

The questionable integrity of self-reported questionnaires of ST has led researchers to look for other solutions. One promising alternative is an application-based ST recorder that is downloaded on a participant's phone. At the current moment, there is no generalized application as such for research purposes, but a growing number of studies utilize application based ST measure (Christensen et al., 2016; Elhai et al., 2018; Gower & Moreno, 2018; Rozgonjuk et al., 2018). In reference to this study, ST will be used in a device-specific manner, measuring duration of smartphone usage.

Impairments of Smartphone Addiction

Preliminary results from studies on SPA suggests impairments and detrimental effects related to CC (Chen et al., 2016; Chun et al., 2018; Gao, Jia, Zhao, & Zhang, 2019), loss of productivity (Duke & Montag, 2017), poor academic performance (Samaha & Hawi, 2016), poor/less sleep (Demirci et al., 2015; Sohn, Krasnoff, Rees, Kalk, & Carter, 2021), anxiety and depression (Demirci et al., 2015; Elhai, Dvorak, Levine, & Hall, 2017; Matar Boumosleh & Jaalouk, 2017; Samaha & Hawi, 2016), among others. Although the evidence is limited given the recent invention of the smartphone, support from closely related fields of study,

such as internet addiction, problematic internet use, digital media use, and ST, further strengthen these results (Brand, Young, & Laier, 2014; Cai et al., 2016; Dong, Lu, Zhou, & Zhao, 2010; Grøntved et al., 2015; Hale & Guan, 2015; Ioannidis et al., 2019; Maras et al., 2015; Twenge, 2019; Yuan et al., 2017). This thesis will primarily focus on IC impairment associated with SPA but will briefly evaluate relevant physiological and psychological associations.

Sleep, anxiety, depression, psychological wellbeing (PWB) are all relevant parameters that co-occur in SPA and influence one another. Detrimental effects of sleep deprivation are for example associated with decreased cognitive and inhibitory performance, increased impulsivity, and heightened anxiety levels (Ma, Dinges, Basner, & Rao, 2015; Pilcher & Huffcutt, 1996; Rossa, Smith, Allan, & Sullivan, 2014). Impulsivity as a personality trait is considered the highest risk factor for developing addiction (Koob & Volkow, 2010). Anxiety and depression coincide with SPA, as illustrated by a meta-analysis of 23 peer-reviewed articles (Elhai et al., 2017). Anxiety has been shown to interfere with top-down control mechanisms that mediate efficient IC (Ansari & Derakshan, 2011; Hallion, Tolin, Assaf, Goethe, & Diefenbach, 2017). Depression has also been shown to influence IC, where elevated depressive symptoms have been linked to deficits in inhibitory processing (Shimony et al., 2021).

PWB can encompass both anxiety and depression by including them on the negative affective spectrum. An inverse relationship between PWB and anxiety and depression has been found (Malone & Wachholtz, 2018), and correlational studies demonstrate a strong link between PWB and anxiety/depression ($p<0.001$) (Ceri & Cicek, 2020; Liu, Shono, & Kitamura, 2009). Absence from positive PWB also predicts depression, as shown in a cohort study (Wood & Joseph, 2010). PWB is negatively correlated with SPA in several studies in different age groups across the world (Buctot et al., 2020; Horwood & Anglim, 2019; Kumar, Lingeswaran, Attalla, & Jeppu, 2020; Kumcagiz & Gündüz, 2016; Tangmunkongvorakul et al., 2019). There are also extensive studies in the neighboring field of ST that support this notion, where ST is negatively associated with PWB (Twenge, 2019; Twenge & Campbell, 2018, 2019; Yan et al., 2017).

However, all researchers do not agree with this claim. The recent study of Orben and Przybylski (2019) criticize previous research on the relationship between PWB and ST. According to the authors, the conflicting results are mainly due to methodological design flaws. They also criticize that many studies draw too strong inferences on correlations when no causality can be ensured. To counter these issues, Orben and Przybylski make use of

specification curve analysis on a sample set of 355,358 individuals. Their findings demonstrate that the effects of ST on PWB are much smaller than previously proposed. They are so small compared to other daily life situations that they may be irrelevant (Orben & Przybylski, 2019). How this analysis translates to the study of SPA is not clear though and similar statistical analysis could be used in future studies address this question.

The complex relationship between the components that co-occur in SPA is difficult to disentangle, but a common denominator is their relation to CC. In neuroscientific studies duration of usage have been associated with compromised structural and functional integrity of circuitry involved in CC/IC, where duration of usage predicts impairment severity (Chun et al., 2018; Horvath et al., 2020; Lee et al., 2019; Wang et al., 2016). These results give support to the association between excessive duration of usage and detrimental effects in IC.

The loss of control in SPA may be attributed to impaired CC/IC as seen in other addictions (Luijten et al., 2014) as CC is essential for efficently managing behavior (Cohen, 2017).

Cognitive and Inhibitory Control

CC or executive functions (synonymously used in the literature) refer to a set of top-down mental processes required for cognitive functions, such as goal-oriented action, attention, decision-making and creative thinking. It relates to effortfully guiding behavior to manage one's actions in accordance with one's intentions (Cohen, 2017; Diamond, 2013). One of the core components of CC is IC (also called inhibition), along with working memory and cognitive flexibility (Diamond, 2013).

IC reflects the ability to suppress unwanted or irrelevant information, responses, or behaviors and is crucial for cognitive functions to operate properly (Cohen, 2017). In the psychological literature, inhibition was previously conceived to be a unitary process. Neuroscientific evidence has shed new light upon this matter and revealed two distinct inhibitory processes with distinct neurobiological networks (Munakata et al., 2011). Both of these inhibitory mechanisms rely upon functions that the PFC provides. This has strong support from lesion studies where patients with PFC lesions have severely compromised inhibitory function (Banich, 2009; Harlow, 1974; Szczepanski, & Knight, 2014).

The prefrontal cortices function in cognitive control. The PFC provides the scaffold for CC, although not exclusively, but critically. The PFC specializes in actively maintaining and representing abstract information (Miller & Cohen, 2001). A prerequisite for maintaining and representing information is working memory, as it provides the ability to

maintain goal-relevant information (Miller, 2000). There are several theories concerning how CC is exerted; this study will mainly focus on three influential ones: the guided activation theory, the bias competition model, and the unified framework of IC. Miller and Cohen produced perhaps the most influential theory on the function of the PFC in CC in their paper: An integrated theory of the PFC (Miller & Cohen, 2001).

The guided activation theory and indirect competitive inhibition. According to the guided activation theory, the primary function of the PFC in CC is its capacity to maintain abstract information, represent goals, and impart rules. This is facilitated by specific properties of the neurons in the PFC, which can learn contingencies and associative relationships between rewards, cues, actions (Miller, 2000). These properties of the neurons enable rules to be extracted from situations that can be imparted in future situations. Based on these rules, goals, and cues, the PFC can exert control through top-down bias signals to other parts of the brain, modulating and inhibiting the competing and less relevant pathways/structures based on situational demands (Miller, 2000; Miller & Cohen, 2001).

