


AKADÉMIAI KIADÓ

Journal of Behavioral Addictions

9 (2020) 1, 58-70

DOI:
10.1556/2006.2020.00010
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Inhibitory control and problematic Internet-pornography use – The important balancing role of the insula

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Received: July 12, 2019 • Revised manuscript received: December 20, 2019; January 30, 2020 • Accepted: February 5, 2020 • Published online: April 7, 2020

FULL-LENGTH REPORT



ABSTRACT

Background and aims: Diminished control over a specific behavior is a core characteristic in addictive behaviors such as problematic Internet-pornography (IP) use. First studies suggest that a hyperactivity of the impulsive system is one reason for impulsive behaviors in the context of problematic IP use. The tripartite-process theory of addiction explains neurocognitive mechanisms beyond common dual-process theories in addictive behaviors. However, the role of the reflective and interoceptive system is still unresolved. *Methods:* The study comprised a stop-signal task (SST) including neutral and pornographic images during fMRI and questionnaires to investigate associations between symptoms of problematic IP use, craving, and neural activity of the impulsive, reflective, and interoceptive system. We examined 28 heterosexual males with varying symptom severity of problematic IP use. *Results:* Data indicates that individuals with more symptoms of problematic IP use showed better performance in the SST which was linked to decreased insula and inferior frontal gyrus activity during pornographic image processing. An increase in craving was associated with lower activity of the ventral striatum during pornographic image processing. The interoceptive system showed varying effects. Increased insula activity during inhibitory control and decreased activity during pornographic image processing were associated with higher inhibitory control performance. *Discussion and Conclusion:* Effects of tolerance and motivational aspects may explain the better inhibitory control performance in individuals with higher symptom severity which was associated with differential activity of the interoceptive and reflective system. Diminished control over IP use presumably results from the interaction between the impulsive, reflective, and interoceptive systems.

KEYWORDS

compulsive sexual behavior, cybersex addiction, dual process theory, Internet use disorder, pornography

INTRODUCTION

The unregulated or problematic use of Internet pornography (IP) is characterized by an intense urge to use IP, a diminished control over the use, and a continued use of IP despite experiencing negative consequences (Wéry & Billieux, 2017). Prevalence estimates from Australia and Europe vary between 0.1 and 5% for women and 2–13% for males, and indicate that especially males seem to be affected (Ballester-Arnal, Castro Calvo, Gil-Llario, & Gil-Julia, 2017; Rissel et al., 2017; Ross, Mansson, & Daneback, 2012). These estimates presumably show a high variance since there are no official diagnostic criteria for problematic IP use up to now. Furthermore, there is an ongoing debate if and under which category it should be classified (Gola & Potenza, 2018; Kraus & Sweeney, 2018; Walton & Bhullar, 2018). Problematic IP use often appears as one manifestation of compulsive sexual behavior (Reid et al., 2012) which was currently included in 11th revision of the International Classification of Diseases for Mortality and Morbidity Statistics in the section of impulse control disorders

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(code: 6C72; World Health Organization, 2019). Some authors, however, emphasize phenomenological and neurobiological parallels to disorders due to addictive behaviors (Kraus et al., 2018; Stark, Klucken, Potenza, Brand, & Strahler, 2018; Wéry & Billieux, 2017). Regardless of the discrimination between both classifications in the ICD-11, both - impulse control disorders and behavioral addictions - share not only common phenomenological but also neurobiological similarities with substance-use disorders such as the critical role of the imbalance between the impulsive (mainly ventral striatum, amygdala) and reflective brain system (mainly dorsolateral and inferior prefrontal cortex) (Bechara, 2005; Brett, Anton, Valabregue, & Poline, 2002; Zheng et al., 2019). Therefore, the current study aimed at investigating the role of the reflective, impulsive, and interoceptive system in the context of problematic IP use.

In the Interaction of Person-Affect-Cognition-Execution (I-PACE) model (Brand et al., 2019) it is argued that the imbalance between neural systems in early stages of addictive behaviors is particularly related to a hyperactive impulsive system. Mechanisms of affective and cognitive biases, incentive sensitization as well as cue-reactivity and craving are considered to be associated with this hyperactivity and reinforce each other within the addiction process (also see Bechara, 2005; Berridge & Robinson, 2016; Volkow & Baler, 2014). In later stages of addictive behaviors, the reflective system may continuously lose control over the impulsive system and the specific behaviors may become habitual despite experiencing negative consequences due to the addictive behaviors (Brand et al., 2019). The I-PACE model differentiates between general and stimuli-specific inhibitory control, depending upon the stages of addictive behaviors (Brand et al., 2019). Recent data suggests that while a general reduction in inhibitory control might be a vulnerability factor for the development of addictive behaviors (Meng, Deng, Wang, Guo, & Li, 2015), reductions of stimuli-specific inhibitory control may become additionally relevant in later stages of the disorder when affected individuals experience increasing reductions in control over their IP usage (Nie, Zhang, Chen, & Li, 2016; van Holst et al., 2012; Yao et al., 2015). On a neural level it has been demonstrated that cue-reactivity in behavioral addictions is linked to neural activity in striatal regions, inferior frontal gyrus (IFG), and cingulate cortex – regions associated with both the impulsive and the reflective system (Starcke, Antons, Trotzke, & Brand, 2018; cf. Wei, Zhang, Turel, Bechara, & He, 2017).

