AKADÉMIAI KIADÓ

Journal of Behavioral Addictions

11 (2022) 2, 506–519

DOI:
10.1556/2006.2022.00037

FULL-LENGTH REPORT

Individual cortisol response to acute stress influences neural processing of sexual cues

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Received: January 15, 2022 • Revised manuscript received: March 28, 2022; April 26, 2022 • Accepted: April 28, 2022
Published online: May 30, 2022

ABSTRACT

Background and aims: Problematic pornography use can be conceptualized as an impulse control disorder or alternatively as a behavioral addiction. Stress is an important trigger in addiction, but less is known about the neural effect of stress in problematic pornography use. Therefore, we aimed at investigating the effect of stress during the anticipation and viewing of sexually explicit material while considering person characteristics related to potentially being at risk for developing problematic pornography use. *Methods:* In an fMRI study (n = 157 men, age: mean = 25.46, SD = 4.11) we used a sexual incentive delay task. A social stress test was used to induce stress in half of the participants. Salivary cortisol was repeatedly measured and person characteristics were considered moderating the effects of cortisol response. *Results:* We found no group differences in the neural responses during the anticipation phase, but a higher reactivity to sexual stimuli in the dACC in the stress group. Acute stress activated a pronounced cortisol response, which positively correlated with neural activations in the reward system (NAcc, dACC) to sexual cues. Further, the individual time spent on pornography use moderated the effect of cortisol in some regions of the reward system (dACC, mOFC). *Discussion and conclusions:* Our results suggest that acute stress related increases in cortisol can enhance the incentive value of cues announcing sexual stimuli. This might explain why acute stress is considered a trigger of pornography use and relapse and why individual stress response might be a risk factor for developing a problematic pornography use.

KEYWORDS

problematic pornography use, reward system, sexual cues, nucleus accumbens, sexual incentive delay task, compulsive sexual behavior disorder

INTRODUCTION

Sexually explicit material (SEM) is highly attractive especially for men as shown by epidemiological studies on pornography use (Beutel et al., 2017; Wright, 2013). While most people use SEM for recreational purposes (Vaillancourt-Morel et al., 2017), in some individuals the use pattern becomes compulsive with clinically relevant symptoms, which can be diagnosed as *Compulsive Sexual Behavior Disorder* (CSBD) in the upcoming ICD-11 (World Health Organization, 2019). Prevalence rates range from 2% up to 10% with significantly higher figures for men than for women (Bőthe et al., 2020; Kraus, Martino, & Potenza, 2016; Odlaug et al., 2013). A recent study has shown that beside other motives, stress reduction is stated often as a reason for using SEM (Bőthe et al., 2021).

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The transition from recreational, to problematic, to pathological use of SEM is not yet well understood. In current theoretical models such as the Interaction of Person-Affect-Cognition-Execution (I-PACE; Brand, Young, Laier, Wölfling, & Potenza, 2016; Brand et al., 2019), escalated impulsive/compulsive/addictive behavior is explained by negative reinforcement along with positive reinforcement learning. Therefore, repeatedly using SEM for stress reduction might pave the way to problematic or pathological use by negative reinforcement and habit formation. However, it is still an open question whether stress would trigger SEM use indirectly via learning history (negative reinforcement), or whether stress could also increase the incentive for the behavior more directly by activating reward related neurocircuitries. A possible importance of cortisol is suggested by different lines of research showing that the reward and the stress systems are closely intertwined (Esch & Stefano, 2004; Ossewaarde et al., 2011; Rutten et al., 2013).

Acute stress results in a fast autonomic norepinephrine driven nervous system response and a delayed response of the hypothalamic-pituitary-adrenal axis (Ulrich-Lai & Herman, 2009). The stress system interacts with numerous peripheral and central systems, particularly with the reward system (Chrousos, 2009). Various studies could show that acute stress activates the mesocortical mesolimbic dopaminergic reward system due to cortisol receptors in the reward system (Belujon & Grace, 2015; Cabib & Puglisi-Allegra, 2012; Pascucci, Ventura, Latagliata, Cabib, & Puglisi-Allegra, 2007). However, studies on effects of acute stress have shown complex results during expectation of rewards and during reward feedback or delivery with both reduced and increased behavioral, subjective, and neural responses of the reward circuitry. In several studies, acute stress was found to be associated with lower responses to reward cues during reward anticipation (Kruse, Leon, Stalder, Stark, & Klucken, 2018; Ossewaarde et al., 2011) and to rewarding stimuli during reward feedback or reward delivery (Berghorst, Bogdan, Frank, & Pizzagalli, 2013; Bogdan & Pizzagalli, 2006; Kumar et al., 2014; Porcelli, Lewis, & Delgado, 2012). In contrast, studies have also shown that acute stress resulted in higher responses in the reward system to reward cues (Kumar et al., 2014; Mantsch, Baker, Funk, Lê, & Shaham, 2016) and to rewarding stimuli (Maier, Makwana, & Hare, 2015; van Leeuwen et al., 2019; Wand et al., 2007). Several studies suggest that special attention should be paid to the individual cortisol response as a result of acute stress (Maier et al., 2015; Oei, Both, van Heemst, & van der Grond, 2014). The importance of cortisol is underscored by studies that have shown altered reward processing under exogenous administration of cortisol (Kinner, Wolf, & Merz, 2016; Montoya, Bos, Terburg, Rosenberger, & van Honk, 2014).

