Computers in Human Behavior Reports 19 (2025) 100728

Contents lists available at ScienceDirect

Computers in Human Behavior Reports

journal homepage: www.sciencedirect.com/journal/computers-in-human-behavior-reports

Increased task-induced mental fatigue in problematic Internet use: an fMRI study

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ARTICLE INFO

Keywords:
Problematic Internet use
Psychomotor vigilance task
Mental fatigue
fMRI

ABSTRACT

According to recent research, the level of problematic Internet use (PIU) is associated with chronic mental fatigue. In contrast to chronic fatigue, the association between PIU and task-induced fatigue has not been investigated. Based on previous scientific work, it is conceivable that task-induced subjective fatigue and PIU may share a common neurological background. Therefore, investigation of the association between them is indispensable. We used the Psychomotor Vigilance Task to induce fatigue and functional magnetic resonance imaging (fMRI) to investigate changes in the blood-oxygen-level-dependent (BOLD) signal during the task, and a self-reported questionnaire to assess PIU. We found that the extent of PIU predicted subjective mental fatigue changes during the task. Task-induced changes in the BOLD signal in the left precuneus, and in the left medial, middle, and superior frontal gyri correlated negatively with the PIU level. In addition, task- and PIU-related changes in the BOLD signal within these areas were negatively associated with the changes in subjective mental fatigue. Our findings highlight the association between PIU and task-induced subjective mental fatigue.

1. Introduction

The Internet has a significant impact on our daily and professional lives. Its functionality allows us to easily access anything in the world, to work from home, and to communicate constantly with others, among other actions. Through these functions, the Internet makes our lives easier, but overuse can lead to the development of a new form of behavioural addiction, such as problematic Internet use (PIU) (Panova & Carbonell, 2018; Young, 1997). PIU is an increasingly common behavioural disorder (Pan et al., 2020) that includes uncontrolled use, obsessive thinking about the Internet, and neglecting daily duties (Demetrovics et al., 2008). Magnetic resonance imaging (MRI) investigations have revealed, structural and functional abnormalities in the reward (Altbäcker et al., 2016), default mode (Darnai et al., 2019), executive (Darnai et al., 2019; G. Dong et al., 2014), inhibitory control (G. Dong et al., 2012), and language (Darnai et al., 2022) systems of the brain in people with PIU. In addition to system-level brain alterations, anxiety, depression (Young & Rogers, 1998), sleep disturbances (Alimoradi et al., 2019), and chronic mental fatigue (CMF) (Bachleda & Darhiri, 2018) are common negative characteristics of PIU.

As CMF has an impact on both personal and professional life, the investigation of CMF in PIU has become widespread (Aziz et al., 2024; Bachleda & Darhiri, 2018; Bener et al., 2019; Liang et al., 2022; Lin et al., 2013). These studies have mainly used self-reported questionnaires, and have found that the extent of PIU independently predicted the subjectively perceived CMF, both prospectively (Liang et al., 2022) and cross-sectionally (Aziz et al., 2024; Bachleda & Darhiri, 2018; Bener et al., 2019; Lin et al., 2013). The reason why problematic users are

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https://doi.org/10.1016/j.chbr.2025.100728
Received 8 October 2024; Received in revised form 20 May 2025; Accepted 17 June 2025
Available online 23 June 2025

chronically more mentally fatigued remains unclear; however, Bachleda and Darhiri (2018) emphasised that reduced sleep time due to hours spent online may play a mediating role in the association. It is also conceivable that poor sleep quality as a result of PIU (Bruni et al., 2015) could enhance the risk of CMF, as worse sleep quality is strongly associated with fatigue (Lavidor et al., 2003). As depression is related to both PIU (Young & Rogers, 1998) and CMF (Fava et al., 2014), it may also mediate the association between them. Furthermore, as craving symptoms are energy-intensive and exhausting processes in addictions (Tiffany, 1999), it is possible that their long-term persistence may contribute to the development of CMF in PIU. To date, this assumption has only been supported by one study, which found an association between the presence of these symptoms and levels of CMF in PIU (Aziz et al., 2024).

Mental fatigue is not always chronic in nature, but it can also emerge when performing a cognitively demanding task (van der Linden, 2011). The task-induced or acute mental fatigue (AMF) is a complex psychobiological state that results from a prolonged mentally demanding performance, and is characterised by its transient nature, as it is relatively easy to recover from (Matuz et al., 2021; van der Linden, 2011). The presence of AMF is associated with a decrease in task performance (Darnai et al., 2023), higher levels of subjectively perceived fatigue (Hopstaken et al., 2015), impairment in executive functions (Boksem et al., 2006), and reduced intrinsic motivation to continue the cognitively demanding task (Boksem & Tops, 2008). It is a well-established observation that with increasing time spent on a cognitively demanding task, higher levels of subjective AMF and progressive decline in performance (e.g., slower reaction times [RTs] and higher error rates) can be expected via the time-on-task (ToT) effect (Csathó et al., 2012; Lim et al., 2012). ToT-induced fatigue has various negative effects on individuals; for example, it was previously associated with safety risks (Nachreiner, 2001), occupational issues (Williamson et al., 2011), and an increased risk of traffic accidents (Van Der Hulst et al., 2001; Zeller et al., 2020).

In contrast to CMF, task-related changes in AMF sensitivity have not been investigated in PIU, although there are several ways to study it, such as through the ToT effect. The bidirectional link between CMF and AMF may be an indicator for research, as CMF can make someone susceptible to AMF (Hanzal et al., 2024; Hess & Knight, 2021), but there is also scientific evidence (Fang et al., 2008, 2013) that AMF can contribute to the development of CMF. Based on these associations, and as well as the relationship between PIU severity and CMF (Aziz et al., 2024; Bachleda & Darhiri, 2018; Bener et al., 2019; Liang et al., 2022; Lin et al., 2013), we assumed that it would be worthwhile to investigate the ToT-induced fatigue in people with PIU, as it may also have an impact on the daily functioning of these individuals. An additional reason for the investigation is that previous MRI studies on different samples (healthy controls (Matuz et al., 2023) and patients with multiple sclerosis (DeLuca et al., 2008; Sepulcre et al., 2009) or with chronic fatigue syndrome [CFS] (Caseras et al., 2008; Cook et al., 2007; Staud et al., 2018)) have found that the objective (performance decline) and subjective (extent of subjective fatigue) characteristics of fatigue are associated with structural and functional alterations in frontal (e.g., superior, middle, and medial frontal gyri) and parietal (e.g., the precuneus [PCu]) brain regions that have previously shown altered functioning (Cheng & Liu, 2020; Darnai et al., 2019; Dong et al., 2012, 2014; Sepede et al., 2016) and altered structural organisation (Solly et al., 2022; Weinstein, 2022) in people with PIU. Unfortunately, despite these scientific findings, there are no behavioural and neuroimaging studies about the association between PIU and AMF. In the absence of existing research in this area, we proposed that such an investigation would open future research directions on the association between specific areas of Internet use (e.g. presleep Internet use, Internet chat addiction) on AMF. In addition, these researches may contribute to the development of prevention methods that can reduce the risk of AMF in PIU.