Recent data and theories suggest that diminished control over the specific behavior in behavioral addictions and substance-use disorders is likely resulting from an imbalance between the impulsive, reflective, and interoceptive (insula) system (cf. Noël, Brevers, & Bechara, 2013; Turel & Bechara, 2016; Wei et al., 2017). However, the interoceptive system as a part of the tripartite-process theory of addiction has been less frequently examined in behavioral addictions (Noël et al., 2013). In substance-use disorders it has been identified as an intermediate component which potentiates the activity of the impulsive system and/or weakens the reflective system

by translating bottom-up, interoceptive signals into subjective output (e.g., craving) (Noël et al., 2013). The interoceptive system has been associated with tendencies to relapse in substance-use disorders (Moeller & Paulus, 2018) and is also considered playing a balancing role between the impulsive and the reflective system (Droutman, Read, & Bechara, 2015). First studies on gaming disorder found increased connectivity between the interoceptive system and regions of the reflective and impulsive system (Chen et al., 2016; Zhang et al., 2016).

The current study aimed at investigating the potential role of these three neural systems during inhibitory control in the context of problematic IP use. Several studies have indicated that also in individuals with higher symptom severity of problematic IP use or compulsive sexual behaviors, the ventral striatum, as part of the impulsive system, and the dorsolateral prefrontal cortex, as part of the reflective system, are hyperactive during cue-reactivity (Brand, Snagowski, Laier, & Maderwald, 2016; Gola et al., 2017; Seok & Sohn, 2015). These studies show that symptom severity is associated with increased processing of sexual stimuli within the impulsive and the reflective system (also see reviews on problematic pornography use and CSBD by Kowalewska et al., 2018; Stark et al., 2018). The hyperactivity of the reflective system may be interpreted as an increase in effort needed by individuals to maintain control over temptations, which are mainly driven by the impulsive system. And also behavioral data show that increased impulsivity in interaction with more impulsive actions are associated with a higher symptom severity of problematic IP use but only when confronted with pornographic images and not when faced with neutral images (Antons & Brand, 2018).

The current study was the third part of a tripartite study which as well included an online survey and laboratory study (see Fig. 1 and Antons, Müller, et al., 2019; Antons, Trotzke, Wegmann, & Brand, 2019 for results of the online survey). The aim of the large scale study was to investigate the role of impulsivity, inhibitory control, and craving in males with problematic IP use. As a first study investigating these interactions we focused on a homogenous group of heterosexual males since sexual practices such as the amount of IP use and the preference of specific pornographic material differ between gender and types of sexual orientation (Bóthe, Bartok, et al., 2018). Within the online-survey it has been shown that craving and some facets of impulsivity (e.g., an impulsive cognitive style) may be aspects differentiating between recreational and problematic IP users (Antons, Müller, et al., 2019) although the effect of impulsivity seems to be lower as expected and its involvement might be enhanced in combination with further situational factors (Antons & Brand, 2018; Bóthe, Tóth-Király, et al., 2018).

Up to now, no study has investigated neural correlates of inhibitory control in the context of problematic IP use. We hypothesize that reduced inhibitory control is associated with a hyperactive impulsive system as well as altered activity within the reflective system and interoceptive system. Due to its centrality in the addiction process and previous results on problematic IP use and CSBD we focus on the

ventral striatum as one structure of the impulsive system. Furthermore, we focus on the IFG pars opercularis as structure of the reflective system which has been repeatedly associated with inhibitory control performance (Aron, Robbins, & Poldrack, 2014; Bari & Robbins, 2013) and has been shown to be involved in cue-reactivity processes (Snagowski, Wegmann, Pekal, Laier, & Brand, 2015; Zheng et al., 2019). Due to mechanisms of incentive-sensitization and cue-reactivity (Berridge & Robinson, 2016; Brand et al., 2019), we hypothesize that the aforementioned effects are higher when pornographic cues are present and for individuals with higher symptom severity of problematic IP use.

METHODS

Participants

Overall, 1,640 participants answered the online survey without missing data. A number of 1,401 participants indicated their interest in participating in the laboratory study; 516 participants were invited to the laboratory study, with the aim to measure a sample of 100 participants with a high variety in symptoms of problematic IP use. We used the short Internet Addiction Test modified for IP (s-IATporn) to evenly fill groups of unproblematic IP, problematic, and pathological IP users (see subsection measures for further details; Laier, Pawlikowski, Pekal, Schulte, & Brand, 2013). A sample of 108 heterosexual males participated in the laboratory study and were informed about the fMRT study and screened for contraindications and exclusion criteria (right-handedness, normal or corrected-to-normal vision including color vision). On average, the online survey was conducted 72 days before the fMRI study. All participants who were interested in participating in the fMRI study and eligible were invited to the fMRI study. Overall, 30 heterosexual male pornography users participated in the present fMRI study (IP use [min/week]: $M = 490.00$, $SD = 963.47$, Min-Max: 15–5,000, please note that IP use in minutes per week is a subjective estimation of IP use assessed during the online survey which was assessed with two questions: frequency per week and minutes per session. The subjective estimation might be biased which may lead to over- or underestimations

of IP use. However, the mean is comparable to results by Laier et al. (2013). All participants provided written informed consent prior to the experiment and were informed about the content of the study and that they could terminate participation at any time without reprisal. One participant was identified as an outlier, due to unusual data in behavioral measures, and was therefore excluded from further analyses (see stop-signal task descriptions, for further details). Furthermore, one participant was excluded due to movement parameters during fMRI. Therefore, the final sample comprises 28 participants ($M_{age} = 29.28$, $SD_{age} = 8.81$). More than half of the participants (57.1%) were in a relationship. Participants could choose between course credits or a monetary incentive of €40 in return for the 3-hour study as remuneration.