The central tenet in the guided activation theory is that one of the fundamental principles of neural processing is that it is competitive. This means that in the processing of context-related information, pathways and structures compete for expressions of the behavior. The winner in the competition will have increased activation while competing pathways/structures will be suppressed (Miller & Cohen, 2001). This view has its basis in the research of Desimone and Duncan (1995), who provided the theory of biased competition in visual attention. They found that neurons in the visual cortex compete with each other via "mutually inhibitory interactions" (Miller & Cohen, 2001, p170). The neurons that win the competition reach higher levels of activity, while the remaining gets suppressed. Miller and Cohen extended the competitive bias theory by not only implicating these bias signals in the visual modalities but instead as a fundamental mechanism by which the PFC exerts control (Miller & Cohen, 2001).

Furthermore, Miller and Cohen propose that both selective attention and behavioral inhibition are two aspects of the same processes. Namely, that attention is the effect of biasing competition, and inhibition is the consequence of the suppression in the competition (Miller & Cohen, 2001). In this view, inhibition occurs in reference to local competition to solve conflict. This perspective of inhibition holds merit today and is referred to as indirect competitive inhibition in more recent works (Munakata et al., 2011; Tiego, Testa, Bellgrove, Pantelis, & Whittle, 2018).

Munakata et al. have further extended this perspective in their 2011 paper, in which they attempt to create a unified framework of inhibition. Central to their argument is that inhibition is not a unified process per se but is mediated by two separate neural mechanisms that depend upon specific prefrontal functions, as previously covered by Miller & Cohen. According to their framework, the PFC produces two different inhibitory effects: Indirect competitive inhibition and directed global inhibition.

Directed global inhibition. Directed global inhibition is mediated by certain PFC projections to sub and archi-cortical (olfactory/hippocampus) regions. These projections can activate gamma-aminobutyric acid (GABA) interneurons in the target area, leading to inhibition of function (Munakata et al., 2011). According to Munakata et al. (2011), two distinct neural mechanisms are supporting direct global inhibition. Either the projections synapse directly onto the interneuron or the projection synapse onto the excitatory neurons of the target area, which in turn synapse onto the areas GABA interneurons. The PFC's excitatory projections enable direct global inhibition of motor output through the subthalamic nucleus (STN), which inhibits the basal ganglia's output (Aron et al., 2007; Munakata et al., 2011).

Given the evidence provided by the guided activation theory, and the unified framework of inhibition, it can be said that IC rests upon functions that the PFC provides. There are two separate inhibitory mechanisms which serve in different context and circuitry of the brain (Miller & Cohen, 2001; Munakata et al., 2011).

Distinctions of inhibitory control. Common distinctions of IC is described by the terms response inhibition (RI) (also referred to as motor inhibition, restraint, behavioral inhibition) and interference control (IFC) (also referred to as attentional inhibition, attentional constraint, resistance to interference, see review: Tiego et al., (2018), p2 for evaluation of terminology). RI is characterized as the suppression of a prepotent or automatic response and is often measured by the psychometric tasks of go/no-go and stop-signal tasks (Liu, Zhu, Ziegler, & Shi, 2015). IFC refers to the ability to resist distracting stimuli/information and is commonly measured by the Simon, flanker, and the Stroop task (Liu et al., 2015).

Interference control and response inhibition; convergence and divergence. To use the constructs of IFC and RI in any meaningful way, it is critical to demonstrate their independence. There has been a long history of dispute surrounding this notion. A pivotal meta-study conducted by Friedman and Miyake (2004) evaluated the relationship between

these two constructs, and a third one referred to as “resistance to proactive interference”, which will not be discussed in this thesis. The result from their analysis displayed a strong correlation (r 0.67) between RI and IFC, so strong that the authors suggested that the constructs should be consolidated into a single construct called “response-distractor inhibition” (Friedman & Miyake, 2004, p125).

Although Friedman and Miyake did not account for underlying contributors to inhibitory function, suggested by Kane and Engle (2002) to be working memory capacity (WMC). Kane et al. (2016) extended the methodological paradigm used by Friedman and Miyake by including a measure of WMC. Their result demonstrated a highly significant relationship between WMC and RI (r -0.64) and IC (r -0.40).

Kornblum’s taxonomy. Both Friedman and Miyake (2004) and Kane et al. (2016) used a taxonomy for the task paradigms that some researchers (Tiego et al., 2018) have proposed is flawed. For example, classifying the Stroop task under RI appears unjust in both a taxonomical and neurobiological sense (see page 12-13). This issue of improper taxonomy within the studies of Friedman and Miyake and Kane has the potential of deflating their results. To counter this issue, Tiego et al. (2018) used Kornblum’s dimensional overlap taxonomy, which identifies two distinct forms of conflict:

1: Stimulus-stimulus conflict, refers to competition between relevant/irrelevant stimuli (related to IFC).

2: Stimulus-response conflict, refers to competition between valid response and invalid prepotent response (related to RI) (Kornblum, Hasbroucq, & Osman, 1990; Tiego et al., 2018)

Based on this taxonomy, Tiego et al. (2018) classified the stop-signal, go no/go, and Simon task to the construct of RI and Stroop, flanker and shape matching to IFC. With this extended design, the researchers illustrated brilliantly that RI and IFC appear to be related in their reliance on WMC, yet distinguishable constructs of inhibition (Tiego et al., 2018).

The reliance on WMC in RI and IFC is consistent with both the guided activation theory and the unified framework of inhibition on CC’s reliance on working memory. The independence of these constructs is further strengthened in the next section when evaluating neurobiological correlates of IC.

The Neurobiology of Interference Control and Response Inhibition

Recent research supports the notion of a distinct neurobiological network in IFC and RI, but with particular circuitry shared. The shared neurobiology relates to the structures of the anterior insula (aI), the dorsolateral prefrontal cortex (dlPFC), the inferior frontal gyrus

(IFG), dorsal anterior cingulate cortex (dACC) extending into pre-supplementary motor area(SMA) and SMA, as well as parietal lobe regions (Hung, Gaillard, Yarmak, & Arsalidou, 2018).

The construct of RI overlap with the dorso-frontal network of IFC (dACC, dlPFC) but also activates a larger-scale network including the fronto-striatal pathway, including vlPFC (containing IFG), the basal ganglia, midbrain regions and parietal-superior temporal regions (Hung et al., 2018).

The shared characteristics between these inhibitory constructs are not surprising as there are several shared functions such as conflict monitoring and resolution and adjustment of CC, which is mainly attributed to the dorsal network (dACC, dlPFC) (Hung et al., 2018). However, RI involves coordination between both dorsal and sensory-motor systems. The distinctions between the networks will be further strengthened in the following sections that provide material of the context of the task paradigms utilized in this study.