Accordingly, the primary aim of the present study was to obtain a comprehensive view of the ToT-induced changes in AMF subjective and objective characteristics in PIU. In addition, we used task-based functional magnetic resonance imaging (fMRI) during the performance of the cognitively demanding Psychomotor Vigilance Task (PVT) to investigate ToT-related neural mechanisms in PIU. Considering the theoretical assumptions and the previous behavioural findings, we assume that ToT-induced changes in AMF characteristics may be associated with the severity of PIU. In addition, our study aims to confirm the assumptions of previous studies suggesting that levels of depression and withdrawal symptoms may play a role in the association between PIU and CMF.

2. Materials and methods

2.1. Participants

All participants were recruited via the Internet through social media platforms (e.g. via Facebook university groups). Applicants were required to complete a Google form that included questions about their Internet use habits, handedness, age, education, gender, possible comorbid addictions (e.g. smoking and excessive alcohol consumption), potential MRI safety risk factors (e.g. metal implant), and previous psychiatric or neurological symptoms. A total of 835 Caucasian university students participated in the online survey. Eighty-two right-handed, healthy students were randomly selected to participate in the study. Two participants, who reported severe depression (score $\geq$19) based on the Beck Depression Inventory (BDI)) (Beck et al., 1961) were excluded. Since the PVT is very sensitive to the propensity of sleep (Thomann et al., 2014), participants who slept less than 6 h before the day of the MRI were also excluded from the investigation (nine participants). The final sample consisted of 71 participants (33 men), aged between 19 and 30 years (mean age = 25.00 $\pm$ 3.25 years). According to the Edinburgh Handedness Inventory scores (Oldfield, 1971), all participants had right-hand dominance (median 100, min–max 63–100). The participants were also asked to not drink alcohol 24 h before the investigation.

A post hoc power analyses were performed using G*Power (Version 3.1.9.7) for the multiple linear regression models. Each model included four predictors and a sample size of 70 participants. The analyses yielded adequate power (0.82 and 0.87) in significant models, based on observed effect sizes and a significance level of $\alpha = 0.05$.

All participants received a small fee for their attendance in the investigation. This research was approved by the National Medical Research Council (registration number: 6843-5/2021/EÜIG). All procedures performed in this study were in accordance with the 1964 Declaration of Helsinki. All participants were informed about the study procedures and signed a written informed consent form.

2.2. Assessment

The participants were asked to rate their sleep quality before the investigation using a 7-point Likert scale ranging from 1 ('extremely poor') to 7 ('extremely good').

Without well-established diagnostic criteria, it is highly recommended to measure PIU with a multidimensional and continuous questionnaire (Poli, 2017). Therefore, we did not form control and PIU groups based on the severity of PIU; rather, we used it as a continuous variable.

2.2.1. Problematic Internet Use Questionnaire (PIUQ)

The Hungarian version of the PIUQ was used to assess PIU (Demetrovics et al., 2008; Koronczai et al., 2011). The PIUQ comprises 18 items, each scored on a 5-point Likert scale. The PIUQ has three subscales. The obsession subscale refers to obsessive thinking of the Internet (e.g., fantasising) and the withdrawal symptoms induced by lack of online state (e.g., craving). The neglect subscale corresponds to the neglect of daily activities caused by heavy Internet usage (e.g., reduced sleep time). Finally, the control disorder subscale assesses the inability to control time spent online. The overall reliability of PIUQ is good with a Cronbach alpha of 0.87 reported by Demetrovics et al. (Demetrovics et al., 2008). In the current sample, the internal consistency was similarly high (Cronbach alpha is also 0.87). Because this study focused on the general association between PIU and fatigue, the PIUQ total score was used for higher-level fMRI analyses; it was computed by summing the scores of all subscales.

2.2.2. Fatigue Impact Scale (FIS)

The Hungarian version of the FIS was used to assess the level of chronic fatigue (Losonczi et al., 2011). The FIS was developed to explore the differential impact of chronic fatigue on individuals' quality of life (Fisk et al., 1994). The FIS has three subscales: cognitive, physical, and social. The overall internal reliability of FIS is excellent (Cronbach alpha is 0.98) on Hungarian sample reported by Losonczi et al. (Losonczi et al., 2011). On our sample the reliability was also high with a Cronbach alpha of 0.97. Because this study focused on the general association between PIU and CMF, the FIS total score was used for statistical analyses.

2.2.3. Beck Depression Inventory

The 21-item self-report BDI was used to assess the presence of depressive symptoms. Higher scores reflect more severe depressive (Beck et al., 1961). The test has adequate internal consistency (Cronbach