Measures

fMRI paradigm for the assessment of inhibitory control and craving. For the current study a modified Stop-Signal Task (SST, Antons & Brand, 2018) was used to measure inhibitory control. To compare SST performance during neutral and pornographic image processing, each participant randomly performed six SST blocks, three comprising pornographic and three comprising neutral images.

In the classic SST, participants have to respond (e.g., with their right index-finger) on go-signals which are followed by a stop-signal in some trials. In these stop-trials, participants are asked to inhibit the already initiated response on the go-signal. In the modified SST version which was used in the current study each trial is initiated by the presentation of an image (neutral or pornographic), which is shown until the end of the trial. The images have no direct relevance for carrying out the task but serve as cues to induce craving in the pornographic condition. Furthermore, informative cues (differently colored dashed frames) are included which inform the participant whether the current trial is a certain or uncertain go-trial. The certain-go cue (green dashed frame) indicates that in this trial no stop-signal is going to appear. Accordingly, participants can be sure that they have to respond to the following go-signal. An uncertain go-trial is introduced by a red dashed frame and indicates that it is uncertain whether a stop-signal is going to appear. After the



Fig. 1. Screening procedure for fMRI study. The fMRI study was the last part of a large scale study which aimed to investigate the role of impulsivity, inhibitory control, and craving in the context of problematic IP use. First, heterosexual males participated in an online study and answered the s-IATporn and BIS-15 besides further questionnaires (for details see Antons, Müller, et al., 2019). After the online study, participants were invited to a laboratory study. The image rating was one part of this laboratory study and participants were briefed comprehensively with regard to the fMRI study. Aiming a high variety in symptom severity of problematic IP use, participants were invited to the fMRI study which consisted of questionnaires, a SST training, and the fMRI study. BIS-15 = Barratt Impulsiveness Scale; HBI = hypersexual behavior inventory; s-IATporn = short Internet addiction test modified for pornography; SST = stop-signal task

cue presentation and a variable inter-stimulus interval (ISI), the go-signal (green, solid frame) is presented. The ISI is included to reduce predictability of the go-signal. Participants have to respond as fast as possible following the go-signal. In one third of all uncertain go-trials, the go-signal is followed by a stop-signal (red, solid frame) after a variable stop-signal-delay (SSD). See Fig. 2 for timing details. Participants are advised that prompt responses on go-signals are as important as staying alert for the stop-signal.

Each SST block consists of 85 trials with 34 certain go-trials, 52 uncertain trials of which 34 are go trials, and 17 are stop trials. Participants were trained before the scan with 45 trials (same proportion of certain go trials and uncertain go and stop trials). The training trials provide feedback for slow or wrong responses, whereas during the experimental blocks no feedback was given. Trials with go-reaction times (go-RT) faster than 100 ms or deviations of more than two standard deviations from the participants' mean go-RT were considered outliers and were therefore excluded from further analyses.

The SST version used in this study measures inhibitory control using three different variables: the certain go-RT as a measure for general response speed in certain situations, the uncertain go-RT as a measure for impulsive action tendencies on go-signals in uncertain situations, which also includes preparatory processes for a possible stop-process, and the stop-signal reaction time (SSRT) as a measure for inhibitory response ability. The SSRT was computed using the integration method (Verbruggen, Chambers, & Logan, 2013). This method requires a nearly equal distribution of false and correct stop-trials and is more robust against the violation of this requirement compared to the mean method. An equal distribution of false and correct stop-trials was attained by using a staircase-tracking procedure for the stop-signal-delay (Verbruggen, Logan, & Stevens, 2008). Since this staircase procedure adapts to the participants' performances from stop-trial to stop-trial, we used the SSD of the last correct stop-trial of the training trials as an initial SSD for the fMRI paradigm. One participant with more than 70%

missed responses in certain go-trials was excluded from the analyses. The task was programmed using the Presentation software package (Neurobehavioral Systems Inc., Albany, CA, USA).

Furthermore, after each block during the fMRI SST paradigm participants were asked to indicate their current urge to use IP ("Please indicate your current urge to use IP right now"). The question had to be answered on a four-point Likert-scale ranging from 1 (*no urge at all*) to 4 (*very high urge*). Answers, which were given after the blocks, were summed up for the three neutral and three pornographic SST blocks as measures for current craving.

Image rating. During the laboratory study which took place before the fMRI study (see Fig. 1), neutral and pornographic images were rated with regard to arousal (from 1 = *not at all arousing* to 5 = *very arousing*), valence (from 1 = *very negative* to 5 = *very positive*), and urge to use IP (from 1 = *not at all* to 5 = *very strong*). Viewing times were also assessed.

The pornographic images were used in earlier studies and showed scenes of male and female sexual vaginal and oral intercourse (Antons & Brand, 2018; Laier, Pawlikowski, & Brand, 2014; Schiebener, Laier, & Brand, 2015). Neutral images showed males and females jogging or hiking as examples for activities with non-sexual connotation which were also already used in an earlier study (Snagowski et al., 2015).