Sexual stimuli are often regarded as natural rewards (Georgiadis, Kringelbach, & Pfaus, 2012), which may help explain the high appeal of pornography, and they are seen as central incentives in current theories of sexual motivation (Toates, 2009). Studies on the effects of stress on the processing of sexual stimuli revealed ambiguous results with stronger (Bancroft et al., 2003; Barlow, Sakheim, & Beck, 1983; Meston & Heiman, 1998) or weaker subjective and physiological sexual responses (Hamilton & Meston, 2013; Mitchell, DiBartolo, Brown, & Barlow, 1998) under stress induction. Studies focusing on the stress hormone cortisol provide indications toward enhanced processing of sexual stimuli. Oei et al. (2014) found that the individual cortisol response to the Trier Social Stress Test (TSST, Kirschbaum, Pirke, & Hellhammer, 1993) was positively correlated with reward system activation (nucleus accumbens) although SEM was presented subliminally. Analyzing the influence of endogenous cortisol levels on sexual approach behavior, Rodríguez-Nieto, Sack, Dewitte, Emmerling, and Schuhmann (2020) found a positive association between cortisol level and medial orbitofrontal cortex (mOFC) activation.

Many experimental differences (e.g. applied stressors, studied response systems) may explain the inconsistencies of studies investigating the effect of stress on reward processing. In our study, we want to address two aspects in particular, which might not have always been adequately considered in the past. First, we want to study the possible differential effect of stress on cues of rewards and rewarding stimuli. Second, we want to study not only the impact of stress induction, but also to consider the individual cortisol response. Consequently, the first goal of our study is to investigate the effect of stress on the subjective, behavioral, and neural responses of the reward system to SEM cues and SEM while taking into account the extent of the cortisol response. Doing this, we hope to gain insights into the potential underlying neurobiological mechanisms of people using pornography to deal with stress. However, the present study is also motivated by a second aim. We want to investigate whether indicators of problematic pornography use moderate the influence of stress on SEM processing. A moderating effect seems plausible under the consideration that problematic pornography use shares communalities with addiction as suggested by several authors (Brand et al., 2022; Kraus, Martino, & Potenza, 2016; Stark, Klucken, Potenza, Brand, & Strahler, 2018). Addiction literature has shown that stress can promote addictive behavior and can trigger relapses during the development of an addiction due to increasing dysregulation of the stress system (Koob & Schulkin, 2019; Piazza & Deroche-Gamonet, 2013; Sinha, 2001). However, less is known about the mechanism underlying the effect of acute stress on cue reactivity and craving in addictive individuals. A recent study showed that the effect of stress differed between addictions with increased craving in nicotine smokers but decreased craving in gamblers (Wemm, Cao, Han, & Wulfert, 2020). Therefore, we aim at investigating whether the effect of stress on SEM processing depends on indicators of problematic pornography use. Although we did not examine a clinical sample, we expected that an effect of stress on behavioral, subjective and neural responses is moderated by two dimensional indicators of problematic pornography use, namely self-reported problems concerning and time spent on pornography use. For both indicators, there are many studies indicating a positive relation with escalating pornography use (subjectively reported problems: Laier, Pawlikowski, Pekal,

Schulte, & Brand, 2013; Mennig, Tennie, & Barke, 2020; Sassover et al., 2021; time spent on pornography: Bőthe et al., 2018; Klucken, Wehrum-Osinsky, Schweckendiek, Kruse, & Stark, 2016; Sinke et al., 2020).

To summarize, the present study aims at providing additional insights into the effects of acute stress on subjective, behavioral, and neural responses while anticipating and viewing SEM. We expect that stress induced by a social stress test will affect the subjective, behavioral, and brain's reward system responses during a sexual incentive delay task. Further, we expect that these altered responses will be moderated by indicators of problematic pornography use (time spent on pornography use, self-reported problems concerning pornography use).

METHODS

Participants

157 healthy men aged between 18 and 40 years (M = 25.46, SD = 4.11) participated in the study. Most of them were students (87.9%). 47.1% of the sample were singles, 47.1% lived in a permanent relationship, 3.8% were married and 1.9% were divorced. 33.8% indicated a religious affiliation. All participants reported heterosexual or bisexual orientation (Kinsey Scale, ranging from 0 = 'exclusively heterosexual' to 6 = 'exclusively homosexual', mean: 0.25, SD = 0.52, range: 0–2). The participants were recruited via social media channels and university emails. Inclusion criteria were absence of current somatic diseases, no current psychotherapeutic or pharmacological treatment of mental disorders, and no harmful use of alcohol or nicotine. In total, 172 participants underwent the experiment, but 15 participants had to be excluded to the following reasons: (a) atypical neuroanatomy (n = 2), (b) anomalies in the fMRI data indicated by more than 10% outlying volumes (n = 1) and (c) technical difficulties (e.g. technical image artefacts) during data collection (n = 12). The participants were randomly assigned to Stress and NoStress group (see below). Subsamples of the NoStress group were analyzed in former studies (Klein et al., 2020; Markert, Klein, Strahler, Kruse, & Stark, 2021).

