The investigation of problematic Internet and smartphone use with functional magnetic resonance imaging

PH.D. Thesis

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1. Introduction

Advances in information technology and information communication over the past two decades have made the Internet an indispensable part of our everyday lives through smart devices such as smartphones and tablets. Smartphones, with their continuous online presence and interactive, multimedia nature, have become some of the most frequently used technological devices today (Mihajlov & Vejmelka, 2017). However, the use of the Internet and smartphones may also have numerous negative consequences. They can contribute to the spread of behavioral addictions such as problematic Internet use (PIU) and problematic smartphone use (PSU) (Demetrovics et al., 2008), which may be associated with negative outcomes including reduced quality and quantity of nocturnal sleep, chronic mental and physical fatigue, depression, anxiety, loneliness, and other health problems (Young, 1998).

Initially, researchers referred to problematic behaviors related to Internet use as addictions. However, most researchers now agree that Internet-use disorders should not be labeled as addictions since, in addiction literature, the term refers to physiological dependence on a stimulus (typically a substance), which clearly does not exist between the immaterial Internet and its users. (Davis, 2001). From both a scientific and a practical perspective, and based on the field's theoretical framework, PIU and PSU should be regarded as umbrella terms denoting the problematic use of online content accessed via the Internet and smartphones across multiple channels (Montag et al., 2021). The I-PACE model, developed by Brand and colleagues (2016), is one of the most widespread neurocognitive theories for characterizing PIU and PSU. The model aims to identify the neurobiological, psychological, and behavioral components that interact to cause problematic Internet and smartphone use. According to the model, both PIU and PSU can be situated on the spectrum of behavioral addictions. They are associated with psychological characteristics, such as internal urges, anxiety, depression, and loneliness, as well as neural alterations that resembling those observed in substance addictions (Brand et al., 2019). Numerous magnetic resonance imaging (MRI) studies have been conducted in recent years to provide empirical support for the model. The results of these studies have confirmed neurobiological overlap between Internet-related disorders and various substance addictions (see Sepede et al., 2016; Weinstein, 2022, for reviews). These MRI-based studies have typically reported reduced volume and altered task-based functional activity in several brain regions involved in reward processing (e.g., the nucleus accumbens and the orbitofrontal cortex), decision-making and executive functions (e.g., the ventrolateral prefrontal cortex and the anterior cingulate gyrus), behavioral inhibition and impulse control (e.g., the dorsomedial prefrontal cortex), emotion regulation (e.g., the anterior cingulate gyrus and the dorsolateral prefrontal cortex), and the symptoms of craving and withdrawal (e.g., the insula and the medial prefrontal cortex) in both PIU and PSU.

2. Objectives

My doctoral dissertation explores the range of cognitive and behavioral functions potentially affected by PIU and PSU that have not yet been thoroughly investigated. The studies presented in this thesis address two under-researched areas.

First, I investigated the effects of PIU and PSU on human social cognitive functions, particularly the recognition of emotional face expressions and the functional neural connections underlying this process.

Second, I investigated how the severity of PIU and PSU influences acute mental fatigue induced by a cognitively demanding task, as well as the associated functional neural correlates.

3. Recognition of emotional face expressions in PIU and PSU

Building on previous findings, the severity of both PIU and PSU may impact the proper functioning of social cognitive processes. Social cognition encompasses the specific cognitive processes that enable us to predict others' behavior and interpret primary social cues, such as emotional face expressions (Beer & Ochsner, 2006). These expressions convey important information about others' mental states, so accurately perceiving them is essential for adequate social functioning (Van Kleef, 2009). The amygdala plays a key role in recognizing emotional facial expressions. Through its functional connections with prefrontal regions, the amygdala plays a central role in detecting and processing emotionally salient stimuli.