Symptom severity of problematic IP use. We assessed the symptom severity of problematic IP use with the German short Internet Addiction Test modified for IP (s-IAT_{porn}, in accordance with Laier et al., 2013). The questionnaire consists of twelve items divided into two sub-scales: craving/social problems and loss of control/time management. Example items are: "How often do you feel depressed, moody, or nervous when you are offline, which goes away once you are back on Internet-pornography?" and "How often do you try to cut down the amount of time you spend

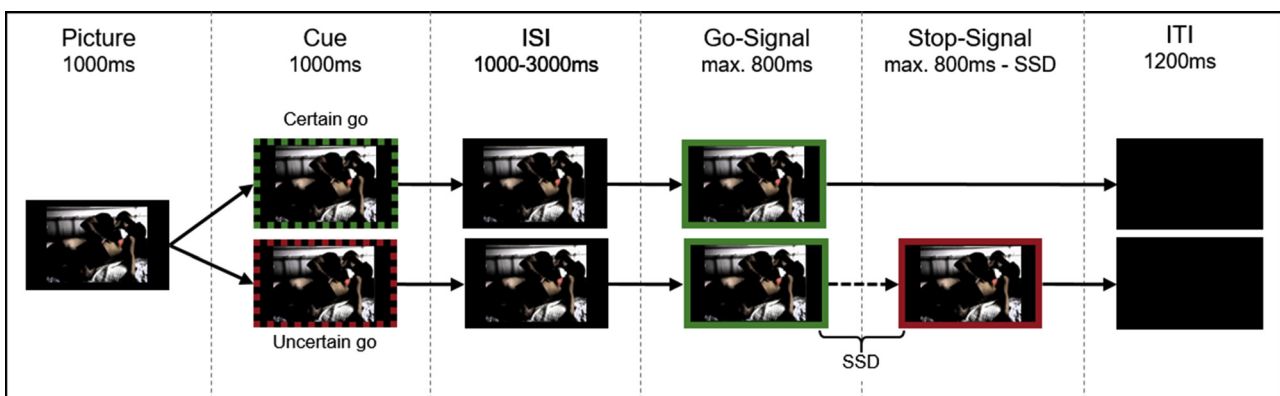


Fig. 2. Stop-signal task as used during fMRI. Each image (neutral or pornographic) lasted for the whole trial. Here, an example for the pornographic condition is presented. Pornographic images were not censored. In the neutral condition images showed people during jogging or hiking. In certain go trials, participants could be sure that no stop-signal will occur. In uncertain go trials, the go-signal was followed by a stop-signal in one third of the cases (represented by a dashed arrow). ISI = inter-stimulus interval; ITI = inter-trial-interval; SSD = stop signal delay

on Internet-pornography and fail?" All items were answered on a Likert scale ranging from 1 (*never*) to 5 (*very often*) resulting in a sum score between twelve and 60. For general Internet-use disorder a cut-off score higher than 30 indicates problematic and higher than 37 pathological behavior (Pawlikowski, Altstötter-Gleich, & Brand, 2013). This cut-off has been used in previous studies as an indicator for problematic IP use (Antons & Brand, 2018; Laier et al., 2013). The s-IATporn was assessed during all three parts of the large scale study and had an excellent internal consistency Cronbach's alpha = 0.927 in the current study.

Hypersexual behavior inventory. The hypersexual behavior inventory (HBI; Reid, Garos, & Carpenter, 2011) in German language (Klein, Rettenberger, Boom, & Briken, 2014) assesses problems due to hypersexual behavior, which is, in comparison to the s-IATporn, not only addressing IP use but includes all sexual activities that stimulate or arouse sexual desire or orgasms. Example items are: "Even though I promised myself I would not repeat a sexual behavior, I find myself returning to it over and over again"; "I use sex to forget about the worries of daily life," and "I sacrifice things I really want in life in order to be sexual." Nineteen items had to be answered on a scale ranging from 1 (*never*) to 5 (*very often*). Three subscales (control, coping, and consequences) were summed up to one HBI score ranging between 19 and 95 with excellent internal consistency in the current sample Cronbach's alpha = 0.949.

Barratt Impulsiveness Scale. Trait impulsivity was assessed with the short version of the German Barratt Impulsiveness Scale (BIS-15; Meule, Vögele, & Kübler, 2011) during the online survey. Within 15 items answered on a four-point Likert scale ranging from 1 (*rarely/never*) to 4 (*almost always/always*) the scale measures the frequency of several common impulsive or non-impulsive behaviors/traits. Example items are: "I am restless at the theater or lectures," "I do things without thinking," and "I plan for job security." A higher sum score (possible range from 15 to 60) indicates increased trait impulsivity. Three subscales attentional, non-planning, and motor impulsivity were summed up to one BIS-15 score (in the current sample good internal consistency with Cronbach's alpha = 0.873).

fMRI data acquisition. See supplementary material.

Statistical analysis

Behavioral data. In accordance with West, Finch, and Curran (1995) data was normally distributed which allows parametric testing. Data from the image rating was analyzed with *t*-tests for dependent samples. Cohen's *d* for repeated measures was calculated using the formula proposed by Dunlap, Cortina, Vaslow, and Burke (1996). Pearson correlations were computed for questionnaire data and SST performance in both conditions.

fMRI data. Imaging data was analyzed using SPM12 (Wellcome Department of Imaging Neuroscience, University College London, London). The following procedure was employed: realignment and unwarp, co-registration, normalization, and smoothing. The first three images of the first fMRI block were removed to allow magnetization equilibration. Images were smoothed with 5 mm full-width half maximum (FWHM) Gaussian distribution.