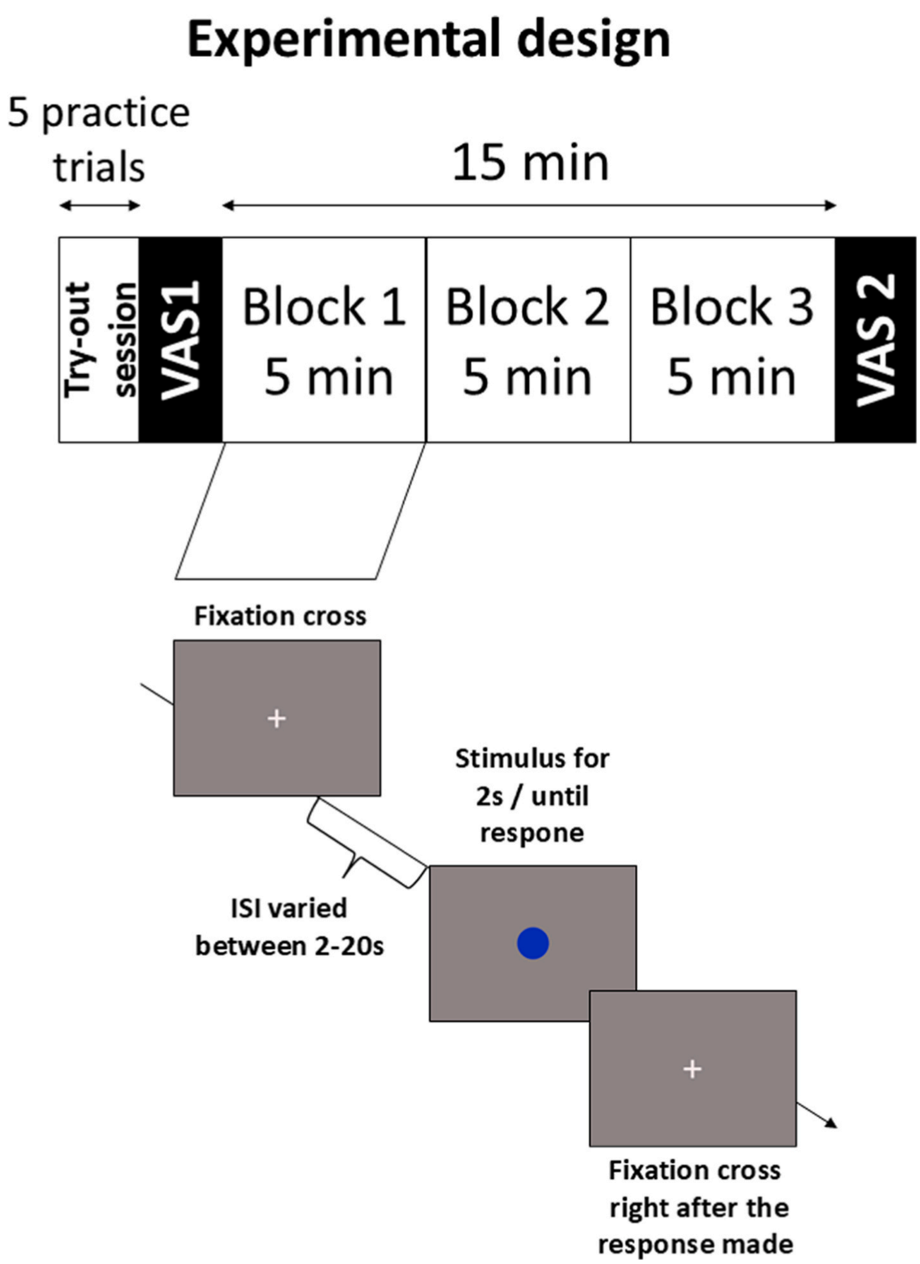

Fig. 1. Schematized sequence and experimental design of the Psychomotor Vigilance Task (PVT) during the fMRI measurement. We used the 15 min long version of the PVT, that comprised three, 5-min long blocks of trials (Block 1, Block 2, and Block 3). Before the fMRI measurement, subjects performed a try-out session in the scanner, which comprised five practice trials. Each trial began with a white fixation cross presented in the middle of the screen. After a pseudo-random inter-stimulus interval (ISI), a blue circle was presented until 2 s passed or a response was made by the subject. Subjects reported their current sense of acute mental fatigue on a Visual Analogue Scale (VAS) before (VAS1) and after (VAS2) the PVT. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

alpha is 0.93) and test-retest reliability in healthy and depressed adults (Beck et al., 1996). In the current sample, internal consistency was acceptable (Cronbach alpha is 0.77).

2.2.4. Spielberger Trait Anxiety Inventory (STAI-T)

The STAI-T was used to assess the trait-level anxiety of the participants (Spielberger, 1983). The 20-item STAI-T is a widely used measure of how ‘generally anxious’ a person feels. Higher scores indicate greater trait anxiety. The test has good internal reliability (Cronbach alpha is 0.88) as reported by Campbell (Campbell, 2009). In the current sample, internal consistency was excellent (Cronbach alpha is 0.91).

2.3. Stimuli

2.3.1. Psychomotor Vigilance Task

The PVT was used to induce higher levels of AMF, and AMF-related neural mechanisms through the ToT effect. The PVT is often used in fatigue research because it is very sensitive to fatigue (Sun et al., 2014) and is a cognitively demanding task that requires a high level of cognitive control (Lim et al., 2012).

Presentation software (Neurobehavioral System, Inc., Berkley, CA, USA) was used to present the PVT during fMRI measurement. The task was presented on an MRI-compatible display system (Cambridge Research Systems Ltd, BoldScreen 24’, Rochester, UK) by means of a mirror attached to the head coil. During the PVT, each trial began with a white fixation cross on a grey background presented in the middle of the screen. After a pseudo-random inter-stimulus interval that varied across trials ranging between 2 and 20 s, a blue circle was presented until 2 s passed or a response was made by the participant. Responses from the participants were collected via MR-compatible response buttons (ResponseGrip, NordicNeuroLab AS, Bergen, Norway). The participants were instructed to press a button with their right thumb as soon as possible when the blue circle appeared on the screen.

2.4. Experimental design

Before the fMRI measurement, the participants performed a practice session in the scanner, which comprised five practice trials. After this, the participants reported their current level of subjective AMF on a Visual Analogue Scale (VAS) by moving a slider from 0 (‘no fatigue at all’) to 10 (‘very severe fatigue’) (VAS1 scores).

The PVT comprised three, 5-min blocks of trials (B1, B2, and B3). The order of inter-stimulus intervals over trials of blocks was identical within and between the participants, but they were not informed about this invariance, nor were they aware of it based on self-reports. After the third experimental block, the level of subjective AMF was recorded again using the VAS (VAS2 scores). RTs were recorded for each trial. ToT-induced changes in task performance were defined as the mean difference in the RT between B3 and B1. The changes in subjective AMF were calculated by subtracting the first VAS score from the second one (VAS2 – VAS1). For more details about the experimental design of the PVT, see Fig. 1.

2.5. Experimental procedure

In the first step (Step 1) of the study, we randomly chosen eighty-two participants according to our inclusion criteria (age >18, no possible comorbid addictions such as smoking, substance use disorder, alcohol use disorder, and no potential MRI safety risks e.g. metal implant) from a previously completed online Google form described above. After the inclusion process, we invited each selected participant to the test session (Step 2). Prior to each examination, we described the assessments and the methods of the investigation (applied questionnaires, MRI sequences and the PVT paradigm), informed them of the MR safety protocols. In the Step 3, the participants completed a brief test battery on a tablet, consisting of demographic questions, STAI-T, BDI, PIUQ, FIS, and