Sexual incentive delay task (SIDT)

The SIDT is based on the established monetary incentive delay task of Knutson, Fong, Adams, Varner, and Hommer (2001) but with SEM as rewards instead of monetary rewards. Figure 1 displays the different parts of a trial.

The SIDT consisted of 63 trials (21 SEM, 21 Control, 21 None) with an anticipation and a delivery phase. Three different geometric forms (CueSEM, CueControl, CueNone) signaled during the anticipation phase (duration: 4 s) that film clips of erotic content, of neutral content, or nothing could be 'won' if the participants react to a target stimulus (white square) within a preset reaction time window. The use of geometric figures has the advantage that there are no previous sexually related associations with these stimuli.

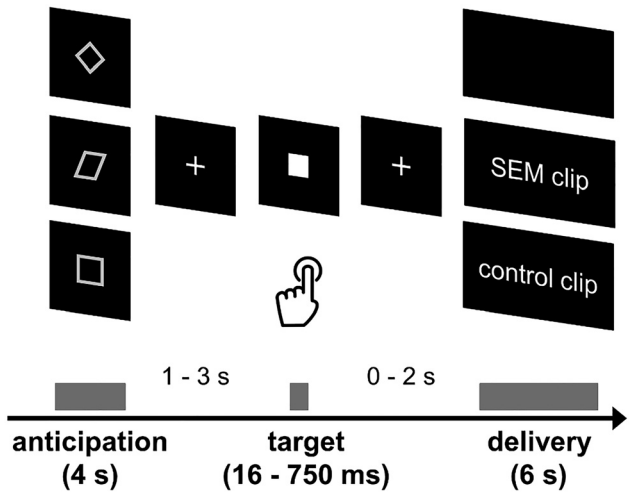

Fig. 1. Scheme of trials in the sexual incentive delay task (SIDT).
Note. During the anticipation phase, the participants saw a cue (geometric figure). Following a variable time interval, a target was presented for a short time, to which the participants were asked to react as quickly as possible by pressing a button. If the cue in the anticipation phase was a CueSEM or a CueControl, a corresponding video could be obtained by reacting quickly to the target (see also Klein et al., 2020; Markert et al., 2021).

During the delivery phase (duration: 6 s) either highly attractive sexual clips (DeliverySEM), control massage film clips (DeliveryControl), or a black screen (DeliveryNone) was shown. The massage clips we used as control stimuli were selected because they were comparable with the SEM videos with regard to depicting social interaction with rhythmic movement and physical properties (e.g. color composition) but without sexual connotation. All film clips were presented without sound. The participants were instructed to always react as fast as possible to the target stimulus. The reaction time window to 'win' a clip was set individually according to reaction times obtained in a training task and was adaptively adjusted throughout the SIDT to ensure that all participants would win in 71% of the SEM and control trials. The whole SIDT lasted around 21 min. The SIDT is described in more detail in the supplemental materials and also in previous publications (Klein et al., 2020; Markert et al., 2021).

Stress induction, cortisol measurement, and mood ratings

The Trier Social Stress Test (TSST, Kirschbaum et al., 1993), which is characterized by high uncontrollability and social evaluation, was used to induce stress and a cortisol response in the Stress group. The NoStress group underwent a Placebo-TSST, which usually induces no significant stress (Het, Rohleder, Schoofs, Kirschbaum, & Wolf, 2009). The TSST as well as the Placebo-TSST lasted around 15 min. See supplemental materials for further details.

To determine cortisol stress responses, several saliva samples were collected before TSST or Placebo-TSST (T_0), after TSST or Placebo-TSST (T_1: 25 min after T_0), before the

magnetic resonance (MR) experiment started (T_2: 35 min after T_0), after the first scanner experiment (T_3: 75 min after T_0), after undergoing further MRI measurements and after leaving the scanner (T_4: 135 min after T_0), and finally after the second set of questionnaires (T_5: 195 min after T_0). Stress-related output of cortisol over time (Stress and NoStress group) was calculated according to the formula proposed by Pruessner, Kirschbaum, Meinlschmid, and Hellhammer (2003) as the 'area under the curve (T_0 to T_5) with respect to increase' (CortisolResponse). See supplemental materials for analysis details of saliva samples. At saliva sampling time point t_0, t_1, t_4, and t_5, participants also filled out the Positive and Negative Affect Schedule (PANAS, Watson, Clark, & Tellegen, 1988) to measure stress-induced changes in affect. The positive and negative affect scales of the PANAS consist of ten 5-point Likert items each. Each item is a mood-related adjective and the participants' rate to which extent the adjectives mirrored their state of mood from 1 (not at all) to 5 (extremely). Therefore, positive as well as the negative scale range from 10 to 50. The range of alphas was 0.744–0.901 for the negative affect scales and 0.822–0.887 for the positive affect scales. All following indices of internal consistency are calculated for the current sample.