In the first level analysis, the onsets in both SST conditions were set on the certain go-cue, uncertain go-cue, certain go-signal, uncertain go-signal, stop-signal, and ITI (see Fig. 2). Thus, seven regressors were entered for each of the six blocks in the general linear model. To account for residual head motion effects, the motion parameters from the realignment procedure were also included into the statistical model. Contrast images were created for the neutral and pornographic conditions comprising all three blocks, respectively. Our primary interest referred to processes of inhibitory control. In accordance with the horse-race model (Verbruggen & Logan, 2009) and previous studies using the SST during fMRI (e.g. Chikazoe et al., 2009; Majid, Cai, Corey-Bloom, & Aron, 2013; Swann et al., 2012), activity at the onset stop with activity during certain go-processing (stop vs. certain go) was contrasted to isolate neural activity specific for inhibitory control. During the whole trial, a neutral or pornographic image was shown. Therefore, this contrast does not only isolate the inhibitory control process from the go-process but also from the image processing. To obtain neural activity for pornographic image processing, activity of all onsets in the pornographic condition with activity of all onsets in the neutral condition (besides ITI, pornographic vs. neutral) was contrasted. To obtain group statistics, contrast images of each participant were entered into a second-level one-sample or paired-sample *t*-test. For whole brain analyses, significance was accepted for clusters exceeding a statistical threshold of $p < 0.05$, family-wise error corrected.

Furthermore, a region of interest (ROI) approach was used to examine estimated values for the ventral striatum, IFG, and insula activity and to perform Pearson correlations on these data and behavioral as well as questionnaire data. The binary masks for the IFG pars opercularis and insula were obtained from Automatic Anatomical Labeling atlas (Tzourio-Mazoyer et al., 2002). The ventral striatum mask was obtained from a large-scale meta-analysis for the term "ventral striatum" in the Neurosynth data base (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011). To isolate ventral striatum activity, we used a threshold of 15. Parameter estimates for the ROIs were extracted using MarsBaR (Brett et al., 2002). All activation loci reported in this work as MNI coordinates were verified using the Anatomy software (Version 2.1; Eickhoff et al., 2007).

Ethics

The study procedures were carried out in accordance with the Declaration of Helsinki. All participants were fully



Table 1. Descriptive statistics of questionnaire data

	Min	Max	M	SD
s-IATporn				
Loss of control/time management	6	27	14.71	5.99
Craving/social problems	6	24	11.50	4.30
Sum	14	51	26.21	9.42
HBI sum	20	81	44.93	14.49
Craving after neutral SST blocks	3	12	4.50	2.29
Craving after pornographic SST blocks	3	11	5.82	2.29
Delta craving	-2	4	1.32	1.44
BIS-15 sum	20	46	32.36	7.52

Note. BIS-15 = Barratt Impulsiveness Scale; HBI = hypersexual behavior inventory; s-IATporn = short Internet addiction test modified for pornography.

instructed and gave informed consent prior to the investigation. The study was approved by the local ethics committee.

RESULTS

Descriptive statistics and behavioral results

Descriptive statistics for questionnaire data are presented in Table 1. At the time of the fMRI study $n = 10$ participants showed an unproblematic IP use, $n = 9$ showed problematic and $n = 9$ pathological symptoms of problematic IP use using the s-IATporn. Neutral and pornographic images were rated significantly different regarding arousal and urge to use IP (see supplementary materials). No significant differences were found regarding valence ratings and viewing times of the three ratings. There were no differences in SST measures between conditions (Table 2).

The SSRT in both conditions correlated negatively with s-IATporn with a high effect size and in the pornographic condition positively with craving also with a high effect size. Higher s-IATporn scores and craving scores in the pornographic condition were associated with faster SSRTs. The HBI did not correlate significantly with SSRT (however, direction of effect is consistent with the correlation between SSRT and s-IATporn). No significant correlations were found between the SSRT in both conditions and BIS-15. There was a significant positive correlation between craving and uncertain go RT in the neutral condition with a high

Table 3. Correlations between stop-signal task measures and questionnaire data

	s-IATporn sum	HBI sum	Craving	BIS-15
Neutral				
Certain go RT	0.048	0.007	0.156	0.029
Uncertain go RT	0.022	0.159	0.380*	-0.136
SSRT	-0.496**	-0.337	-0.118	-0.047
Pornographic				
Certain go RT	0.190	0.185	0.239	-0.004
Uncertain go RT	-0.013	0.143	0.281	-0.186
SSRT	-0.520**	-0.372	-0.550**	0.056

Note. BIS-15 = Barratt Impulsiveness Scale; HBI = hypersexual behavior inventory; s-IATporn = short Internet addiction test modified for Internet-Pornography; SSRT = stop-signal reaction time.

* $p < 0.05$; ** $p < 0.001$.

effect size (Table 3). The s-IATporn significantly correlated with craving after the pornographic ($r = 0.664, p < 0.001$) and neutral ($r = 0.655, p < 0.001$) SST conditions, but not with the delta craving (difference between craving ratings before and after the pornographic and neutral condition, $r = -0.054, p = 0.783$)

Neural results

Consistent with behavioral data, also the neural data showed no or marginal differences between conditions in inhibitory control processing and pornographic image processing (see supplementary material)

During pornographic image processing, activity in the left IFG pars opercularis was moderately and negatively associated with symptom severity of problematic IP use (s-IATporn). Right insula activity correlated positively with SSRT (high effect size) and negatively with the craving/social problems subscale of the s-IATporn (moderate effects size). Furthermore, delta craving (pornographic - neutral) correlated negatively with activity of the ventral striatum during pornographic image processing (Table 4 and Fig. 3).