Impairments in recognizing emotional face expressions negatively affect social cognitive functioning in several substance use disorders. For example, individuals with alcohol dependence show a reduced ability to recognize emotions, accompanied by functional alterations in the fronto-limbic circuit responsible for emotion regulation (Le Berre, 2019). Similar findings were reported by Salloum et al. (2007), who also observed functional changes in several cortical regions involved in recognizing emotional face expressions (e.g., prefrontal structures, ACG, amygdala, and insula) in individuals with alcohol dependence. Although online social life and communication may influence social cognitive functions, few studies have examined the psychological and neural processes involved in recognizing emotional face expressions in the context of PIU and PSU. The only task-based functional MRI (fMRI) study thus far found deactivation in frontal regions involved in recognizing and processing emotional face expressions among problematic smartphone users (Chun et al., 2017). In light of these neuroscientific findings, we deemed it worthwhile to investigate the task-induced functional connectivity (FC) of the amygdala involved in emotional face expression recognition in PIU and PSU as well. One of the most suitable methods to investigate FCs related to emotional face expression recognition is the Facial Emotion Recognition Paradigm (FERP), developed by Hariri and colleagues (2002). This task robustly engages the amygdala and activates corticolimbic functional networks involved in emotion recognition when processing socio-emotional stimuli. Leveraging the FERP's properties, my study employed psychophysiological interaction (PPI) analysis to investigate task-induced functional connectivity in the bilateral amygdala.

The present study aims to explore how the severity of PIU and PSU affects the functioning of the FCs underlying emotional face expression recognition by combining FERP and fMRI.

4. Methods

A total of 65 young university students (32 males) between 18 and 30 years (mean = 22.5 years, SD = 2.68) participated in the study. Only participants who did not report any prior psychiatric (e.g., depression) or neurological disorders and who did not presented no safety risks for MRI scanning (e.g., metal implants, pregnancy) were included in the recruitment process.

4.1. Assessment

The severity of participants' PIU was assessed using the Hungarian version of the Problematic Internet Use Questionnaire (PIUQ) developed by Demetrovics and colleagues (2008). The severity of PSU was measured with the Hungarian version of the Short Smartphone Addiction Scale (S-SAS) (Csibi et al., 2016). Depressive symptoms were assessed using the 21-item self-report Beck Depression Inventory (Beck et al., 1961).

4.2. Stimuli

The emotional face expressions used in the FERP task were selected from the FACES database (Ebner et al., 2010). The FERP administered during the fMRI measurements consisted of two tasks. In the emotion-matching condition, a target facial expression was presented in the upper central part of the monitor while two test facial expressions were displayed in triangular arrangement in the lower left and right corners. Participants were instructed to select the test face that expressed the same emotion (fear, anger, or sadness) as the target face. As a control task, blocks of geometric shape matching alternated with blocks of emotional face expression matching. In these control trials, participants matched emotionally neutral, abstract geometric shapes (circles and vertically or horizontally oriented ellipses). These tasks-maintained participants' attention and allowed corticolimbic neural responses associated with recognizing emotional face expressions to return to baseline.

4.3. MRI acquisition and analysis

All MRI measurements, including task-based and structural scans, were performed on the same 3 Tesla MRI scanner (MAGNETOM Prismafit, Siemens Healthcare, Erlangen, Germany), with a 20-channel head-neck coil.

BOLD signal analysis was used to obtain an overview of the average activation pattern observed in the emotional condition of the FERP. To examine the FCs underlying emotional face expression recognition, I conducted PPI analyses using the left and right amygdala as separate seed regions. The primary aim of this analysis was to identify brain regions that showed a stronger correlation with the time series of the seed region (the amygdala) in a given psychological state (the emotional face-matching condition) than in another state (the geometric shape-matching condition). To investigate FCs associated with the severity of PIU and PSU, I performed ROI analyses focusing on the FCs between the left and right amygdalae and the neural structures involved in emotional face expression recognition: the bilateral anterior cingulate gyrus (ACG), posterior cingulate gyrus (PCG), frontal pole (FP), superior frontal gyrus (SFG), supramarginal gyrus (SMG), and middle temporal gyrus (MTG).

5. Results

Behavioral statistical analyses revealed no associations between the severity of PIU and PSU and reaction times (RTs) or error rates in the emotional face expression recognition task.

Based on the PPI and ROI analyses, the positive correlations between the FCs of the left amygdala seed and PIUQ and S-SAS scores did not remain significant after applying Benjamini–Hochberg corrections. By contrast, the FCs between the right amygdala and frontal regions (the bilateral FP and SFG) implicated in cognitive control remained positively correlated with questionnaire scores (PIUQ and S-SAS) even after corrections ($p < 0.05$). Furthermore, the FCs between the right amygdala and regions involved in emotion recognition (MTG, ACG, PCG, and SMG) were also positively correlated with questionnaire scores (PIUQ and S-SAS) after corrections ($p < 0.05$).