Self-reports and questionnaires

A single item "How much time did you spend viewing pornographic material within the last month" was used to assess time spent on pornography use (h/month). Participants could indicate the time spent on pornography use either as time per day, time per week, or time per month. Answers were then transformed into hours per month (h/month) based on the definitions that a month consists of 30 days, a week of 7 days, a day of 24 h and an hour of 60 min. The short version Internet Addiction Test adapted for pornography (s-IATsex, Laier et al., 2013) with two subscales were used to measure self-reported problems concerning pornography use. Twelve items (e.g., "How often do you find that you stay on sex sites on the Internet longer than you intended?") were answered on a scale from 1 (never) to 5 (very often) resulting in sum scores ranging from 12 to 60. Beside the sum score (s-IATsex_Sum: α = 0.89) two subscales were additionally calculated: loss of control (s-IATsex_LossOfControl: 6 items, α = 0.89) and craving (s-IATsex_Craving: 6 items, α = 0.67). Sum scores exceeding 30 are classified to be indicative of problematic pornography use.

Procedure

To ensure similar baseline cortisol levels, appointments always took place in the afternoon (between 1 p.m. and 6 p.m.) and participants came in at least 30 min before giving the first saliva sample. At the beginning, all participants provided informed consent after the experiment was explained and all remaining questions were answered. After this, they received instructions regarding the cue-clip associations in the experiment and performed a training version of the SIDT outside of the scanner. Then the Stress group underwent the TSST (Kirschbaum et al., 1993) and the NoStress group the Placebo-TSST (Het et al., 2009), respectively. Thereafter the participants were placed in the MR scanner and after a field map measurement, the SIDT started (duration: 21 min). After leaving the scanner, a set of personality questionnaires were filled in. Finally, all participants rated the 21 SEM clips and the 21 control clips on a valence scale ("how pleasant do you find this clip?", 9-point Likert scale from "not at all" to "very much") and sexual arousal scale ("How sexually arousing do you find this clip", 5-point Likert scale from "not at all" to "very much") on a computer. For further details, see supplemental materials.

Statistics

Behavioral, endocrinological, and subjective data. First, the effect of stress induction was tested by a group (2) × time (6) ANOVA and the effect on affect by a group (2) × time (4) ANOVA. These ANOVAs were conducted for endocrinological data (cortisol, α-amylase) and for mood ratings (positive and negative mood). For behavioral data (mean reaction times in the SIDT trials) a group (2) × trial type (3) ANOVA was applied to test the effect of stress induction. The effect of stress induction on the ratings of the video clips (valence, sexual arousal) were tested by a group (2) × clip type (2) ANOVA. The Greenhouse–Geisser adjustment was used to correct for violations of sphericity. Pearson correlations were calculated between cortisol responses and affect ratings measured by PANAS (Watson et al., 1988), reaction times within the SIDT, and the ratings of the valence and sexual arousal of the SEM and control clips. These analyses were done by the statistic software SPSS (IBM SPSS Statistics for Windows, Version 28.0. Armonk, NY: IBM Corp). For all moderator analyses, multiple regressions were performed with standardized predictors and an additional interaction regressor as moderator by using R (version 4.1.1) with the package psych (version 2.1.6).

MRI data and group statistics. MR images were acquired using a 3 T whole-body magnetic resonance tomograph (MRT Prisma, Siemens, Erlangen, Germany) with a 64-channel head coil. A whole brain fieldmap was acquired with a dual-echo sequence (FoV = 220 × 220 mm^2, matrix size = 110 × 110, 36 slices, slice thickness = 3.5 mm, gap = 0.77 mm, TE_1 = 10 ms, TE_2 = 12.46 ms, TR = 1.0 s, flip angle = 90°). The structural image acquisition used an MPRAGE sequence with 176 T1-weighted sagittal slices (FoV = 240 × 240 mm^2, matrix size = 256 × 256, slice thickness = 0.94 mm, TE = 2.3 ms, TR = 1.58 s, flip angle = 8°). For functional imaging, a total of 632 images were recorded using a $T2^*$-weighted gradient echo-planar imaging (EPI) sequence with 36 axial slices covering the whole brain (FoV = 192 × 192 mm^2, matrix size = 64 × 64, slice thickness = 3.5 mm, gap = 0.77 mm, TE = 30 ms, TR = 2.0 s, flip angle = 75°, GRAPPA = 2). The field of view was realigned to the AC-PC line with an angle of −30°. We used Statistical Parametrical Mapping (SPM12, Wellcome Department of Cognitive