The Stroop task. The Stroop task has extensively been used to study attention, inhibition, and conflict processing and is considered a measure of gold standard (MacLeod, 1991; Scarpina & Tagini, 2017; Stroop, 1935). The most used Stroop task is the Stroop Color and Word Task (SCWT). It operates by asking the test subject to identify the color of a word during two conditions. In the congruent condition, the word matches the ink color (word spelling: blue, in blue color). In the incongruent condition, the color does not match the word (word spelling: green, in red color), and interference is created, leading to an increase in reaction time (RT). The increase in RT is because the participant needs to overcome the tendency to rely on the automatic process of reading the word and instead naming the color, requiring CC (Scarpina & Tagini, 2017).

There is a variety of Stroop tasks, ranging from verbal, spatial to emotional and the neurobiological correlates between the different tasks are basically identical (excluding emotional Stroop tasks) except for stronger activation in the inferior orbital gyrus in word-based Stroop (Cieslik, Mueller, Eickhoff, Langner, & Eickhoff, 2015).

Neurobiology of the task. The Stroop task is intrinsically intertwined with the inhibitory construct of IFC and is often studied in reference to it. This is supported in terms of neural activation patterns, as shown in sixty-one Stroop studies with functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) in the regions of the aI, ACC, dlPFC, posterior and inferior parietal cortex, pre-SMA and the IFG (Cieslik et al., 2015). This converges very well with the overall activation patterns of IFC.

The overall function of the ACC in IFC is suggested to be related to conflict monitoring and adjustment of CC for resolving interference (Xu, Xu & Yang, 2016). The dlPFC is involved in top-down control and can bias processing when there is competition, serving task-relevant information in goal-directed behaviors (Banich, 2009). The posterior parietal cortex regulates attention and action planning at a stimuli representation level. The role of the aI has been associated with several functions such as response selection, RI, monitoring, goal-directed attention (Xu et al., 2016). The pre-SMA is associated with the ability to inhibit competing motor plans when there is response conflict, and the IFG has previously been linked to suppressing interference (Xu et al., 2016).

According to the cascade of control model provided by Banich (2019), the Stroop effect is generated at several stages in the brain, e.g. a cascade of events that is unfolding. The PFC maintains the relevant representation (naming of the color, instead of reading the word) and produces bias signals to excite posterior regions for enhancing associated representations (information about the color). The enhanced representation can then inhibit the competing representations. The increase in RT is due to latency created from the competition (and resolution) along the cascade of processing (Banich, 2019).

Finally, it can be said that the neural activation patterns between the Stroop task and IFC converge well, which validates the classification of Stroop under the construct. The Stroop task is subject to indirect competitive inhibitory mechanisms, which further distinguish it from the stop-signal task.

The Stop-signal task. In the stop-signal task, subjects perform two different actions. In the go trial, one is requested to respond to a stimulus by pressing a corresponding button as fast as possible. Occasionally a stop-sign is introduced with a short delay after the stimuli (the stop-signal trial). When that happens, the subject is requested to withhold their response, thus attempting to inhibit the already initiated action (Verbruggen & Logan, 2008). To stop a response, a fast mechanism of control is required (e.g. preventing the initiated action), along with a slower mechanism of control that allows monitoring and adjustment for increased efficiency/performance in future encounters of the situation (Verbruggen & Logan, 2008).

The theoretical foundation of the modern stop-signal task rests upon Logan and Cowan's work in 1984, where they introduced the so-called horse-race model of RI. In this model, the horse-race reflects a competition between a go process and a stop process that competes over the final execution over the action (Verbruggen & Logan, 2009). By varying the delays of when the stop-signal is introduced, it is possible to compute the main variable in the task: The stop-signal reaction time (SSRT). The SSRT can be seen as the estimated speed

at which the brain can stop a process. Performance-wise, a lower SSRT reflects better inhibitory function (Verbruggen & Logan, 2008).

The SSRT has proven to be a useful measure both in the study of CC and in clinical setting. It carries real-life implications, demonstrating ecological validity where both psychopathological and neurological disorders display RI deficits with heightened SSRT. SSRT is also prolonged in substance abuse disorders and OCD, which are generally associated with IC deficits (Verbruggen & Logan, 2008).

Neurobiology of the task. The neural and inhibitory basis of the stop-signal task is closely intertwined with RI and follows the directed global inhibitory process. The task has two components: the go process and the stop process. The go process is linked to activation in the cortico-basal-ganglia-thalamo-cortical circuit. While the stopping process is linked to activation in the fronto-basal-ganglia circuit which includes the IFG, dlPFC, medial frontal gyrus, and basal ganglia (Verbruggen & Logan, 2008).

The IFG is a key node in RI; when successfully stopping an action, the IFG display increased activation, and the magnitude of activation is negatively correlated with SSRT (Verbruggen & Logan, 2008). Some researchers have also attributed the IFG to be a crucial point in the network supporting a generalized inhibitory mechanism (Chambers et al., 2009); this may have merit, as it is activated in IFC as well.

The role of preSMA/SMA has previously been declared to be involved in motor planning (Chambers et al., 2009). The pre-SMA is activated in successful stopping, but the activity is not correlated with SSRT (Chambers et al., 2009). The involvement of IFG and pre-SMA in the stop-signal task is further strengthened by transcranial magnetic stimulation, and lesion studies, where artificially lesioned rIFG and pre-SMA impair stopping, but not going (Verbruggen & Logan, 2009).

The basal ganglia are also considered a key convergence point in RI. Lesions of the basal ganglia compromise SSRT to a similar degree as prefrontal damage (Chambers et al., 2009). Psychiatric conditions such as OCD and ADHD are also linked to impaired function of the basal ganglia and are strongly associated with IC (Chambers et al., 2009).

The fronto-basal-ganglia model of RI proposes that inhibition in the stop-signal task operates in the following way: when the stop-signal is introduced, the hyper-direct pathway is activated connecting the IFG to the STN. The STN can then inhibit the basal ganglia, providing a sort of “kill switch” for stopping the initiated action (Chambers et al., 2009). However, this is not the only pathway mediating inhibition through the STN; projections through the ACC and pre-SMA can also project to the STN, which can inhibit the basal

ganglia (Munakata et al., 2011)

In conclusion, it can be said that that the inhibitory mechanism behind the stop-signal task is closely related to the inhibitory construct of RI. It follows directed global inhibition and share the dorso-frontal network with IFC (Hung et al., 2018) but also extends to the vlPFC, basal ganglia and subcortical structures.

Neuroimaging Correlates in Smartphone Addiction

There are some preliminary findings on neurobiological impairments in SPA that converge with structures and pathways that mediate IC. However, it is hard to independetly distinguish IC as there is no one-to-one covergence of structure and function.