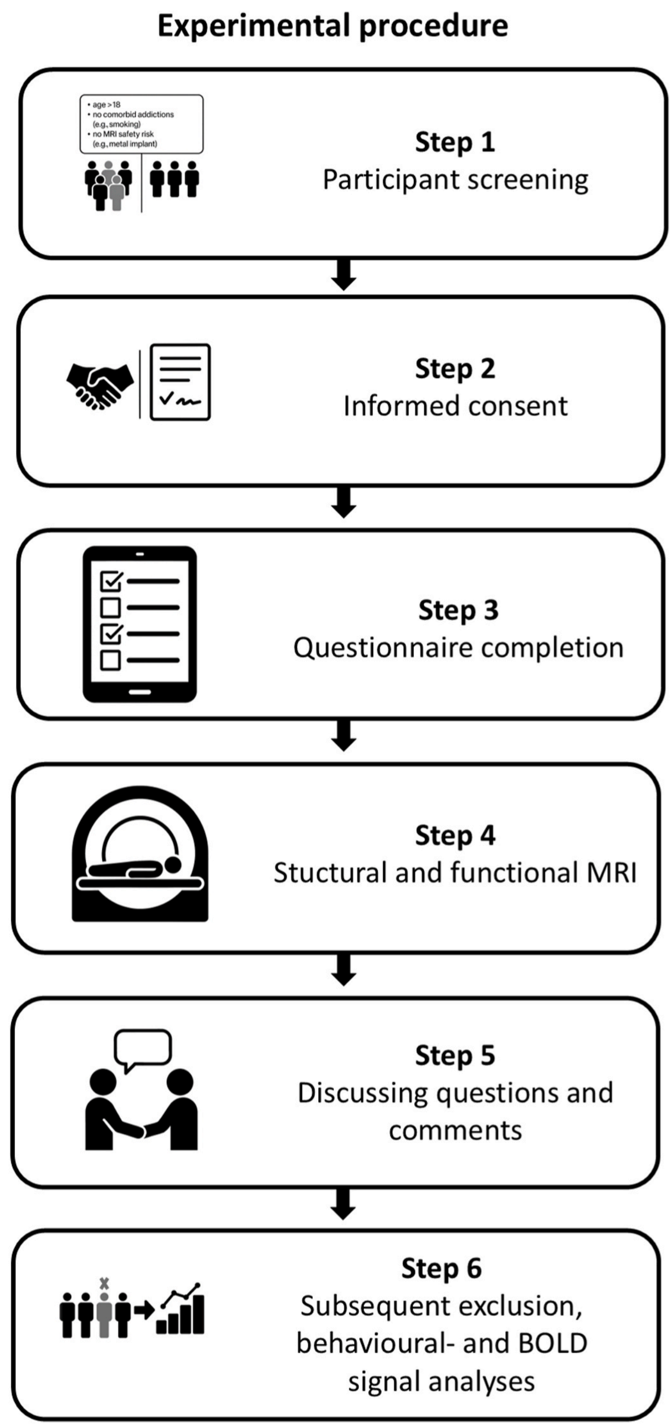

Fig. 2. Schematized sequential steps of the experimental procedure. Step1: Recruit subjects for the research, based on the pre-defined inclusion criteria. Step 2: Present the research methodology and tools to the participants. Step 3: Complete of the short test battery. Step 4: Structural MRI and fMRI (during PVT implementation) measurements. Step 5: Discuss any questions that may have arisen with the participants. Step 6: Post hoc exclusion based on the behavioural data, followed by questionnaire and BOLD signal analyses. BOLD- Blood-oxygen-level-dependent.

questions about the last night’s sleep duration (time to get up and go to bed) and quality. This step was followed by the structural MRI sequence, and the functional MRI (Step 4). In the next section (Step 5), if the participant had any questions or comments about the research (e.g. test battery, MRI paradigms etc.), these were discussed and small fee was given to them. This was followed by the final part (Step 6), in which a preliminary processing of the questionnaire data was performed, based on which some subjects (N = 11) were subsequently excluded from the further analyses due to severe depression scores or insufficient sleep time. After that, we conducted the statistical analyses of the behavioural and fMRI data related to our research questions. The sequential steps of the experimental procedure are shown in Fig. 2.

2.6. Imaging data acquisition and visual analysis

All measurements were performed on a 3T Magnetom PrismaFit human whole-body scanner (SIEMENS Healthcare, Erlangen, Germany) with a 20-chanel head coil.

Functional images for the PVT were acquired using a 2D single-shot echo-planar imaging (EPI) sequence with the following parameters: repetition time (TR)/Echo time (TE) = 2000/30 ms; flip angle (FA) = 76°; 36 axial slices with a thickness of 3 mm, no gap, interleaved slice order to avoid crosstalk between contiguous slices; field of view (FOV) = 210 × 210 mm^2; matrix size = 70x70; receiver bandwidth = 2040Hz/pixel.

For distortion correction purposes, field mapping sequence (TR/TE1/TE2 = 400/4.92/7.38 ms; FA = 60°; 36 axial slices; slice thickness = 3 mm, distance factor = 25 %; FOV = 210 × 210 mm^2; matrix size = 70 × 70; receiver bandwidth = 290 Hz/pixel) with the same orientation and adjustment parameters as the fMRI scan was acquired right after the fMRI measurement.

Anatomical images were obtained using the T1-weighted 3D magnetisation-prepared rapid gradient echo (MPRAGE) sequence (TR/TI/TE = 2530/1100/3.41 ms; FA = 7°; 176 sagittal slices with thickness of 1 mm; FOV = 256 × 256 mm^2; matrix size = 256 × 256; receiver bandwidth = 200 Hz/pixel). The MPRAGE anatomical and the functional images were visually checked by MRI experts. There were no brain abnormalities according to the visual analysis of the MR images.

2.7. fMRI data pre-processing

Pre-processing steps and additional statistical analyses were performed using the freely available FMRI Expert Analysis Tool (FEAT) version 6.0, part of FMRIB's Software Library (FSL; www.fmrib.ox.ac.uk/fsl).

Pre-processing steps included MCFLIRT motion correction (Jenkinson et al., 2002), brain extraction (Smith, 2002), spatial smoothing (Gaussian kernel, 5 mm full width at half maximum), EPI distortion correction with FSL FUGUE (Jenkinson, 2004), and high-pass temporal filtering with a 90-s cut-off. Single-session data sets were registered into the MNI152 standard space, using a two-step process. First, the EPI image of each participant was registered to that participant's high-resolution T1-weighted structural scan using Boundary-Based Registration (BBR, 6 degrees of freedom [DOF]) (Greve & Fischl, 2009), which includes simultaneous distortion correction combined with the FUGUE tool. Then, each participant's T1 image was registered to the 2-mm MNI152 standard space using a 12 DOF linear fit followed by FMRIB's non-linear image registration approach (FNIRT; warp resolution = 8 mm) (Andersson et al., 2008). Next, for each participant, these two registrations were combined and applied to the first-level statistical maps to take them into standard space.

2.8. Blood-oxygen-level-dependent (BOLD) signal analysis

Since the primary aim of the present study was to obtain a comprehensive view of the ToT-induced changes in AMF and its' neural underpinnings in PIU, we used BOLD signal analysis to evaluate AMF-related changes in brain activity during the PVT. As a first step of the BOLD signal analysis, we explored the subject-level changes in neural activity during the PVT (Stage 1), and their subject-level increases and decreases induced by the AMF (ToT effect) (Stage 2). In the next part, we implemented a group-level regression analysis to see if these subject-level increases or decreases in the neural activity were associated with PIU severity (Stage 3). Subsequently, we used a group-level post hoc analysis to investigate whether the PIU-dependent neural changes from Stage 3 were due to the ToT-effect per se (Stage 4). Finally, a group-level regression analyses were performed to determine, whether the PIU and ToT effect-dependent neural changes were associated with the subjective and objective characteristics of AMF (Stage 5). A more detailed description of the BOLD signal and post hoc analyses is provided below.

Stage 1 – The whole brain general linear model (GLM) time-series statistical analyses of individual data sets were carried out using FMRIB's Improved Linear Model (FILM, part of the FSL) with local autocorrelation correction. (a) The 15-min fMRI time series of PVT was split into three 5-min blocks (B1, B2, and B3, in accordance with the experimental blocks of the task) for each participant. Each block contained 150 scans. (b) First-level analyses were implemented separately for the B1 and B3 blocks. Both analyses included one regressor: subjects' RTs for each trial in the B1 or B3 blocks. The two first-level analyses generated contrast images of the parameter estimate (PE) for the task regressor for each participant.

Stage 2 – Since we were interested in the brain changes (both increases and decreases in BOLD signal) during the PVT, COPE images were calculated for the pre-specified contrasts (B3 > B1 and B1 > B3), separately for each participant, using fixed-effect analysis.

Stage 3 – In the second-level analysis, we aimed to investigate whether the ToT-induced changes in the BOLD signal were related to the extent of PIU. Group-level, mixed-effect regression analyses were

Table 1
Descriptive statistics and Spearman's rank correlations' results of behavioural data. Spearman's rank correlation coefficients (rho) are presented; V-Variables; PIUQ–Problematic Internet Use Questionnaire; BDI-Beck Depression Inventory; STAI-T-Spielberger Trait Anxiety Inventory; FIS-Fatigue Impact Scale; RT-reaction time in msec; VAS-Visual Analogue Scale; *$p < 0.05$, **$p < 0.01$.