Overall, during inhibitory control processing neural activity of the ventral striatum, the IFG pars opercularis, and the insula were not associated with behavioral measures of inhibitory control and craving or symptom severity of problematic IP use. There was only one moderate significant

Table 2. Descriptive values and test statistics of comparisons between neutral and pornographic inhibitory control performance during fMRI scanning

	Neutral		Pornographic		$t(27)$	p	Cohen's d	95% CI
	M	SD	M	SD				
Certain go RT	331.22	41.43	330.80	50.37	0.10	0.918	-0.02	[-0.55, 0.50]
Uncertain go RT	501.16	111.10	495.11	106.80	1.23	0.213	-0.23	[-0.76, 0.30]
SSRT	242.71	39.00	234.74	43.72	1.32	0.198	-0.27	[-0.79, 0.26]
Correct stop (%)	51.58	4.11	49.10	6.88	1.49	0.556	-0.41	[-0.94, 0.12]
SSD	255.47	124.41	258.58	133.14	-0.60	0.556	0.12	[-0.40, 0.65]

Note. CI = confidence interval; SSD = stop-signal delay; SSRT = stop-signal reaction time.

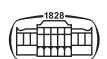


Table 4. Correlations between measures of inhibitory control and regions of interest during pornographic image processing

	Ventral striatum		IFG pars opercularis		Insula	
	L	R	L	R	L	R
Pornographic condition:						
Uncertain go-RT	-0.245	-0.280	-0.058	-0.013	-0.131	-0.367
SSRT	-0.032	0.145	0.313	0.161	0.261	0.502**
Craving	-0.253	-0.192	-0.097	0.124	-0.255	-0.057
Delta craving	-0.408*	-0.339	0.111	-0.127	-0.199	-0.177
s-IATporn						
Loss of control/time Management	-0.078	-0.041	-0.392*	-0.014	-0.201	-0.077
Craving/social problems	-0.044	0.086	-0.447*	-0.128	-0.364	-0.392*
Sum	-0.070	0.013	-0.453*	-0.067	-0.294	-0.228

Note. IFG = inferior frontal gyrus; s-IATporn = short Internet addiction test modified for Internet-Pornography; SSRT = stop-signal reaction time.

* $p < 0.05$; ** $p < 0.001$.

negative correlation between right insula and SSRT in the pornographic condition, indicating that better inhibitory control is associated with higher right insula activity (Table 5 and Fig. 4).

DISCUSSION

The aim of the current study was to investigate the neural correlates of inhibitory control when confronted with neutral and pornographic stimuli and its association with craving and symptoms of problematic IP use. The main result of the current study is that higher symptom severity of

problematic IP use and craving were associated with better inhibitory control performance (lower SSRT), especially when pornographic images were present. Compared with previous studies (Antons & Brand, 2018; Nie et al., 2016; van Holst et al., 2012; Yao et al., 2015), this result was somehow unexpected, but neural data show a consistent pattern with this behavioral finding. Symptom severity of problematic IP use was associated with decreased activity of the reflective (IFG pars opercularis) and interoceptive (insula) system during pornographic image processing. An increase in craving (delta craving) was associated with lower activity of the impulsive system (ventral striatum) during pornographic image processing which also contrasts results from previous

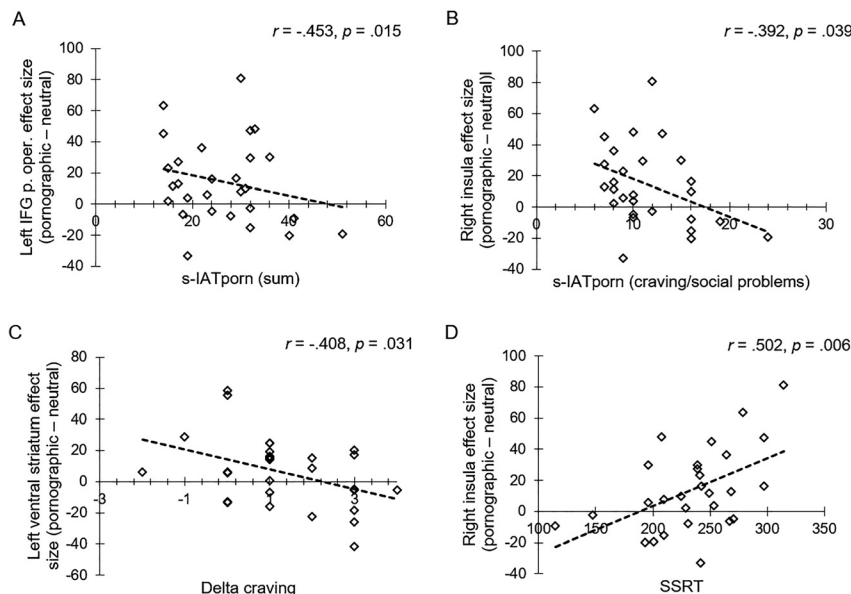


Figure 3. Correlations of neural effect sizes during pornographic image processing on measures of symptom severity of problematic Internet-pornography use, craving and inhibitory control. Neural effect sizes (contrast beta) was taken from the contrast of pornographic images – neutral images. A shows the correlation between left inferior frontal gyrus pars opercularis and symptom severity of problematic Internet-pornography use (s-IATporn sum), B between right insula and symptom severity of problematic Internet-pornography use (s-IATporn craving and social problems subscale), C between left ventral striatum effect size and the craving delta (pornographic – neutral), and D between the right insula and inhibitory control ability (stop-signal reaction time, SSRT)