Structural and functional correlates of SPA. Gray matter volume (GMV) alterations have been found in circuitry that is associated with inhibitory function, including the ACC, aI, IFG, OFC and midcingulate cortex (Chun et al., 2018; Horvath et al., 2020; Lee et al., 2019; Wang et al., 2016).

The orbitofrontal cortex. GMV abnormalities have been found in the OFC in individuals with SPA (Horvath et al., 2020; Lee et al., 2019) and have previously been linked to impaired adaptive decision-making, increased impulsivity and habit formation (Lee et al., 2019). Dysfunctional OFC is involved in many disorders that rely upon IC, such as ADHD, Tourette's syndrome, OCD, substance abuse disorder (Bryden & Roesch, 2015). Lesions to the OFC produce RI deficits, and excitatory pharmacological administration into the OFC improves stop-signal performance. However, the exact role of OFC in inhibition is still controversial (Bryden & Roesch, 2015). The functional characteristics of the OFC play an important role in drug and behavioral addictions (Hu et al., 2017; Luijten et al., 2014). This is consistent with the research of SPA where a link between engagement level, addictive symptoms, and the structural integrity of the OFC has been found (Horvath et al., 2020; Lee et al., 2019).

The anterior cingulate cortex. The ACC is framed in previous research to have an important role in IC through conflict monitoring and response selection (Chan et al., 2011; Nieuwenhuis, Yeung, Van Den Wildenberg, & Ridderinkhof, 2003; Posner & Petersen, 1990). ACC volume is correlated with go no-go performance in developmental studies (Casey et al., 1997) and in adults (Nieuwenhuis et al., 2003). In a meta-analysis analyzing 19 ERP studies and 22 fMRI studies on addiction, the dACC was attributed to be the key area for conflict monitoring, which is critically involved in IC, suggested to be involved in the loss of control found in addiction (Luijten et al., 2014). This is consistent with the literature on SPA

where GMV abnormalities have been found in the ACC, correlated with SPA severity (Horvath et al., 2020; Wang et al., 2016).

The insula. GMV alterations in the insula have also been found in individuals with SPA (Horvath et al., 2020). All task paradigms related to IC activates the aI (Cieslik et al., 2015; Hung et al., 2018). The aI functions as an outflow gate that initiates and maintain control-driven mechanisms (Hung et al., 2018). Nevertheless, the involvement of the insula in IC is still controversial as it is difficult to distinguish it from the co-activation of the right inferior frontal cortex (Cai, Ryali, Chen, Li, & Menon, 2014).

Other gray matter changes. Abnormalities in circuitry associated with IC have also been found in the temporal cortex, rIFG, superior frontal gyrus, and the thalamus (Horvath et al., 2020; Lee et al., 2019; Wang et al., 2016).

White matter changes. Apart from GM changes, compromised white matter (WM) integrity has been shown in individuals with SPA. The study of Hu et al. (2017) observed fractional anisotropy in subjects with SPA and found remarkable significant between-group differences in the cortico-striatal pathway. As previously covered, the cortico-striatal pathway is critical in addiction, through motivational and cognitive aspects of goal-oriented action (Feil et al., 2010). Additionally, it can provide global direct inhibition through the PFC GABAergic projections, which can inhibit the dorsal striatum (Rock, Zurita, Wilson, & Apicella, 2016).

Other white matter changes have been found in the superior longitudinal fasciculus (SLF). The SLF is thought to be vital in processing memory, attention, language, and emotion, and the left SLF is associated with CC and IC (Hu et al., 2017; Urger et al., 2015).

Resting-state functional connectivity. Studies observing resting-state functional connectivity (rsFC) converge with the structural data demonstrating abnormal connectivity in the fronto-striatal circuitry in SPA subjects (Chun et al., 2018). Weaker rsFC in the rOFC and rNAcc and between left OFC and midcingulate cortex have been found while stronger rsFC between MCC and NAcc (Chun et al., 2018).

Electrophysiological correlates of SPA. Electrophysiological data further provide support for IC impairments in SPA. Two event-related potentials (ERP) components have been associated with IC (Luijten et al., 2014). The N2 component represents a negative spike presented 200-300 milliseconds after the stimulus. The N2 is suggested to emerge from the ACC and rIFG. The P300 component is a positive spike presented 300-500ms after the stimulus and is suggested to emerge around the motor and premotor cortices. The P300

appears in the later stage of the inhibitory process and is related to inhibiting motor plans and actions (Luijten et al., 2014).

There is some evidence that points to N2 alterations in individuals with SPA. An ERP study with a no-go task, found larger amplitude in the N2 component in the SPA group compared to control. Larger N2 amplitude suggests an inhibitory deficit in the early stages of processing (Chen et al., 2016). However, a similar study observing social network abuse found no group difference in the N2 component (Gao et al., 2019). This conflicting result could be due to differences in contents engaged, but it is not possible to draw any conclusions with such limited data.

The study of Chen et al. (2016) also found weaker P300 in SPA group compared to control, consistent with the study of Gao et al. (2019). Similar results have also be found in the literature on internet addiction (Dong et al., 2010; Dong, DeVito, Du, & Cui, 2012).

Given the evidence provided from the several methodological domains, it seems plausible to assert that SPA carries with it abnormalities in GM and WM and electrophysiological changes associated with circuitry of IC and processing.

The Present Study

The evidence provided above supports the notion of IC impairments in SPA, and show a correlation between degree of usage and structural and functional integrity of the brain related to IC circuitry (Horvath et al., 2020; Hu et al., 2017; Lee et al., 2019; Wang et al., 2016).

The purpose of the present study is to investigate how/if the degree of smartphone usage relates to IC function in a sample of healthy individuals. The present study will also observe if there are group differences between high and low ST users on inhibitory performance. Whereas the majority of previous research on SPA utilizes questionnaire type measures of excessive usage, the present study utilizes an application based ST measure that is feasible to provide a more objective and reliable measure of smartphone usage. This study observes duration of usage and will not include an analysis of frequency of usage.

It is recognized that duration of usage is not synonymous with SPA; nevertheless, it is a strong predictor and a key component and therefore assessed to be highly relevant in the context. Additionally, few studies attempt to study healthy individuals on the proposed relationship. Given the popularity of the smartphone, it is important to evaluate how or if the proposed relationship is found across different user groups, which the following design may provide insight into.

Method

Participants

Thirty-two participants, with a mean age of 30.15 (SD ± 5), were recruited from the University of Skövde and social media. The following inclusion criteria were used: age between 20-45 and native Swedish speakers. The age criterion was based upon evidence that indicates a decline in RT in older adults (MacLeod, 1991), and the lower bound demarcation was based upon evidence that the PFC does not fully develop until early/mid-twenties (Arain et al., 2013). The Stroop task is also highly affected by language processing with measurable differences between first and second language (MacLeod, 1991). Therefore, native Swedish speakers were only included in the study.