6. Conclusions

In the present study, I demonstrated the functional involvement of two higher-order systems in PIU and PSU. Altered functioning of the FCs that support cognitive control is a fundamental phenomenon across various addictive disorders. Therefore, it is not surprising that changes in these FCs also play a role in recognizing emotional face expressions in PIU and PSU. The results highlight the potential involvement of social cognitive functions, such as mentalizing and recognizing emotional facial expressions, in PIU and PSU, since FCs between the amygdala and the ACG, PCG, MTG, and SMG are fundamental for intact social cognitive functioning. These findings may elucidate one aspect of altered social cognitive functioning in PIU and PSU and serve as a solid foundation for future research.

As an increasing proportion of our social interactions takes place online, face-to-face encounters are gradually decreasing. This process may be accompanied by changes in social perception, communication, and more broadly, social cognitive functions. Since the long-term consequences of an extensive online social life are unknown, longitudinal investigations of social cognitive functions in the context of PIU and PSU are essential.

7. Task-induced mental fatigue in PIU and PSU

Over the past decade, chronic mental fatigue (CMF) has become a widespread topic of research on Internet-based disorders (Aziz et al., 2024; Bachleda et al., 2018; Lin et al., 2013). Using self-report questionnaires, most of these studies have concluded that the severity of PIU and PSU alone can predict the level of CMF in both prospective (Liang et al., 2022) and cross-sectional designs (Aziz et al., 2024; Bachleda et al., 2018).

However, mental fatigue may manifest not only in a chronic form, but also acutely during the execution of a cognitively demanding task (Van der Linden, 2011). Acute mental fatigue (AMF) is a transient psychobiological state that occurs during prolonged performance of a mentally demanding task (Matuz et al., 2021). AMF is accompanied by decreased task performance (Darnai et al., 2023), higher levels of subjective fatigue (Hopstaken et al., 2015), and reduced intrinsic motivation to continue the task (Boksem et al., 2006). AMF is most easily induced via the time-on-task (ToT) effect (Csathó et al., 2012); increasing time spent on a demanding cognitive task is associated with higher subjective fatigue levels and a decline in performance (e.g., slower reaction times).

Unlike CMF, changes in AMF have not yet been examined in the context of PIU and PSU. From a research perspective, the bidirectional relationship between chronic mental fatigue and

AMF may be particularly informative, as chronic mental fatigue may make individuals more susceptible to developing AMF (Hanzal et al., 2024; Hess & Knight, 2021). Scientific findings also suggest that repeated exposure to AMF may contribute to the development of CMF (Fang et al., 2008, 2013). Given these associations and the robust link between PIU, PSU severity, and CMF, I hypothesized that investigating ToT-induced AMF in PIU and PSU would be worthwhile.

The aims are also supported by MRI studies of various populations, including healthy controls (Matuz et al., 2023), individuals with multiple sclerosis (DeLuca et al., 2008), and patients with chronic fatigue syndrome (Cook et al., 2007; Staud et al., 2018). These studies have linked objective features of AMF, such as performance decline, and subjective features, such as subjective mental fatigue (SMF), to structural and functional alterations in frontal and parietal regions. Altered functionality (Darnai et al., 2019; Sepede et al., 2016) and structural organization (Weinstein, 2022) have also been demonstrated in these regions in the context of PIU and PSU.

Against this background, the primary aim of the study was to obtain a comprehensive view of changes in the subjective and objective characteristics of ToT-induced AMF in PIU and PSU. I implemented task-based fMRI while participants performed a cognitively demanding Psychomotor Vigilance Task (PVT) to examine neural processes associated with the ToT effect induced AMF.

8. Methods

A total of 71 young university students (33 males) between the ages of 19 and 30 (mean age = 25.00 ± 3.25) participated in the study. Only participants who did not report any prior diagnosis of psychiatric (e.g., depression) or neurological disorders and who did not present any safety risks for MRI scanning (e.g., metal implants or pregnancy) were included in the recruitment process. Since the PVT used in the study is sensitive to daytime sleepiness (Thomann et al., 2014), only participants who had slept for at least six hours the night before the MRI session were enrolled.