Neurology, London, UK; 2014) implemented in Matlab (Version 2019b, Mathworks Inc., Sherbourn, MA; 2012) for preprocessing the raw data, as well as first and second level analyses. Preprocessing of the EPI images comprised realignment and unwarping, normalization to a Montreal Neurological Institute (MNI) template via segmentation, slice time correction, as well as smoothing with a Gaussian kernel at 6 mm FWHM. Functional data were analyzed for outlying volumes using a distribution free approach for skewed data (Schweckendiek et al., 2013). Each resulting outlying volume was later modeled within the general linear model (GLM) as a regressor of no interest. Each of the experimental conditions (CueSEM, CueControl, CueNone, DeliverySEM, NoDeliverySEM, DeliveryControl, NoDeliveryControl, NoDeliveryNone and target stimulus) was modeled as a regressor of interest in an intrasubject model. Three NoDelivery regressors (NoDeliverySEM, NoDeliveryControl, NoDeliveryNone) modeled black screen delivery phases (1) in no-win CueSEM trials, (2) in no-win CueControl trials, and (3) in CueNone trials. All regressors were convolved with the canonical hemodynamic response function. Six movement parameters were entered as covariates in addition to the regressors for the identified outlying volumes. The time series was filtered with a high pass filter (time constant = 128 s).

We analyzed the contrasts CueSEM minus CueControl and DeliverySEM minus DeliveryControl at group-level. One-Sample *T*-tests of these contrasts were conducted to assess main effects of the task, in the whole sample and separately for Stress and NoStress group. Two-Sample *T*-tests for independent groups were used to test the influence of stress induction on hemodynamic responses in these contrasts. Further, CortisolResponse was used in regression analyses analyzing the effect of cortisol responses on the contrasts for the whole sample and separately for Stress and NoStress group. Finally, we investigated whether person characteristics, which are linked to problematic pornography use (time spent on pornography use, self-reported problems concerning pornography use), moderate the effect of cortisol on the hemodynamic responses. For these analyses, multiple regressions were performed with standardized predictors and an additional interaction regressor as moderator, in the whole sample and separately in the Stress and NoStress group. For group statistics, ROI analyses on the voxel level were conducted using the small volume correction feature of SPM. Caudate, nucleus accumbens (NAcc), putamen, dorsal anterior cingulate cortex (dACC), amygdala, insula, medial OFC (mOFC), and thalamus were chosen as ROIs because they have been previously reported in studies on cue reactivity and SEM processing (Ruesink & Georgiadis, 2017; Stoléru, Fonteille, Cornelis, Joyal, & Moulier, 2012). Anatomical ROI masks for mOFC were created in MARINA (Walter et al., 2003); all other masks were taken from the Harvard Oxford Cortical Atlas delivered with FSL (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/Atlases). For dACC the Harvard Oxford masks for the anterior cingulate cortex and the paracingulate gyrus were merged and truncated to obtain a region described by Vogt (2009) as anterior midcingulate cortex. The left and right variants of a ROI were merged to one mask. For these eight ROIs, analyses on the voxel level were conducted with $P < 0.05$ family-wise error (FEW)-corrected. Additionally, whole brain analyses were conducted.

The effect of stress induction was tested by two sample *T* tests (Stress group vs. NoStress group) and by regression analysis using CortisolResonse as regressor. Further, we examined whether person characteristics linked to problematic pornography use (time spent on pornography use, self-reported problems concerning pornography use) moderate the influence of cortisol response on subjective, behavioral and neural responses. See supplemental materials for further information.

Ethics

The study was approved by the local ethics committee and was conducted in accordance with the 1964 declaration of Helsinki and its later amendments. All participants provided written informed consent prior to any assessment.

RESULTS

Table 1 summarizes the descriptive data of the whole sample and separately for the two experimental groups Stress and NoStress. The groups did not differ with regard to age, the time spent on pornography use per month, self-reported problems concerning pornography use as well as to cortisol level and mood ratings at baseline.

The person characteristics time spent on pornography use, self-reported problems concerning pornography use, and the sexual arousal ratings of the SEM clips were significantly correlated as shown in Table 2. Reaction times to SEM cues showed no significant correlation with the other variables.

The SIDT led to the expected results: For the Stress group as well as for the NoStress group there were significant activations in all ROIs for the contrasts CueSEM minus CueControl and DeliverySEM minus DeliveryControl. See detailed Table S1–S3 in the supplemental materials for results in the whole group and separately in the Stress and NoStress group.

Effect of stress induction – endocrinological data, behavioral data, subjective data

As expected, TSST and Placebo-TSST led to significantly different CortisolResponse ($P = 0.016$, see Table 1). The group (2) × time (6) ANOVA revealed a significant interaction ($P < 0.001$) for the cortisol level (for ANOVA details in this section see table S1). Figure 2 and Table 1 show that cortisol levels were significantly higher after TSST in contrast to Placebo-TSST at T_1 ($P < 0.001$), T_2 ($P < 0.001$), and T_3 ($P = 0.001$).