Individuals with the following conditions were excluded from the study: major psychiatric disorders (ADHD, autism, OCD, major depressive disorder, schizophrenia, and bipolar disorder), colorblindness, dyslexia, and recent drug use (two days), as they have been associated with influencing psychometric tests (MacLeod, 1991; Verbruggen & Logan, 2008). The inclusion and exclusion criterion was based upon self-report and could not be validated with any objective measurement.

One participant had to be excluded from further analysis due to incomplete ST time data. Five participants initiated the ST measurement but did not complete the psychometric tests and had to be excluded from further analysis. One participant initiated the Stroop task two times; this individual's first Stroop task result was excluded as it was assessed to be faulty. One subject encountered an error on the stop-signal task, resulting in timeouts on all trials. Therefore, the subject's data were excluded from the analysis. In total, data from 26 participants, mean age: 30.15(SD=5.37), were analyzed, 26 in the Stroop task and 25 in the stop-signal task.

Ethics. Consent from all participants was obtained through an online form prior to measurement, following the World Medical Association Declaration of Helsinki (2013). Personal information was not recorded in any stage of the empirical investigation; thus, GDPR was not necessary to be followed.

General Research Context and Design

The present study made use of a correlational design and a between-groups design. Key terms of inquiry were operationalized by the following measures: duration of smartphone usage as ST given in minutes, RI as SSRT, IFC as Stroop interference score (SI). The psychometric taxonomy was based upon Kornblum's dimensional taxonomy and

neuroscientific evidence that support distinctions in brain networks involved in the processing of IFC and RI (Cieslik et al., 2015; Hung et al., 2018; Kornblum et al., 1990). Error rates were also considered important variables for the operationalization of inhibitory performance and were analyzed in parallel. Error rates in the Stroop task (both conditions) will be referred to as ER_{Tot}, while error rating in the stop-signal task will be referred to as ER_{Go} and $ER_{NoGo.}$

The empirical investigation took place online with two consecutive parts. The first part included a Google docs form containing a participation/consent form, inclusion/exclusion criteria, and information to the participant covering details on the ST measurement.

The second part included a Psytoolkit survey consisting of a questionnaire and two psychometric tests. Psytoolkit is a free to use online psychological test platform containing several psychometric tests (Stoet, 2010, 2017). With the use of Psytoolkit surveys, one can program a sequence of questions and sequences of psychometric tests.

Materials and Measurements

Screen time measurement. The measurement of the ST data was recorded from the participant's smartphone through an app. For Android, the app Screen Time, by developers Iridium Dust Limited was used. The app allows reading data that is already stored on the phone and can read the ST data retrospectively. Therefore, it was considered highly applicable to the study as the participants did not have to wait a week for the data to be gathered. For iPhone the native app Screen Time (developed by Apple) was used; this app could not read data retrospectively. This led to that the individuals who had not activated the app prior-testing, had to wait one week for the ST data to be recorded.

Both ST recorders monitor the amount of time the users spend on different apps and give a total of daily and weekly ST. An analysis of the reliability of the ST recorders was not carried out; therefore, the objectivity and reliability of the ST measure could not be verified. However, previous analysis of a similar ST app has been carried out with reliable and valid results (Elhai et al., 2018; Rozgonjuk et al., 2018)

Psytoolkit configuration. The study included a pre-designed computerized Psytoolkit (Stoet, 2010, 2017,v2.61) version of the SCWT and stop-signal task and was modified to suit the needs of the empirical design. The use of mobile phones/tablets and the web browser Safari was excluded in the configuration of the Psytoolkit survey due to recommendations from the Psytoolkit creator; therefore this part had to be executed on a computer.

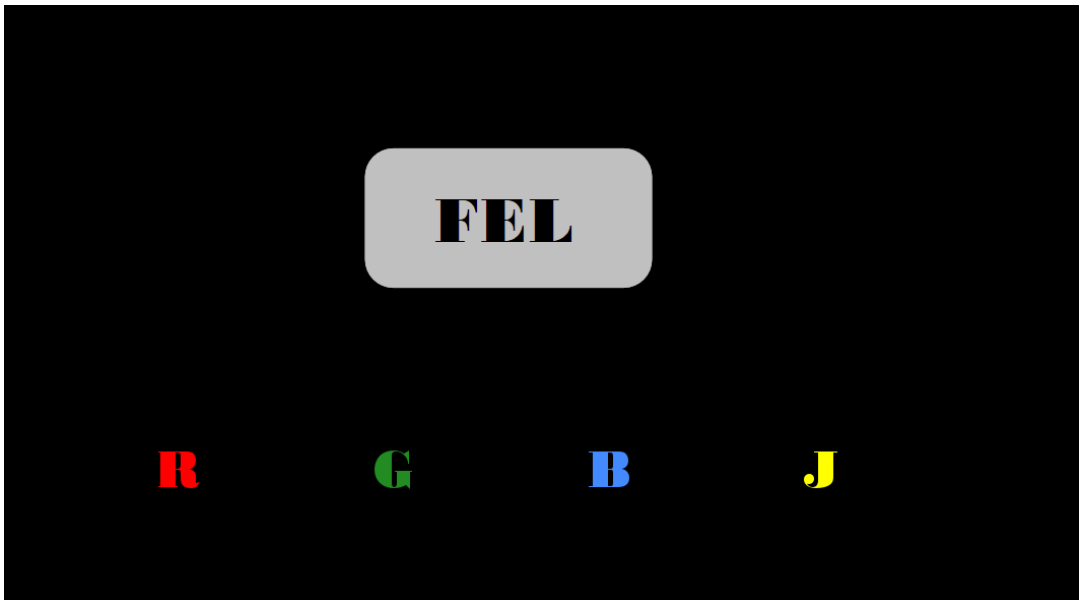
The Stroop color and word task. The Psytoolkit version of the SCWT task (Stoet, 2010, 2017) operates by responding to a stimulus using a computer keyboard and pressing the key that corresponds to the correct color. A feedback sign is displayed after each trial to illustrate if the response was correct or not. The stimuli consisted of words of colors, written in capital letters (font: standard, size: 52). Each letter was written in four different ink colors and was translated from English to Swedish (RÖD, GRÖN, BLÅ, GUL), requiring modifications to the bitmaps. The color-words were randomly generated and displayed in the center of the screen against a black background. The key mappings for the corresponding colors were set to: RÖD(R), GRÖN(G), BLÅ(B), GUL(J). The key mapping of GUL was changed from the original letter Y to the letter J for improved finger coordination. This decision was made based on complaints from beta testers of tangled finger positions. As native to the Psytoolkit version of the Stroop task, only congruent and incongruent trials were used.

After instructions of the key mappings and performing the task, a practice round was introduced consisting of 20 trials. The practice round was modified to include a panel of the key mappings on the trial feedback, based upon remarks of the beta testers who did not remember the corresponding color to the corresponding key (Figure 1). The data from the practice round was excluded from the analysis. After the practice round, 80 trials followed. The duration of the stimuli presentation was kept at 2000ms, meaning the subjects had two seconds to commit their answer. After the feedback presentation (200ms), a new trial started with a 500ms delay.