8.1. Assessment

The severity of the participants' PIU was assessed using the Hungarian version of the Problematic Internet Use Questionnaire (PIUQ) (Demetrovics et al., 2008). PSU severity was measured using the Hungarian version of the Smartphone Withdrawal Scale (SWS) (Csibi et al., 2019). Chronic mental fatigue was assessed using the Hungarian version of the Fatigue

Impact Scale (FIS) (Losonczi et al., 2011). Depressive symptoms were measured using the 21-item Beck Depression Inventory (Beck et al., 1961). Trait anxiety was assessed using Spielberger's Trait Anxiety Inventory (Spielberger, 1983).

8.2. Stimulus and paradigm

The present study used the PVT via the time-on-task (ToT) effect to induce AMF and elicit neural processes associated with fatigue. The task was displayed on an MRI-compatible screen that participants viewed through a mirror attached to the head coil. Each PVT trial began with a white fixation cross displayed in the center of the screen against a gray background. After an interstimulus interval that varied pseudorandomly between 2 and 20 seconds, the fixation cross was replaced by a blue circle. The circle remained on the screen for two seconds or until a response was given. Participants were instructed to respond as quickly as possible once the blue circle appeared.

The PVT consisted of three five-minute blocks (B1, B2, and B3). Before the first experimental block (VAS1) and after the third (VAS2), participants indicated their current level of SMF on a Visual Analog Scale (VAS). Reaction times were recorded for each trial. The ToT-related change in performance was quantified as the difference in mean reaction times between B3 and B1 (B3-B1 RT). Similarly, ToT-induced changes in subjective mental fatigue (SMF) were operationalized as the difference in VAS scores, calculated by subtracting VAS1 from VAS2 (VAS2 - VAS1).

8.3. MRI acquisition and analysis

All MRI measurements (task-based and structural) were performed on a 3 Tesla Siemens MAGNETOM Prismafit scanner (Siemens Healthcare, Erlangen, Germany) using a 20-channel head coil.

The primary aim of the study was to obtain a comprehensive picture of ToT-induced changes in AMF and its neural underpinnings in the context of PIU and PSU. To this end, I used BOLD signal analysis to examine neural changes associated with PIU and PSU scores, as well as PVT-induced AMF.

After conducting group-level BOLD signal analysis, I performed post hoc regression analyses to determine if the neural changes associated with PIU and the ToT effect were related to the subjective and objective characteristics of AMF.

9. Results

The results of the Wilcoxon test on VAS score differences ($Z = -5.74$, $p < .001$) and the Friedman test on performance changes during the PVT ($\chi^2(2) = 80.648$, $p < .001$) revealed that increased mental fatigue was successfully induced via the ToT effect in this study.

Multiple linear regression analyses revealed that PIU severity (PIUQ total score) independently predicted SMF changes (VAS difference scores) [$\beta = 0.349$, $t(70) = 2.935$, $p = .005$], while controlling for BDI and STAI-T scores. Similarly, controlling for BDI and STAI-T scores revealed that the severity of PSU (SWS total score) independently predicted task-related changes in SMF [$\beta = 0.416$, $t(70) = 3.073$, $p = .003$].

In the BOLD signal analyses, no association was found between ToT-induced BOLD signal changes during the PVT and SWS total scores. However, a negative association was observed between ToT-induced BOLD signal changes (B3 > B1 contrast) and PIUQ total scores in the left precuneus (PCu; cluster 1) and the left medial frontal gyrus (MeFG), middle frontal gyrus (MFG), and superior frontal gyrus (SFG; cluster 2) at a cluster-corrected significance threshold of $z > 2.3$ and $p = .05$.

Post hoc regression analyses revealed that activation changes within clusters 1 and 2 did not predict ToT-induced performance changes (B3 - B1 RT) (Cluster 1: $n = 70$, $\beta = -0.039$, $t(69) = -0.317$, $p = .752$; Cluster 2: $n = 70$, $\beta = -0.120$, $t(69) = -0.989$, $p = .326$). However, ToT-induced and PIU-dependent BOLD signal changes predicted SMF (VAS2 − VAS1) changes independently within both clusters [Cluster 1: $n = 70$, $\beta = -0.298$, $t(69) = -2.547$, $p = .013$; Cluster 2: $n = 70$, $\beta = -0.237$, $t(69) = -2.034$, $p = .046$], even when controlling for FIS, BDI, and STAI-T scores.