Table 5. Correlations between measures of inhibitory control and regions of interest during inhibitory control processing

	Ventral striatum		IFG pars opercularis		Insula	
	L	R	L	R	L	R
Neutral condition						
Uncertain go-RT	0.029	0.108	-0.094	-0.150	-0.054	0.130
SSRT	-0.029	-0.100	-0.314	-0.159	-0.297	-0.350
Craving	0.017	-0.001	-0.081	0.048	-0.024	0.099
s-IATporn						
Loss of control/time management	-0.271	-0.258	-0.040	0.060	-0.086	0.018
Craving/social problems	-0.308	-0.166	0.002	0.010	0.062	0.086
Sum	-0.313	-0.239	-0.024	0.043	-0.026	0.051
Pornographic condition						
Uncertain go-RT	0.030	0.103	-0.011	0.001	-0.053	0.201
SSRT	0.216	-0.028	-0.142	-0.120	-0.093	-0.455*
Craving	-0.065	0.271	-0.015	-0.103	-0.128	0.210
Delta craving	-0.034	-0.259	0.057	-0.234	-0.031	0.002
s-IATporn						
Loss of control/time management	-0.109	0.177	-0.207	-0.137	-0.244	-0.050
Craving/social problems	-0.094	0.180	-0.141	-0.123	-0.206	-0.022
Sum	-0.112	0.195	-0.196	-0.143	-0.249	-0.042

Note. IFG = inferior frontal gyrus; s-IATporn = short Internet addiction test modified for Internet-Pornography; SSRT = stop-signal reaction time.

* $p < 0.05$.

studies (Brand, Snagowski, Laier, & Maderwald, 2016; Gola et al., 2017; Kühn & Gallinat, 2011). Furthermore, better inhibitory control performance was associated with increased activity of the interoceptive system (insula) during inhibitory control processing. Combining this effect with the decreased activity during pornographic image processing the results may suggest the differential and balancing role of the interoceptive system in addictive behaviors.

The associations between symptom severity of problematic IP use and activity of the reflective and interoceptive system are consistent with the altered function of both systems in the course of the development of addiction, as it

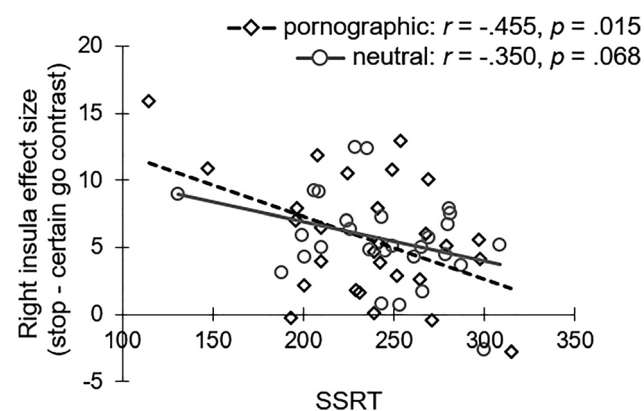


Fig. 4 Correlation of neural effect size in right insula during inhibitory control processing on stop-signal reaction time (SSRT). Neural effect size (contrast beta) was taken from the contrast of stop-certain go for the neutral and pornographic condition

is proposed in the tripartite-process model for substance-use disorders and gaming disorder (Noël et al., 2013; Wei et al., 2017). However, we found activity of the left IFG pars opercularis to be negatively and inhibitory control ability to be positively associated with symptom severity of problematic IP use. This indicates that individuals with higher symptom severity performed better in the task which might be mediated by reduced control by the reflective system. Also in the context of alcohol-use disorder, it has been shown that individuals with heavy alcohol use show reduced activity in prefrontal regions compared to social drinkers (Vollstädt-Klein et al., 2010). The activation of the reflective system may prevent social drinkers and individuals with regulated IP use to lose control over their behavior. Although the left IFG has been identified as critical node in inhibitory control (Swick, Ashley, & Turken, 2008), it also has been shown to be involved in speech, empathy, and working memory which might be relevant in pornographic image processing (Liakakis, Nickel, & Seitz, 2011). In the addiction context it has been shown that individuals with more symptoms show less emotional empathy (Ferrari, Smeraldi, Bottero, & Politi, 2014). Also problematic IP use has been associated with socio-emotional problems (Efrati & Gola, 2018; Tonioni et al., 2018). Accordingly, it might be possible that the processing of pornographic images was less intense due to the reduced processing of socio-emotional signs in the pornographic images which may be the reason why less resources of the left IFG were needed.

Furthermore, we found a negative instead of a positive association between the increase in craving (as a subjective measure of cue-reactivity) and activity of the impulsive system (ventral striatum) and a non-significant association

between the increase in craving and symptom severity of problematic IP use. This result may be interpreted in the context of tolerance and shifts from urge-driven to habitual behavior in individuals with higher symptom severity (Brand et al., 2019; Everitt & Robbins, 2013). It is assumed that this shift is mediated by a decrease in processing via the ventral striatum and an increase of processing via the dorsal striatum. Consistent with this also Vollstädt-Klein et al. (2010) found craving to be negatively associated with ventral striatum activity in the context of alcohol-use disorder.