V	Median (min-max)	PIUQ total	PIUQ obsession	PIUQ neglect	PIUQ control	BDI	STAI-T	FIS	Sleep quality	RT difference (msec)	VAS difference
PIUQ total	31 (18–51)	–	0.732**	0.881**	0.917**	0.294*	0.278*	0.452**	−0.153	0.118	0.338**
PIUQ obsession	8.50 (6–17)	–	–	0.504**	0.525**	0.178	0.153	0.397**	−0.158	0.093	0.324**
PIUQ neglect	11 (6–20)	–	–	–	0.733**	0.230	0.289*	0.390**	−0.231	0.154	0.303*
PIUQ control	10 (6–22)	–	–	–	–	0.281*	0.248*	0.341**	−0.041	0.092'	0.277*
BDI	4 (0-16)	–	–	–	–	–	0.600**	0.490**	−0.110	0.039	0.237*
STAI-T	37 (21–65)	–	–	–	–	–	–	0.457**	−0.080	−0.062	0.134
FIS	22 (0–105)	–	–	–	–	–	–	–	−0.130	−0.027	0.156
Sleep quality	5 (3–7)	–	–	–	–	–	–	–	–	0.181	0.221
RT difference (msec)	32.41 (−22.91-129.89)	–	–	–	–	–	–	–	–	–	0.302*
VAS difference	1 (-2 -4)	–	–	–	–	–	–	–	–	–	–

According to the results of multiple linear regressions, the PIUQ total scores independently predicted the VAS difference [$\beta = 0.349$, $t(70) = 2.935$; $p = 0.005$], when the effects of the BDI and STAI-T were controlled.

implemented separately to investigate the association between the PIUQ total scores and the subject-level mean changes in the B3 > B1 and B1 > B3 contrasts. Regression analyses were carried out using FMRIB's Local Analysis of Mixed Effects (FLAME; stage 1). Statistical maps were considered to be significant at Z > 2.3 and a familywise error–corrected cluster significance threshold of p = 0.05 (Worsley, 2001). The BDI and STAI-T scores were used as covariates because there were strong positive associations between the PIUQ, BDI, and STAI-T scores in the sample (see Table 1 for the Spearman's rank correlation results).

Stage 4 – We then sought to confirm that the clusters which were found to be associated with PIU in Stage 3 are influenced by the ToT effect per se. (a) Binarized cluster masks from Stage 3 were used in the FSL Featquery (Mumford, 2014) to separately extract each participant's mean PE value from the subject-level COPE images of the B1 and B3 blocks. The PE values correspond to the magnitude of the task-evoked brain activation/deactivation. (b) Then, the difference between PE values was tested using the Wilcoxon signed-rank test to investigate the effect of ToT on the changes in BOLD signal within the clusters (see the 'Statistical analysis' subsection).

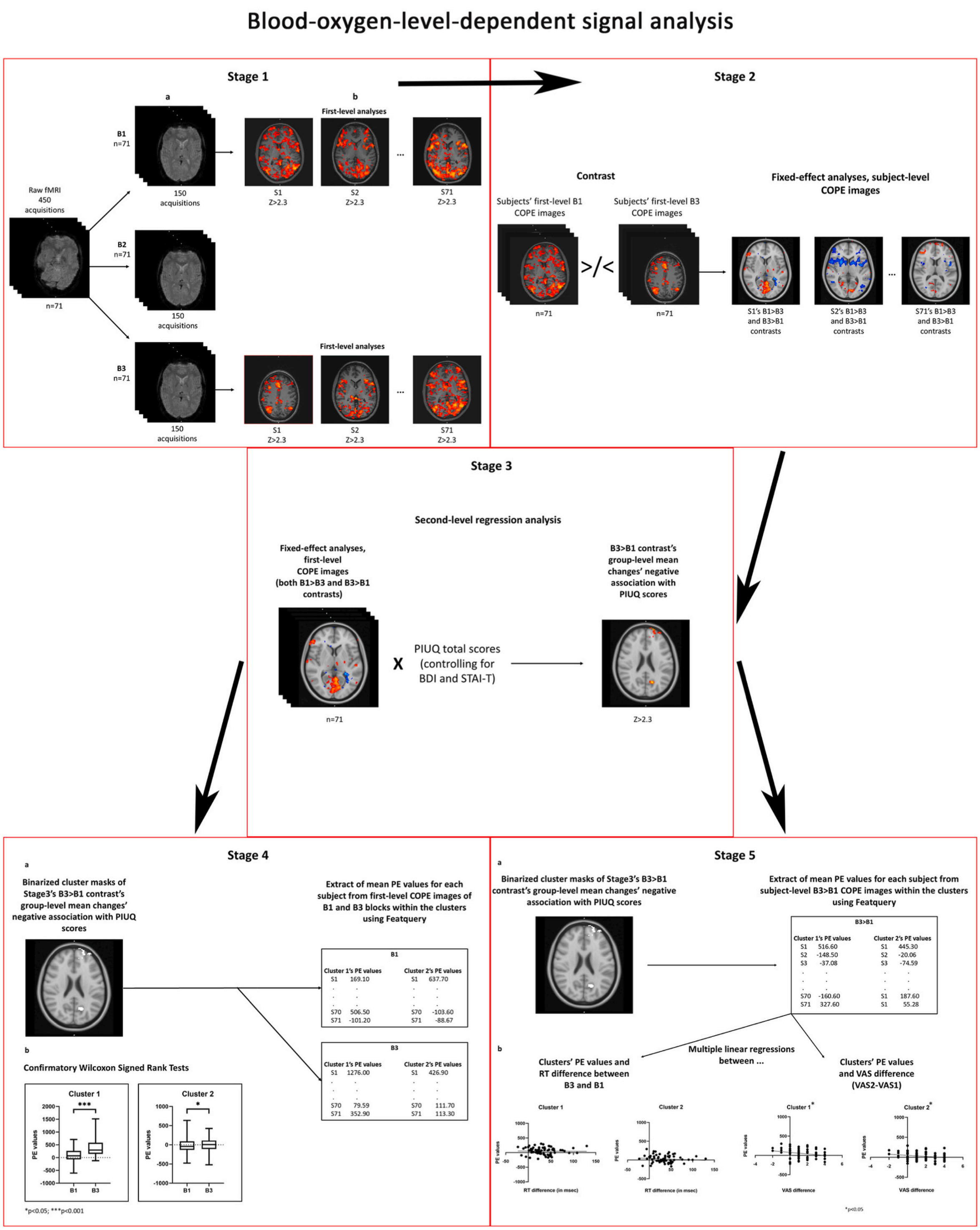

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Fig. 3. Blood-oxygen-level-dependent (BOLD) signal analysis. Schematic design of the analysis.