10. Conclusions

This is the first study to demonstrate that the severity of PIU and PSU independently predict changes in the subjective parameter of mental fatigue associated with performing a cognitively demanding task. During the study we did not find an association between changes in task performance and the severity of PIU or PSU. Based on these results, it can be concluded that the severity of PIU and PSU does not affect performance changes during a demanding cognitive task. Rather, it can be assumed that individuals more strongly affected by PIU feel more mentally fatigued after completing a cognitively demanding task.

BOLD signal analysis revealed a negative association between task-induced changes in the BOLD signal in the left PCu (Cluster 1) and the left MFG, MeFG, and SFG (Cluster 2) and

PIUQ total scores. Task-induced BOLD signal changes in these regions were negatively related to changes in SMF. These findings suggest that the relationship between PIU and SMF changes may be linked to BOLD signal changes within these clusters. This indicates that the study captured neural regions whose functioning plays an important role in increased sensitivity to subjective fatigue in the context of PIU.

Increased exposure to AMF entails several risks, including negative effects on psychological well-being. Elevated levels of mental and physical fatigue may contribute to associated symptoms, such as depression, anxiety, and poor sleep. Therefore, it is important to emphasize everyday recreational activities to preserve mental health.

11. General conclusions

My doctoral dissertation aimed to present studies examining cognitive and behavioral functions that had not previously been investigated in the context of problematic internet and smartphone use. This line of scientific inquiry is essential for a more thorough understanding of the pathogenesis and symptomatology of these disorders. Based on the findings of these studies, I confirmed the pre-formulated hypotheses and presented novel results that have not yet been reported in the scientific literature on this topic.

12. Publications

12.1. Publications related to the thesis

Arató, Á., Nagy, S. A., Perlaki, G., Orsi, G., Szente, A. T., Kis-Jakab, G., ... & Darnai, G. (2023). Emotional face expression recognition in problematic internet use and excessive smartphone use: task-based fMRI study. *Scientific Reports*, *13*(1), 354.

IF: 3.80; SJR: Q1/D1

Arató, Á., Szente, A. T., Matuz, A., Áfra, E., Alhour, H. A., Perlaki, G., ... & Darnai, G. (2025). Increased task-induced mental fatigue in problematic Internet Use: an fMRI study. *Computers in Human Behavior Reports*, *19*, 100728.

IF: 5.80; SJR: Q1/D1

∑IF: 9.60

12.2. Publications unrelated to the thesis

Darnai, G., Perlaki, G., Orsi, G., Arató, Á., Szente, A., Horváth, R., ... & Janszky, J. (2022). Language processing in Internet use disorder: Task-based fMRI study. *Plos one*, *17*(6), e0269979.

IF: 3.70; SJR: Q1

Darnai, G., Matuz, A., Alhour, H. A., Perlaki, G., Orsi, G., Arató, Á., ... & Csathó, Á. (2023). The neural correlates of mental fatigue and reward processing: A task-based fMRI study. *Neuroimage*, *265*, 119812.

IF: 4.70; SJR: Q1/D1

Szente, A., Alhour, H. A., Áfra, E., Arató, Á., Dudás, B., Szűcs, A., ... & Janszky, J. (2024). Frequency and categorization of presleep fantasies. *Scientific Reports*, *14*(1), 31975.

IF: 3.90; SJR: Q1

Perlaki, G., Darnai, G., Arató, Á., Alhour, H. A., Szente, A., Áfra, E., ... & Janszky, J. (2024). Gray matter changes following mild COVID-19: An MR morphometric study in healthy Young people. *Journal of Magnetic Resonance Imaging*, *59*(6), 2152-2161.

IF: 3.50; SJR: Q1

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IF: 2.40; SJR: Q1

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IF: 4.50; SJR: Q1/D1

12.3. Lectures and posters related to the thesis

Akos, A., Eszter, A., Anna, S., Gergely, D., & Jozsef, J. (2020). The effect of screen media activity on social cognition- an fMRI study. In Medical Conference for PhD Students and Experts of Clinical Sciences (pp. 50–50).

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12.4. Lectures and posters unrelated to the thesis

Eszter, Á., **Ákos, A**., Anna, S., Gergely, D., & József, J. (2020). The effects of a smartphone's presence on the attention. In Medical Conference for PhD Students and Experts of Clinical Sciences (p. 60).

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