For reaction times in the trial types SEM, Control, None (variable: trial_type) the trial_type (3) × group (2) ANOVA revealed a main effect of trial_type ($P < 0.001$), but no group main effect or interaction (see Table S1). Subsequent

Table 1. Descriptive statistics and group comparisons

	Group							
	Total n = 157		Stress n = 79	No stress n = 78				
	Mean (SD)	*Range*	*Mean (SD)*	*Mean (SD)*	*t*	*df*	*P*	*d*
Age [years]	25.46 (4.11)	18–40	25.43 (3.84)	25.49 (4.39)	0.09	155	0.931	0.01
Time spent on pornography use [hours/month]	7.29 (8.97)	0–75	7.67 (10.48)	6.9 (7.17)	−0.53	155	0.595	−0.08
s-IATsex								
s-IATsex_Loss [6..30]	10.68 (4.65)	6–30	10.47 (4.62)	10.88 (4.7)	0.56	155	0.576	0.09
s-IATsex_Craving [6..30]	9.47 (3.27)	6–26	9.16 (2.88)	9.78 (3.61)	1.19	155	0.238	0.19
s-IATsex_Sum [12..60]	20.15 (7.41)	12–56	19.63 (6.92)	20.67 (7.89)	0.87	155	0.384	0.14
Cortisol level [nmol L^{-1}]								
T_0	6.35 (4.52)	0.80–25.19	6.55 (4.83)	6.15 (4.22)	−0.55	155	0.586	−0.09
T_1	8.79 (6.39)	1.38–29.99	10.64 (6.36)	6.91 (5.89)	−3.81	155	<0.001	−0.61
T_2	9.78 (7.9)	1.21–38.21	12.82 (8.45)	6.71 (5.93)	−5.23	155	<0.001	−0.83
T_3	7.25 (5.23)	0.88–32.91	8.65 (5.42)	5.82 (4.63)	−3.51	155	0.001	−0.56
CortisolResponse	61.91 (757.77)	−3,793–1,995	205.52 (794)	−83.56 (694)	−2.43	155	0.016	−0.39
PANASneg [10..50]								
T_0	12.11 (2.81)	10–28	12.29 (2.88)	11.92 (2.76)	−0.81	150	0.422	−0.13
T_1	15.00 (6.08)	10–36	17.72 (6.79)	12.28 (3.64)	−6.16	150	<0.001	−1.00
T_4	12.18 (3.38)	10–31	12.00 (3.22)	12.37 (3.54)	0.67	150	0.503	0.11
PANASpos [10..50]								
T_0	29.50 (5.80)	14–43	29.84 (5.84)	29.16 (5.77)	−0.73	150	0.469	−0.12
T_1	30.33 (6.68)	14–48	31.00 (6.68)	29.66 (6.67)	−1.24	150	0.217	−0.20
T_4	24.89 (7.12)	13–41	25.49 (7.27)	24.29 (6.96)	−1.04	150	0.301	0.02
Reaction times [ms]								
SEM	242.85 (43.68)	180–391	246.99 (44.94)	238.64 (42.25)	−1.20	155	0.232	−0.19
Control	283.52 (60.46)	186–491	285.57 (59.25)	281.45 (61.98)	−0.43	155	0.671	−0.07
None	292.71 (63.80)	184–558	293.51 (56.87)	291.9 (70.57)	−0.16	154	0.875	−0.03
Valence [1..9]								
Control clips	5.64 (1.24)	2.52–8.95	5.76 (1.2)	5.52 (1.28)	−1.20	155	0.231	−0.19
SEM clips	6.33 (1.18)	2.14–8.86	6.32 (1.19)	6.33 (1.17)	0.09	155	0.931	0.01
Sexual arousal [1..9]								
Control clips	1.95 (0.95)	1.00–5.00	1.99 (0.96)	1.91 (0.95)	−0.53	155	0.597	−0.08
SEM clips	6.56 (1.18)	2.14–8.81	6.55 (1.16)	6.58 (1.19)	0.16	155	0.873	0.03

Note. s-IATsex = Internet Addiction Test adapted for pornography use (Laier et al., 2013); PANASneg = Positive Affect and Negative Affect Scales – negative scale (Watson et al., 1988); PANASpos = Positive Affect and Negative Affect Scales – positive scale (Watson et al., 1988); SEM = sexually explicit material; T_0 = before Trier Social Stress Test (TSST) or placebo-TSST; T_1 = after TSST; T_2 = before entering the scanner; T_3 = after sexual incentive delay task (SIDT); d = Cohen's d.

Table 2. Pearson correlations of person characteristics

	s-IATsex_Sum			Reaction times to SEM cues			Sexual arousal ratings SEM		
	r	*P*	95% CI	*r*	*P*	95% CI	*r*	*P*	95% CI
Time spent on pornography use	0.538	<0.001	[0.355, 0.691]	−0.085	0.292	[−0.192, 0.008]	0.174	0.029	[0.069, 0.294]
s-IATsex_Sum				−0.069	0.392	[−0.202, 0.076]	0.200	0.012	[0.075, 0.314]
Reaction times to SEM cues							−0.046	0.568	[−0.191, 0.112]

Note. s-IATsex_SUM = Internet Addiction Test adapted for pornography use; SEM = sexually explicit material; CI = bootstrap confidence interval from 2,000 samples.

pairwise comparisons showed significant differences between all three trial types with reaction times lowest for SEM, second lowest for Control, and highest for None ($D_{SEM\text{-}Control} = -40.7$, $P < 0.001$; $D_{SEM\text{-}None} = -49.7$, $P < 0.001$; $D_{Control\text{-}None} = -9.7$, $P < 0.001$).