The data from the Stroop task was individually filtered, first by excluding erroneous trials and then filtered on RT based on an SD of 3 for the individuals RT mean. This practice has previously been used to filter raw Stroop data (Khng & Lee, 2014; Parris, 2014). The mean RT was then calculated in each condition and the SI was finally calculated by subtracting the mean RT of the incongruent condition from the mean RT of the congruent condition.

Figure 1

Modified practice round



Note. This figure illustrates the modified practice round in the Stroop task, which includes the key mappings and their respective colors.

The Stop-Signal Task. The Stop-signal task provided in Psytoolkit (v2.61) operates by letting the subject respond to a visual stimulus (arrows) as quickly as possible by pressing a corresponding key (b for left arrow, n for right arrow). In the go phase, the subject only responds to the arrows, which will give the goRT distribution of values. In the NoGo phase, the subject similarly responds to the arrows, but when a stop sign is presented, the subject ought not to respond.

The Go phase was set to 50 trials, and the Go/NoGo phase set to 60 Go trials and 20 NoGo trials. The maximum response time for the keypresses was kept at 500ms as initially set by Psytoolkit (Stoet, 2017). The NoGo phase introduces a stop-sign with three different timings, e.g the stop-signal delay (SSD) and was modified from the original delays of 50/100/450 milliseconds to 50/100/150 milliseconds. This reduction was motivated by other stop-signal task designs which use proportional response time to the SSD (Li, Yan, Sinha, & Lee, 2008; Wang et al., 2013). The first 20 trials were considered practice trials and were removed before analysis. The bitmaps for the stop-signal stimuli were doubled in size as the original size was considered too small to see the stop-signal sign effectively.

As covered before, the SSRT reflect the time it takes for the brain to inhibit an already initiated response. It reflects a relationship between the RT in the Go trials (GoRT)

and the successful/unsuccessful trials in the NoGo condition. The SSRT cannot be read straight from the results but requires a computational approach; two such approaches exist, the mean method and the integration method. The present study made use of the integration method for calculating SSRT. This decision was based upon the concluding remarks of the study of Verbruggen, Chambers and Logan (2013) that suggest the mean method should be abandoned in favor of the integration method for a more accurate estimate of IC.

Calculating SSRT. In the NoGo condition, timeouts and erroneous trials create an index between successful and unsuccessful inhibited responses (Verbruggen & Logan, 2008). The error-index is then used to find the corresponding percentile in the GoRT distribution. Finally, the RT at the corresponding percentile is subtracted from the SSD to receive the SSRT. For example, if a participant produces an error rate of 83% in the NoGo trial with an SSD of 200ms, and say that the 83% percentile of the GoRT distribution is 420ms. Then the SSD is subtracted from the goRT (420-200), meaning the SSRT will be 220. The rest of the SSRT was calculated by the same procedure. Because the current task design utilized a maximum RT of 500ms, leaving small margins for response time, it was decided to filter out timeouts (<500ms) and erroneous trials in the GoRT condition.

Due to some error in the programming of the stop-signal task, the data only included two SSD's (50ms and 200ms). A third SSD was calculated from probability using the range of the two other SSD's and dividing it in two (50+200/2), giving an SSD of 125ms. This line of calculation follows from the independent horse race model, which allows moderately accurate calculation of any probability of an SSRT from a given SSD (Logan & Cowan, 1984). Finally, the three SSRT's was averaged, giving a final SSRT score.

Procedure

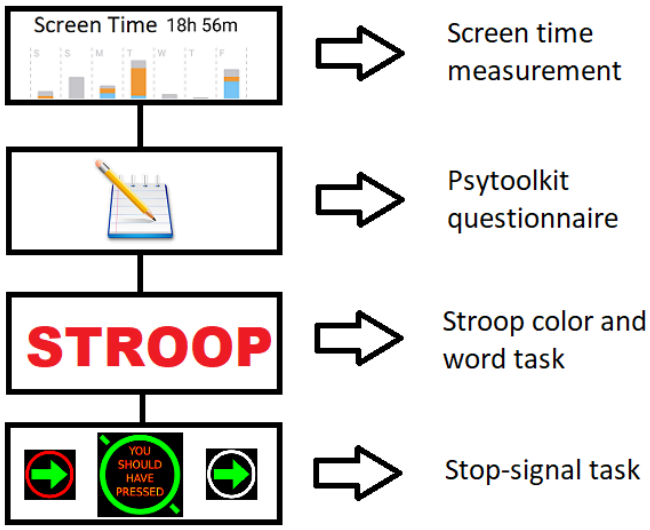
The study was carried out entirely online in subsequent steps without supervision from the researcher. First, the participants were given a link with the Google doc's survey and had to give answers through a yes/no button system to proceed in the survey. Then, after giving informed consent, the participants had to fill out a self-reported questionnaire containing inclusion/exclusion criteria's. If the participants did not meet the criteria's, he/she would be led to an exit page, thus ending further participation. Once the informed consent and participation form had been answered and submitted, instructions followed to guide the participant through the ST measurement. The instructions explained how to install/activate the ST app on the participant's smartphone, take a screenshot of the acquired data (one week of ST), and send it to the researcher through an anonymous third-party service for insured

anonymity. Once the ST measurement had been completed, a link was given to the Psytookit survey.

In the Psytoolkit survey, a questionnaire including questions of age and handedness was followed by instructions requesting the participant to isolate him/herself in a quiet location, put the phone in flight mode and try to eliminate as many distractions as possible. Subsequently, the Stroop task and stop-signal task followed in sequence.

Figure 2

The steps of the procedure



Statistical Analysis. A power analysis was conducted prior to the empirical investigation using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009) a priori correlation-bivariate normal model (ρ H1=0.45, α 0.05, power: 1-β =0.9). It provided the following results: critical r =0.287±, n=47, power=0.90. The parameters utilized in the power analysis were post-facto realized to be inappropriate considering the alpha level in the study and correlation effect size of H1.

The statistical analysis was made in SPSS (v26) with the significance level set to α= 0.05. A two-tailed bivariate Pearson's r analysis was used to investigate the relationship between the variables of ST and SI, SSRT, and error ratings (ER_{Tot}, ER_{Go}, ER_{NoGo}).

A two-tailed independent t-test compared the sample based on high ST users (Above 75% of the ST mean) and low ST users (below 25% of the ST mean) on the variable of SSRT. The normality of data distribution in the variable of SI was not typical to meet the requirements of the assumptions of a t-test; therefore, the non-parametric test of Mann-Whitney U was utilized.

Results

The Relationship Between Screen Time and Stroop/Stop-Signal Performance

Descriptive statistics. The descriptive results can be found in Table 1.