Stage 1: (a) First, the 15-min fMRI time series of the Psychomotor Vigilance Task (PVT) was split into three blocks (B1, B2, and B3, in accordance with the experimental blocks of the task) for each participant. **(b)** Then, first-level analyses were implemented on B1 and B3 blocks. For visualisation purposes, statistical maps were considered to be significant at $Z > 2.3$ and a family wise error corrected cluster significance threshold of $p = 0.05$.
Stage 2: COPE images were calculated of the time-on-task (ToT)-induced changes in BOLD signal (for decreases B1 > B3 [indicated by blue-light blue colours] and for increases B3 > B1 [indicated by red-yellow colours]); separately for each subject, using fixed-effect analysis.
Stage 3: Second level analyses then examined the associations between ToT-induced changes in BOLD signal and levels of problematic Internet use (PIU). BDI and STAI-T scores were used as covariates. Similar to Stage 2, the red-yellow colours indicate an increase in BOLD signal.
Stage 4: We confirmed that the clusters which were found to be associated with PIU in Stage 3 are influenced by the ToT. **(a)** Cluster masks form Stage 3 analyses were used to separately extract each subject's mean parameter estimate (PE) value from the first-level COPE images of B1 and B3 blocks. **(b)** Wilcoxon signed rank tests were used to compare the mean PE values of the clusters between B1 and B3 to investigate the effect of ToT on the changes in BOLD signal within the clusters.
Stage 5: We explored the relationship between the clusters which were found to be associated with PIU in Stage 3 and the changes in subjective mental fatigue and task performance. (a) Cluster masks from Stage 4 were used to extract each subject's mean PE values regarding the subject-level B3 > B1 contrast. (b) Then, multiple linear regression analyses were used to reveal associations between ToT- and PIUQ related BOLD signalchanges and the extent of changes in subjective acute mental fatigue (differences in VAS scores) and performance changes (RT difference between B3 and B1).

PIUQ- Problematic Internet Use Questionnaire; BDI- Beck Depression Inventory; STAI-T Spielberger Trait Anxiety Inventory; RT-reaction time; VAS- Visual Analogue Scale; S1- Subject One, S2- Subject Two; S3- Subject Three; S71- Subject Seventy-one; C1- Cluster 1; C2- Cluster 2.

Stage 5 – In the next step, we intended to explore the associations between the changes in BOLD signal in Clusters 1 and 2, which were found to be associated with PIU in Stage 3, and the changes in subjective mental fatigue and task performance. (a) A similar approach was applied as in Stage 4: binarized cluster masks from Stage 3 were used in FSL Featquery to extract the mean PE value for each participant from the second-level COPE images from Stage 2 (the B3 > B1 contrast). Here, the PE values correspond to the magnitude of the task-evoked changes in the BOLD signal within the brain areas that were associated with PIU. (b) The associations between the clusters' mean PE values and the changes in task performance and subjective AMF were tested with multiple linear regression analyses (see the 'Statistical analysis' subsection). See Fig. 3 for details of the steps in the BOLD signal analysis.

3. Statistical analysis

Statistical analyses for the behavioural results were performed using SPSS Statistics for Windows 27.0 (IBM Corp, Armonk, NY, USA). Because none of the behavioural data showed a normal distribution, Wilcoxon signed-rank and Friedman tests were used to determine whether the PVT successfully induced fatigue via the ToT effect. Differences in VAS scores (with Wilcoxon test) and mean RTs across the three blocks (with Friedman test) were investigated separately. Spearman's rank correlation was used to investigate the associations between task performance decrease, VAS difference, and the questionnaire scores (PIUQ total, FIS total, BDI, STAI-T, and sleep quality).

In accordance with the correlation results, multiple linear regression analyses were performed to predict the changes in subjective AMF based on the severity of PIU. In the model, the dependent variable was the change in subjective AMF, while the independent variable was the PIUQ total score. The BDI and STAI-T scores were used as covariates to control for their effects. Outliers, independence, the normality assumptions of the residuals, and homoscedasticity were checked during the analyses (Chan, 2004). There were no outliers according to the results of the regression analyses. A p-value <0.05 was considered to be significant.

In Stage 4, the Wilcoxon signed-rank test was used to confirm whether the clusters which were found to be associated with PIU in Stage 3 were also influenced by the ToT effect per se.

In Stage 5, multiple linear regression analyses were used to reveal associations between the ToT- and PIU-related changes in the BOLD signal, and subjective AMF changes and the task performance changes. In the model, the dependent variable was the change in subjective mental fatigue or the change in task performance, while the independent variable was the ToT-induced and PIU-related change in the BOLD signal from the significant clusters of Stage 3. Due to the association between AMF, CMF, depression and anxiety, the FIS, BDI and STAI-T scores were used as covariates to control for their effect. Following the outlier screening, two participants were excluded prior to the analyses (one per analysis) based on exceptional changes in the subject-level BOLD signal within the significant clusters of Stage 3.

4. Results

4.1. Behavioural results

The Wilcoxon signed-rank test for changes in subjective AMF revealed that the level of fatigue was significantly higher after the PVT (VAS2 median = 4; min–max = 1–10) than before (VAS1 median = 3; min–max = 0–7) ($Z = -5.74$; $p < 0.001$). Similarly, the Friedman test for changes in task performance showed that mean RTs increased across the blocks (first block: median = 269.39 ms; min–max = 219.30–350.33 ms; second block: median = 288.30 ms; min–max = 223.58–387.15 ms; and third block: median = 300.65 ms; min–max = 238.15–441.00 ms) ($\chi^2 (2) = 80.648$; $p < 0.001$). The analysis of both behavioural and self-reported data indicated an increased level of fatigue induced by ToT.

The descriptive statistics and Spearman's rank correlation results are presented in Table 1. The BDI scores showed positive correlations with the STAI-T, PIUQ total, and FIS total scores, and the VAS difference. The STAI-T scores showed positive correlations with the PIUQ total, FIS total, and BDI scores. The FIS total scores showed positive correlations with the PIUQ total, BDI, and STAI scores. The VAS difference showed positive correlations with the BDI and PIUQ total scores, and with the changes in task performance. Performance changes were not correlated with the questionnaire scores, only with the VAS difference. Sleep quality scores showed no correlations with other behavioural data.

4.2. BOLD signal analysis results

There were negative associations between the ToT-induced changes in the BOLD signal (the B3 > B1 contrast) and the total PIUQ scores in the left PCu (Cluster 1) and in the left medial (MeFG), middle (MFG) and superior (SFG) frontal gyri (Cluster 2). The results of the second-level regression analysis are shown in Supplementary Table 1 and Fig. 4.