For ratings of valence and sexual arousal clip_type (2) × group (2) ANOVAs resulted only in a main effect of clip_type (valence: $P < 0.001$; sexual arousal: $P < 0.001$, see Table S1). SEM clips were rated higher in valence and sexual arousal than control clips (see Table 1).

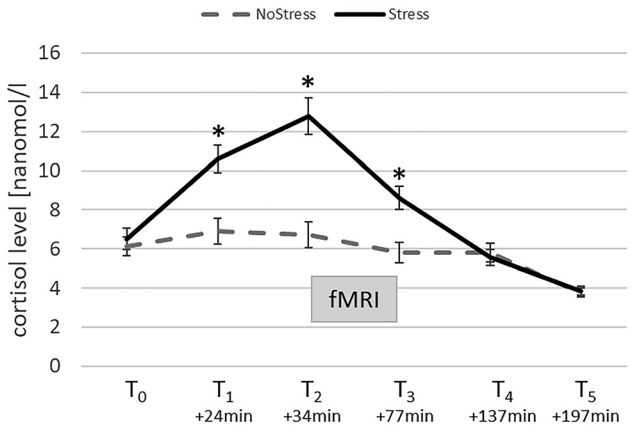

Fig. 2. Cortisol levels of stress and NoStress groups at different time points of the experiment.

Note. T_0 = before TSST and placebo-TSST, respectively; T_1 = after stress induction; T_2 = before entering the scanner; T_3 = after sexual incentive delay task (SIDT); T_4 = after leaving the scanner; T_5: after filling in questionnaires. Error bars depict standard errors. * indicates significant post-hoc tests ($P < 0.05$). The fMRI bar shows the time window of the fMRI experiment reported.

Effect of stress induction – fMRI data

None of the two-sample *t*-tests revealed activation differences between the Stress group and the NoStress group in the ROIs and whole brain analyses for the contrast CueSEM minus CueControl. However, stress induction resulted in significantly higher contrast values DeliverySEM minus DeliveryControl in the dACC (see Table 3).

Effect of cortisol response – correlations with subjective and behavioral data

CortisolResponse was significantly correlated with SexArousal_SEM ($r = 0.17$, $P = 0.032$), however not with any of the reaction time measures.

Effects of cortisol response – correlations with fMRI data

Regression analyses revealed a significant effect of CortisolResponse on the contrast CueSEM minus CueControl in the left and right NAcc and the left dACC (see Table 4 and Fig. 3) for the whole sample. Analyzing the Stress group separately, there was a significant bilateral effect in the NAcc and in the right putamen (see Table 4). For the contrast DeliverySEM minus DeliveryControl, there were no significant correlations in any of the ROIs neither in the whole sample nor in the separate analyses.

Table 4. Regression of fMRI Contrast CueSEM minus CueControl on CortisolResponse

Brain region	Side	MNI coordinates of peak voxel x	y	z	t_{max}	P_{FWE}
		Whole sample				
NAcc	L	−12	14	−10	3.32	0.026
	R	12	14	−8	2.99	0.048
dACC	R	−8	18	30	3.65	0.035
		Stress group				
NAcc	L	−10	14	−10	3.45	0.017
	R	12	12	−10	3.56	0.012
putamen	R	14	12	−10	3.92	0.028

Note. FWE = familywise error corrected; NAcc = nucleus accumbens; dACC = dorsal anterior cingulate cortex.

Moderator analyses (cortisol × person characteristics) – subjective and behavioral data

The moderator analyses, whether the effect of cortisol response on sexual arousal ratings and reaction times were moderated by indices of problematic pornography use, i.e. time spent on pornography use and self-reported problems concerning pornography use (s-IATsex_Sum), revealed no significant results.

Moderator analyses (cortisol × person characteristics) – fMRI data

The regression of the fMRI contrast CueSEM minus CueControl on CortisolResponse was dependent on time spent on pornography use (see Table 5 and Fig. 4). Under low time spent on pornography use ($z = -1$), the correlation of cortisol response and fMRI contrast in dACC appeared negative whereas under high time spent on pornography use ($z = 1$) the correlation appeared positive. In mOFC the moderation effect was the opposite. Low time spent on pornography use ($z = -1$) was associated with a positive correlation of cortisol response and fMRI contrast whereas high time spent on pornography use ($z = 1$) was associated with a negative correlation. We also found the same pattern

Table 3. Comparison of stress and NoStress Group for the fMRI Contrasts CueSEM minus CueControl and DeliverySEM minus DeliveryControl

Result	Brain region	Side	MNI coordinates of peak voxel x	y	z	t_{max}	P_{FWE}
			Contrast CueSEM minus CueControl				
Not significant							
			Contrast DeliverySEM minus DeliveryControl				
Stress > noStress	dACC	L/R	4	32	36	3.83	0.022

Note. FWE = familywise error corrected; dACC = dorsal anterior cingulate cortex.