Furthermore, it has to be considered that the inhibitory control performance can be affected by situational factors such as behavior-specific cues but also by motivational incentives (Jones, Christiansen, Nederkoorn, Houben, & Field, 2013; Leotti & Wager, 2010). One further explanation could therefore be that individuals with higher symptom severity were more motivated to perform well in the inhibitory control task or to suppress feelings of craving. The insula is involved in balancing between the impulsive and reflective system, which can be realized by re-focusing attention towards salient stimuli (Cai, Ryali, Chen, Li, & Menon, 2014; Drouman, Bechara, & Read, 2015). It is possible that individuals with higher symptom severity of problematic IP use voluntarily shifted their attention from pornographic images (negative association between inhibitory control and insula activity during pornographic image processing) to the more salient stop-signals in this situation (positive association between inhibitory control and insula activity during inhibitory control processing) which increased inhibitory control performance. In contrast, participants with increased insula activity during pornographic image processing performed worse in the inhibitory control task. This is consistent with a study by Li et al. (2008) showing that strategic adjustments of behaviors are associated with increased insula activity (e.g., during inhibitory control). Interestingly, increased insula activity during inhibitory control has been identified as a predictor for the ability to maintain tobacco abstinence (Gilman et al., 2018). Also, Moeller and Paulus (2018) identified the insula as a marker of clinical outcomes. In the current study, participants were invited based on the s-IATporn assessed during an online survey on average 72 days before the fMRI study. In the meantime, participants participated in a laboratory study. During all three assessments participants answered the s-IATporn. We compared s-IATporn scores between the three assessments, which revealed that the s-IATporn score decreased in 22 participants in comparison to the fMRI study (means and standard deviations are presented in the supplementary material). Since this decrease in symptom severity is present between the fMRI study and both the online survey and laboratory study, we do not assume that it can be explained by effects of social desirability. It is possible that a high number of participants in the current sample reflected on their IP use and became aware of the negative consequences resulting from their IP use. This might have triggered a need to control their IP-use behavior and craving and to ignore or avoid pornographic images which is consistent with studies showing that higher symptoms are associated with a more

negative attitude towards IP and both approach and avoidance tendencies in terms of a U-shape relationship (Antons, Müller, et al., 2019; Snagowski & Brand, 2015).

The study has several limitations: Consistent with previous studies (e.g., Antons & Brand, 2018; Brand, Snagowski, Laier, & Maderwald, 2016; Gola et al., 2017; Laier et al., 2013), we found a high correlation between subjective craving and symptom severity of problematic IP use in both conditions. However, the increase in craving as measure for cue-reactivity was not associated with symptom severity of problematic IP use, this may relate to tolerance (cf. Wéry & Billieux, 2017) given that the pornographic images used in this study were not individualized in terms of subjective preferences. Therefore, the standardized pornographic material used may not be strong enough for inducing cue-reactivity in individuals with high symptom severity associated with low effects on the impulsive, reflective, and interoceptive systems as well as inhibitory control ability. Furthermore, since altered neural processing in addictive behaviors is assumed to develop with increasing symptom severity (Brand, Young, Laier, Wölfling, & Potenza, 2016), we decided to investigate individuals with varying degrees of symptom severity of problematic IP use. Future studies should (1) compare individuals with regulated IP use and those with problematic IP use and (2) investigate shifts from urge-driven to habitual behavior and its neural processing (e.g., ventral vs. dorsal striatum) in longitudinal studies. In addition, the sample size of $N = 30$ was chosen because of experience in a previous and similar study by Brand, Snagowski, et al. (2016). In this study a picture paradigm including preferred and non-preferred pornographic materials was used which is similar to the current SST paradigm with regard to processes of cue-reactivity, but which did not include an inhibitory control task. Therefore, an fMRI power analysis for effects on inhibitory control were impossible. Nevertheless, the current fMRI data should be used for power analysis in future replication studies. Our current study should be seen as a first approach inspiring future investigations regarding the associations between psychological and neural mechanisms of craving, problematic IP use, motivation to change behavior, and inhibitory control.

CONCLUSION

Taken together, the insula as the key structure representing the interoceptive system plays a pivotal role in inhibitory control when pornographic images are present. Data suggest that individuals with higher symptom severity of problematic IP use performed better in the task due to decreased insula activity during image processing and increased activity during inhibitory control processing. This pattern of activity might be based on effects of tolerance, that is, less hyperactivity of the impulsive system causes less controlling resources of the interoceptive and reflective system. Hence, a shift from impulsive to compulsive behaviors as a consequence of developing problematic IP use or a motivational (avoidance-

related) aspect might be relevant, so that all resources were focused on the task and away from pornographic images. The study contributes to a better understanding of diminished control over IP use which is presumably not only a result of an imbalance between dual systems but of the interaction between impulsive, reflective, and interoceptive systems.

Funding sources: No financial support was received for this study.

Authors' contribution: MB and SA designed the study. Data collection was carried out by SA. SA conducted the statistical analysis, interpreted the results, and wrote the first and final draft of the manuscript. MB supervised the interpretation of the data and writing of the manuscript. All authors had full access to all data, contributed to and have approved the final version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

Acknowledgments: We thank Dr. Stefan Maderwald and Lena Schäfer for their valuable contributions to Data collection and technical support.

SUPPLEMENTARY MATERIAL

The online version of this article offers supplementary material (<https://doi.org/10.1556/2006.2020.00010>).

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