Inferential statistics. The distribution in the sample was sufficiently typical to meet the a priori requirements for conducting an inferential correlational analysis: skewness: ST=1.07 (SD=0.46), SI=0.822 (SD=0.46), SSRT=-1.05 (SD=0.46), ER_{tot}= 0.61 (SD=0.46), ER_Go=0.49 (SD=0.46), ER_NoGo=-0.702 (SD=0.464). The guiding principle here was skewness levels (≤1), and even though ST and SSRT were marginally over (≤1) they were considered acceptable. The kurtosis levels were typical enough to satisfy the a priori requirements for a Pearson correlation (<3 SD): ST=0.13, ER_{Tot}= 0.89, ER_{Go} = -0.65, ER_{NoGo}= 0.45, SI= 2.47 (SD=0.887) and SSRT=2.36 (SD=0.902).

A Pearson's correlation analysis was performed to test the hypothesis of a statistically significant relationship between study variables. No statistically significant relationship between the variables of interest was found. The results are presented in Table 1, and Figure 3 illustrates the results. The predicted outcome of a relationship between ST and stop-signal/Stroop task performance was not satisfied; thus, H0 was retained.

Table 1

Descriptive statistics and correlations for study variables

Variable	n	M	SD	1	2	3	4	5	6
ST	26	1623	1047		-0.125	0.204	0.005	-0.078	-0.003
SI	26	79.31	68.65	-0.125		0.156	-0.005	0.263	-0.070
SSRT	25	257.94	37.45	0.204	0.156		-0.201	0.265	0.018
ER_{Tot}	26	11.38	8.24	0.005	-0.005	-0.201		0.117	0.099
ER_{Go}	25	12.73	7.36	-0.078	0.263	0.265	0.117		0.011
ER_{NoGo}	25	60.40	11.81	-0.003	-0.070	0.018	0.099	-0.502*	

*Correlation is significant at the 0.05 level (2-tailed)

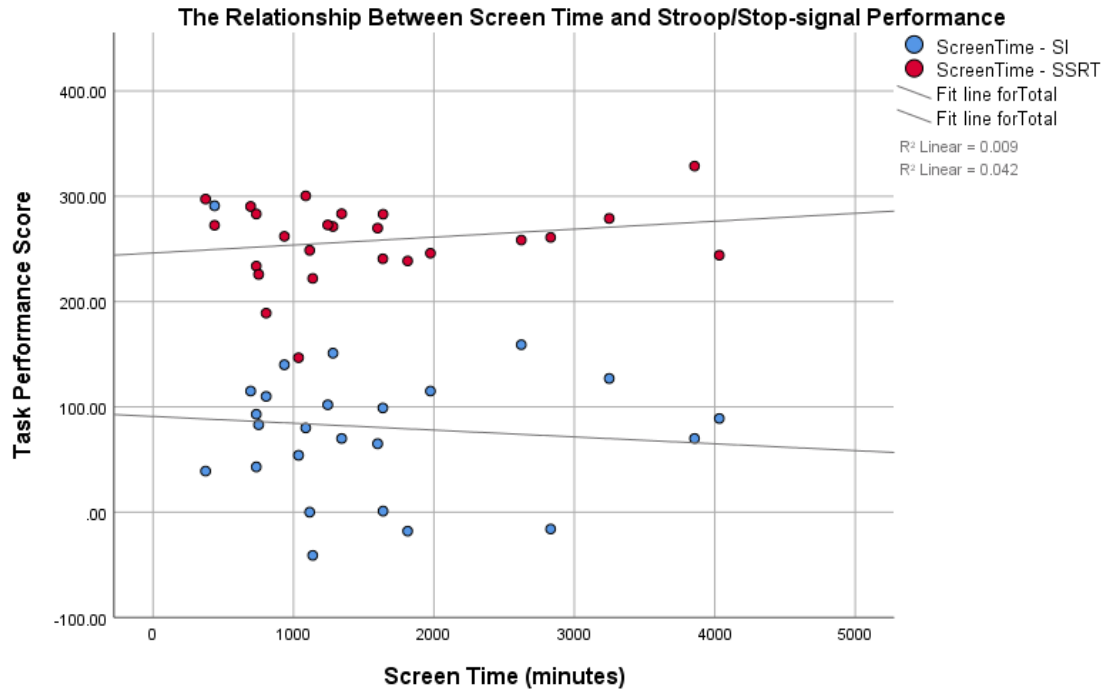


Figure 3. The figure depicts the correlation between ST and task performance score (SI/SSRT).

Group Comparison Screen Time and Stroop/Stop-Signal Task

Descriptive statistics. The low ST group (n=6) had a mean SI of 110.67 (SD=93.1) and a mean SSRT of 267.15 (SD=30.18). In comparison, the high ST group (n=5), displayed lower SI, mean=71.33 (SD=62.11) and higher SSRT: mean=274.22 (SD=32.9).

Inferential statistics. An independent t-test was conducted to test the hypothesis of a statistically significant difference between the low ST group (1) and high ST group (2) on the variables of SI and SSRT. The distribution of the sample was sufficiently typical to meet the a priori requirements for conducting a t-test for the variable of SSRT (skewness 0.32, kurtosis 0.01). However, a kurtosis and skewness issue was identified in the SI variable's distribution of the low ST group (skewness 1.43, kurtosis 3.38). Therefore, the non-parametric test of Mann-Whitney U was performed instead. Additionally, a Levene's test of homogeneity was performed to test the assumption of homogeneity of variance and was satisfied for SSRT: F= 3.646, p=0.69.

No statistically significant difference was found between the low ST group and the high ST group in independent t-test on the SI variable (t=0.37, ρ=0.72) and neither from the Mann-Whitney U test on SSRT (U=16, z=0.32, ρ=0.75). Thus, the predicted group

differences on task performance were not met, and H0 was retained. Figure 3 illustrates the results.