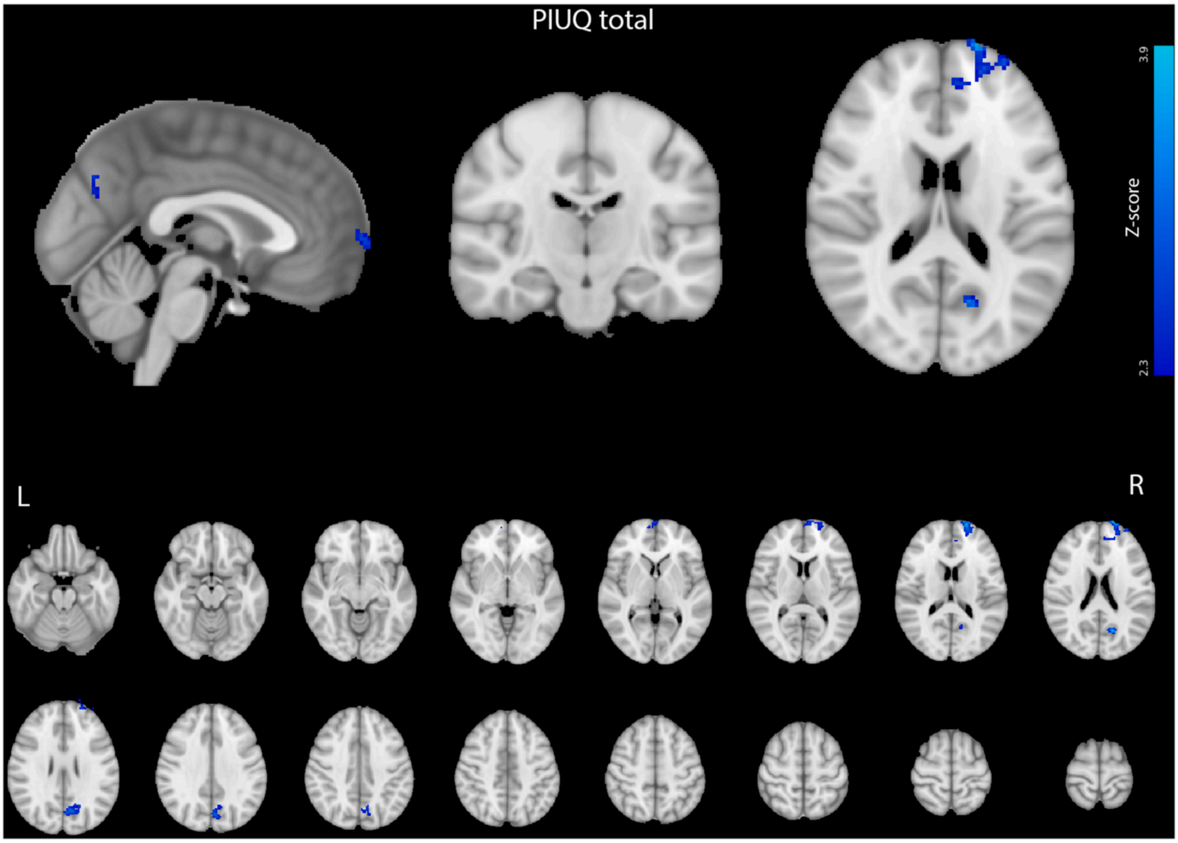

Fig. 4. Negative associations between BOLD signal changes from the first to the third block, and PIUQ total scores. Blue-light blue colour bar indicates negative associations between the scores of PIUQ total and the changes in BOLD signal. The figure was thresholded using cluster determined by Z > 2.3 and a corrected cluster significance threshold of p = 0.05.; Axial slices are shown in radiological convention.; PIUQ -Problematic Internet Use Questionnaire. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.3. Post hoc analysis results of clusters 1 and 2 from stage 3

According to the post hoc Wilcoxon signed-rank test results for Stage 4, we confirmed that the PE values within Cluster 1 ($Z = -5.38$; $p < 0.001$) and Cluster 2 ($Z = -2.10$; $p = 0.035$) showed significant differences between B1 and B3. In other words, the BOLD signal within the regions associated with the PIUQ also changed with the ToT effect (Supplementary Fig. 1).

4.4. Associations between the ToT- and PIU-related BOLD signal and changes in fatigue

We explored associations between ToT- and PIU-related changes in the BOLD signal from Cluster 1 and 2, and the changes in subjective fatigue and task performance. According to the results of the multiple linear regressions, the PE values within the clusters did not predict the ToT-induced changes in RT [Cluster 1: $n = 70$; $\beta = -0.039$, $t(69) = -0.317$; $p = 0.752$; Cluster 2: $n = 70$; $\beta = -0.120$, $t(69) = -0.989$; $p = 0.326$]. On the other hand, PIU- and ToT-related BOLD signal changes within the clusters independently predicted the VAS difference [Cluster 1: $n = 70$; $\beta = -0.298$, $t(69) = -2.547$; $p = 0.013$; Cluster 2: $n = 70$; $\beta = -0.237$, $t(69) = -2.034$; $p = 0.046$], when the effects of FIS, BDI and STAI-T were controlled.

4.5. Summary of the behavioural and fMRI results

Taken together, we found that the extent of PIU independently predicts the changes in subjective AMF induced by a cognitively demanding task. Similarly, we found a positive association between PIU and CMF. In addition, the greater the PIU, the smaller the ToT-induced change in the BOLD signal in the left PCu, left MFG, left MeFG, and left SFG during task performance. Furthermore, negative associations suggest that the smaller the PIU-related change in the BOLD signal within the left PCu, left SFG, MFG, and MeFG, the greater the change in subjective AMF.

5. Discussion

Given the lack of prior research in this area, our primary aim was to obtain a comprehensive view of the PVT-induced changes in AMF in PIU. We used task-based fMRI during the performance of the PVT to investigate whether PIU- and ToT-related changes in the BOLD signal are related to AMF characteristics.

The positive correlation between the FIS and PIU confirms previous findings on the association between PIU and CMF (Aziz et al., 2024; Bachleda & Darhiri, 2018; Bener et al., 2019; Liang et al., 2022; Lin et al., 2013). The correlational findings between the BDI, PIUQ obsession, and FIS total scores may complement previous findings and assumptions on the field, which state that the level of depression (based on the BDI) (Fava et al., 2014; Young & Rogers, 1998) and withdrawal symptoms (based on the PIUQ obsession subscale) (Aziz et al., 2024; Tiffany, 1999) may play a role in the association between PIU and CMF. Contrary to our assumption, we found that CMF and PIU, were not related to perceived sleep quality, so sleep quality did not play a role in the association between CMF and PIU in our sample.

The PVT successfully induced AMF with increasing ToT, as reflected in slower RTs and increased levels of subjective AMF. At present, this is the first study to find that the severity of PIU predicts the changes in subjective AMF induced by a cognitively demanding task. There was no association between the changes in task performance and PIU, therefore we assume that the level of PIU does not affect the changes in performance. Instead, participants with higher PIU scores are likely to feel more fatigued after a prolonged task. A possible explanation for this could be the presence of high levels of craving in people with PIU in the absence of their devices. In line with the correlation between the PIUQ obsession subscale (which mainly corresponds to craving) and VAS2 – VAS1 scores, it is conceivable that similarly to the relationship between CMF and PIU (Aziz et al., 2024), the presence of the energy-intensive craving symptoms make people with PIU feel more challenged to perform a cognitively demanding task, and they may perceive themselves as more fatigued after performance. It is also possible that the increased readiness for Internet-related cues (e.g., a kind of standby mode for smartphone notifications) could influence the association (Johannes & Verwijmeren, 2018). This readiness could also affect task performance and the subjective AMF level after a demanding task (Jacquet et al., 2023; Johannes & Verwijmeren, 2018), as it could reduce cognitive capacity (Ward et al., 2017). There was a weak positive correlation between the BDI and VAS2 – VAS1 scores, therefore, the role of depression should not be ignored in subsequent research, as depression is frequent symptom in PIU (Young & Rogers, 1998). Based on our results, it may appear that craving plays a role in the association between fatigue and PIU, both task induced and long term, but additional studies are needed to confirm and clarify its role in the associations.