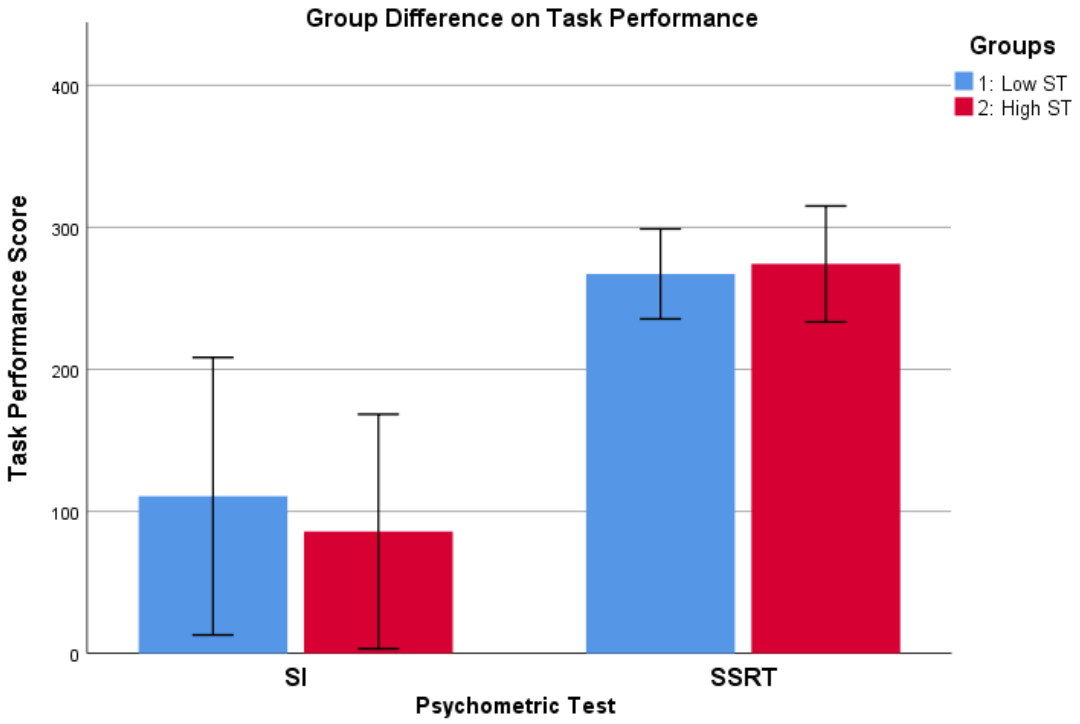


Figure 3. The figure illustrates group differences in the variables of SI and SSRT (represented by task score). Error bar demonstrates 95% confidence interval.

Discussion

The present study investigated the relationship between duration of smartphone usage and IC. No statistically significant relationship was found between the variables of interest, and neither did the group comparison reach statistical significance. Thus, the data collected could not support the hypothesis in the study. This is not altogether surprising as there were various confounds and limitations to the study that greatly compromised validity and power in the analysis.

Behavioural measures in studies on SPA have previously been shown to be insufficiently powerful to demonstrate significant effects (Chen et al., 2016; Gao et al., 2019). There are currently not more than a few studies in the literature covering smartphone usage and IC. However, when examining the closely related literature on internet addiction, a body of evidence exists, and similar results can be found with no statistical significance on behavioral measures of RT and ER (Cai et al., 2016; Dong et al., 2010, 2012).

Although the present study could not find a statistically significant link between

duration of smartphone usage and IC, neuroimaging studies have provided preliminary support for alterations in GM, WM, rsFC and electrophysiology in subjects with SPA that are involved in inhibitory processing (Chen et al., 2016; Chun et al., 2018; Gao et al., 2019; Horvath et al., 2020; Lee et al., 2019; Wang et al., 2016). Given the time constraints of the bachelor thesis, it was not possible to accompany the behavioral measures with a brain imaging technique. Future research could extend the current methodological paradigm, including an EEG measure, observing the ERP components of N200 and P300. This could provide more in-depth results on the proposed relationship and follows the early results of studies showing electrophysiological inhibitory deficits in SPA, which needs further validation (Chen et al., 2016; Gao et al., 2019).

The current study also made use of a recent measurement tool, an application-based ST recorder. The use of an application that can objectively and reliably measure ST do carry promise. However, it would be more appropriate to program a ST recorder that is designed for research purposes only. It should be noted that with the multifaceted device the smartphone is, the purpose of usage is highly dynamic. It is not clear at this moment how the content engaged is relevant to the problem behind SPA. A more carefully designed application could introduce further constraints on the ST data sampling and exclude unwanted data (for example, work-related ST). This could provide further directions of research investigating differences between content engaged versus time spent on the device. Additionally, the use of both frequency and duration of usage should be considered in future studies. Frequency of usage is an important predictor of SPA (Salehan & Negahban, 2013) and may provide further analysis of behaviors that duration of usage cannot supply.

Given the small sample size, power could have been increased by utilizing a within-group design instead of a between-subjects design. The between-group design also introduced difficulty in comparing inhibitory performance, as the difference between individuals could not be known beforehand.

One possibility that should not be overlooked is that the analysis of the data collected holds merit, and there simply is no relevant relationship between duration of smartphone usage and IC. Orben and Przybylski (2019) found that the relationship between ST and PWB was overemphasized, and the relevance of previous results inflated. Although Orben and Pryzbylski did not inquire about the relationship between ST and IC, their criticism of research methodologies and analysis methods appears justified in the literature of SPA. The majority of studies in the limited literature on SPA is primarily low constraint research and cannot infer causation. In order to address the complex nature of causality behind the

relationship between IC and smartphone usage, more high constraint research, different cohorts, longitudinal studies, and more complex statistical methods are necessary.

Limitations. A major limitation of the study was the insufficient sample size. The sample size did not reach the required sample size provided by the power analysis and greatly decreased the power in the statistical analysis. This may partly have accounted for the non-statistically significant results. Another limitation concerning the sample was selection bias. The current sample was recruited from peers, friends and acquaintances and most certainly do not reflect the general public. Gender was also not recorded as a demographical variable; this was post facto realized to be a strong limitation as studies have shown there are significant differences in smartphone usage between the genders (Kim et al., 2016) and in IC (Mansouri, Fehring, Gaillard, Jaberzadeh, & Parkington, 2016). Substance use disorder was not included in the exclusion criteria and was also considered a confound as it has been consistently demonstrated to have effects upon IC (Luijten et al., 2014).

The Covid-19 outbreak introduced several limitations to the study, and it could not be executed as planned initially, leading to reconstructions in the design, psychometric setup and other relevant implementations. This introduced several confounds due to reduced constraints, supervision while increasing the time constraints.

The measurement of ST had limitations as well. Two different ST applications were used based upon the operating system of the participant's smartphone. The applications underlying mechanics, reliability, and validity were out of the scope of this thesis to evaluate. Therefore, it is unclear how these two applications compare and if the applications are reliable enough to use for research purposes. One example in pinpointing this issue concern ST data from five participants who lacked a small part of the last day (for unknown reasons). In this case, the issues were calculated and assessed to be negligible, thus not altering the data to any significant degree.

The stop-signal task paradigm had several limitations. In the programming of the task, it was specified to have a fixed number of trials (20 NoGo and 80 Go trials), but some flaw led to randomly generated trials ranging from 63 to 104; this was a major confound affecting the calculation of SSRT. The few stop-signal trials interfered with the error-indexing in the integration method. This was especially problematic in calculating the SSRT for certain participants, where the lack of trials decreased the total variance, thus affecting the calculation of SSRT.

Conclusion

The data collected could not support the hypothesis of a relationship between IC and duration of smartphone usage. This may have been due to several methodological flaws and limitations. Another possibility is that the results hold merit, and there is no relationship to be found. Nevertheless, given the wide use of smartphones, the question in this study is vital to address. Both low and high constraint research is necessary to bridge the gap and finally understand the connection between IC and smartphone usage.

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