We found significant negative associations between the ToT-induced changes in the BOLD signal within the left PCu (Cluster 1) and the left MeFG, MFG, and SFG (Cluster 2), and the PIUQ total scores. In addition, the ToT- and PIU-related changes in the BOLD signal within these clusters negatively associated with the changes in subjective AMF, i.e. decreasing BOLD signal is associated with greater subjective AMF. According to our results, it is conceivable that the association between PIU and the changes in subjective AMF may be related to the BOLD signal changes within the clusters, suggesting that the functioning of these areas may be play a role in the increased susceptibility to subjective AMF in PIU. The PCu is responsible for self-referential processes (Cavanna & Trimble, 2006; Lyu et al., 2021), such as the perception of subjective AMF (Cook et al., 2007; Staud et al., 2018). More specifically, participants with CFS showed reduced regional cerebral blood flow in the PCu, which associated negatively with the subjectively perceived AMF level after a cognitively demanding task (Staud et al., 2018). Similarly, there was a negative association between the level of subjective AMF and the task-induced brain activation in the left PCu in participants with CFS (Cook et al., 2007). In addition, greater task-related increases in subjective AMF correlated negatively with the bilateral PCu thickness in healthy young participants (Matuz et al., 2023). Based on prior research, the SFG, MeFG, and MFG are also associated with task-related fatigue (Caseras et al., 2008; DeLuca et al., 2008; Matuz et al., 2023; Sepulcre et al., 2009). In a study of patients with multiple sclerosis (DeLuca et al., 2008), task-induced performance decrements correlated positively with activation changes within the SFG, MeFG, and MFG. In another study, there was a significant group difference in the activation increase in the MFG due to AMF induction between patients with CFS and healthy controls (Caseras et al., 2008). Additionally, left SFG thickness was associated negatively with increases in subjective AMF during a cognitively demanding task (Matuz et al., 2023).

It is also important to note that functional alterations in the PCu and frontal regions have previously been found to be associated with the severity of craving and withdrawal in Internet-related behavioural disorders (Dong et al., 2021; Zhang, Hu, Li, et al., 2020; Zhang, Hu, Wang, et al., 2020; Zhou et al., 2021) as well as with major depression (Zhang et al., 2018). These findings support our theoretical assumption that the severity of depression and craving symptoms is involved in the relationship between PIU and changes in subjective AMF. Indeed, people with PIU show altered functioning in these regions, associated with disrupted reward (Yuan et al., 2011), cognitive control (Darnai et al., 2019; Dong et al., 2012), and executive (Dong et al., 2014) processes. Moreover, these higher-level alterations contribute to the development and maintenance of Internet-related behavioural problems (Brand et al., 2016, 2019). Considering all the evidence mentioned above, our findings suggest that task-related changes in subjective AMF may also be associated with PIU, and that the functioning of the PCu, SFG, MFG, and MeFG may play a role in the increased susceptibility to subjective AMF, in addition to their important role in the pathogenesis of PIU.

There are some limitations to our study that need to be considered. First, our sample did not include many individuals with extremely high scores on the PIUQ, so it would be worthwhile to replicate the study with a sample that better represents the population. Second, the most plausible explanation for the lack of association between PIU, CMF and sleep quality is that the majority of participants reported high sleep quality levels; thus, individuals with poor sleep quality were underrepresented in this study. Third, as PIU is associated with CMF, moreover CMF may also affect AMF (Fang et al., 2008; Hanzal et al., 2024; Hess & Knight, 2021) and has similar neural underpinnings as AMF, in vain we controlled for the effect of CMF in post hoc multiple linear regressions, the aforementioned associations must be considered when interpreting the results, and therefore our findings and their explanations must be treated with caution. Finally, the cross-sectional nature of the study limits our ability to distinguish cause and effect in the associations. We do not know whether altered brain functioning behind PIU leads to a greater AMF, or vice versa. Longitudinal studies are needed to better understand the nature of the association.

In conclusion, we found that the severity of PIU predicts the changes in subjective AMF induced by a cognitively demanding task. Our results indicate that participants with higher PIU level are likely to feel more fatigued after a prolonged task. We also revealed task- and PIU-dependent functional changes within the left PCu, SFG, MFG, and MeFG. The changes within these regions associated negatively with the changes in subjective AMF, leading us to conclude that we were able to describe that the functioning of these regions play a role in the increased susceptibility to subjective AMF. This susceptibility to AMF could pose numerous risks, including a negative impact on psychological well-being. Increased fatigue can be associated with various comorbid symptoms (e.g., depression, anxiety, and poor sleep), so it is important to place appropriate emphasis on recreational activities to maintain mental health and functioning. Nevertheless, the current findings highlight that, in addition to the well-known impairments in cognitive functions, task-related subjective AMF may also be associated with PIU.

CRediT authorship contribution statement

Ákos Arató: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Anna Tímea Szente:** Data curation, Writing – review & editing. **András Matuz:** Formal analysis, Methodology, Writing – review & editing. **Eszter Áfra:** Data curation. **Husamalddin Ali Alhour:** Writing – review & editing. **Gábor Perlaki:** Data curation, Formal analysis, Methodology, Writing – review & editing. **Gergely Orsi:** Data curation, Formal analysis, Writing – review & editing. **Gréta Szabó:** Data curation, Writing – review & editing. **Barnabás Dudás:** Writing – review & editing. **Szilvia Anett Nagy:** Writing – review & editing. **Norbert Kovács:** Supervision. **Árpád Csathó:** Conceptualization, Methodology, Writing – review & editing. **József Janszky:** Conceptualization, Supervision, Writing – review & editing. **Gergely Darnai:** Conceptualization, Data curation, Formal analysis, Supervision, Writing – review & editing.

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors did not use AI and AI-assisted technologies in the writing process.

Declaration of competing interest

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

Acknowledgment

This study was supported by the Hungarian Brain Research Program 2017-1.2.1-NKP−2017-00002 government-based fund. Our research was partly financed by the Higher Education Institutional Excellence Program of the Ministry of Human Capacities in Hungary, within the framework of the 5th thematic program of the University of Pécs, Hungary (20765/3/2018/FEKUSTRAT), by the National Research, Development and Innovation Fund of Hungary's Thematic Excellence Programmes [TKP2021-EGA-16] and [TKP2021-EGA-13] and by the National Laboratory of Translational Neuroscience, within the program of "Adult Nervous System Disorders-RRF-2.3.1-21-2022-00011" framework. Á.A. was supported by the University Research Scholarship Program (EKÖP-24-4-I-PTE-38) by National Research, Development and Innovation Fund of Hungary. S.A.N. was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. J.J. was supported by National Research, Development and Innovation Fund of Hungary (NKFIH-K142479). Similarly, Á.C., A.M. and G.D. were supported by a National Research, Development and Innovation Fund (NKFIH-K1422321).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chbr.2025.100728.

Data availability

Data will be made available on request.

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