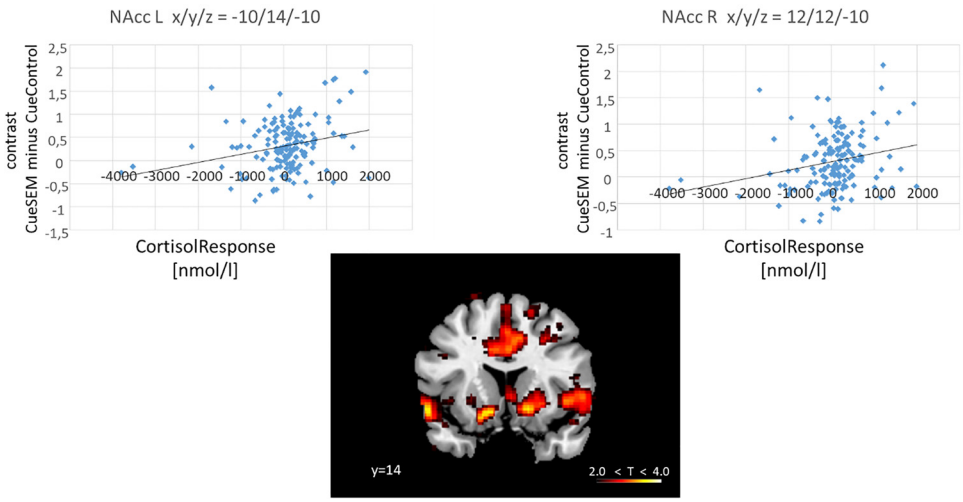

Fig. 3. Correlation Between Contrast Values and Cortisol Response in the left and the right NAcc.
Note. On the left, the linear regression of the contrast CueSEM minus CueControl on CortisolResponse is displayed. On the right, the contrast CueSEM minus CueControl is plotted against the CortisolResponse. Below, a sagittal section (y = 14) of the t-map of the contrast CueSEM minus CueControl is shown.

Table 5. Moderation of the regression of fMRI contrasts on Cortisol Response by average time spent on pornography use

Effect	*B*	*SE*	*t*	*P*	95% CI
		Contrast CueSEM minus CueControl			
		dACC at x/y/z = 0/28/34			
Constant	0.53	0.05	10.57	<0.001	[0.43, 0.63]
CortisolResponse	0.07	0.05	1.36	0.175	[−0.03, 0.17]
Time spent on pornography use	0.24	0.05	4.69	<0.001	[0.14, 0.34]
CortisolResponse × Time spent on pornography use	0.21	0.05	4.15	<0.001	[0.11, 0.31]
		mOFC at x/y/z = 2/64/−8			
Constant	0.06	0.05	1.22	0.223	[−0.04, 0.16]
CortisolResponse	−0.02	0.05	−0.35	0.728	[−0.12, 0.08]
Time spent on pornography use	0.09	0.05	1.82	0.071	[−0.01, 0.19]
CortisolResponse × Time spent on pornography use	−0.27	0.05	−5.26	<0.001	[−0.37, −0.17]
		Contrast DeliverySEM minus DeliveryControl			
		mOFC at x/y/z = 10/62/−12			
Constant	0.30	0.05	6.56	<0.001	[0.21, 0.40]
CortisolResponse	0.02	0.05	0.48	0.631	[−0.07, 0.11]
Time spent on pornography use	0.12	0.05	2.61	0.010	[0.03, 0.22]
CortisolResponse × Time spent on pornography use	−0.19	0.05	−4.11	<0.001	[−0.29, −0.10]

Note. All interaction effects are significant after familywise error correction for the number of voxels in the ROI ($p_{FWE} < 0.05$).
CI = confidence interval; x/y/z = MNI coordinates; dACC = dorsal anterior cingulate cortex; mOFC = medial orbitofrontal cortex.

of moderation in the mOFC for the contrast DeliverySEM minus DeliveryControl.

DISCUSSION

Stress is often reported as motivation for pornography use (Bőthe et al., 2021; Paul & Shim, 2008; Reid et al., 2011). Open questions remain regarding mechanism, namely whether the use of pornography is primarily driven by negative reinforcement learning (pornography use leads to distraction from stress related negative mood states) or also by direct stress and/or cortisol effects on the processing of SEM by increasing the motivational salience of SEM. Further, it is not clear whether the processing of SEM cues and SEM are affected by stress/cortisol in the same way. To address these important research questions, the present study aimed at investigating the effect of stress and of the corresponding level of cortisol on behavioral, subjective and neural responses of the reward system to SEM cues and SEM. A second goal of the present study was to investigate whether the stress effects on the processing of SEM cues and SEM are moderated by indicators of problematic pornography use in generally healthy individuals. Assuming problematic pornography use

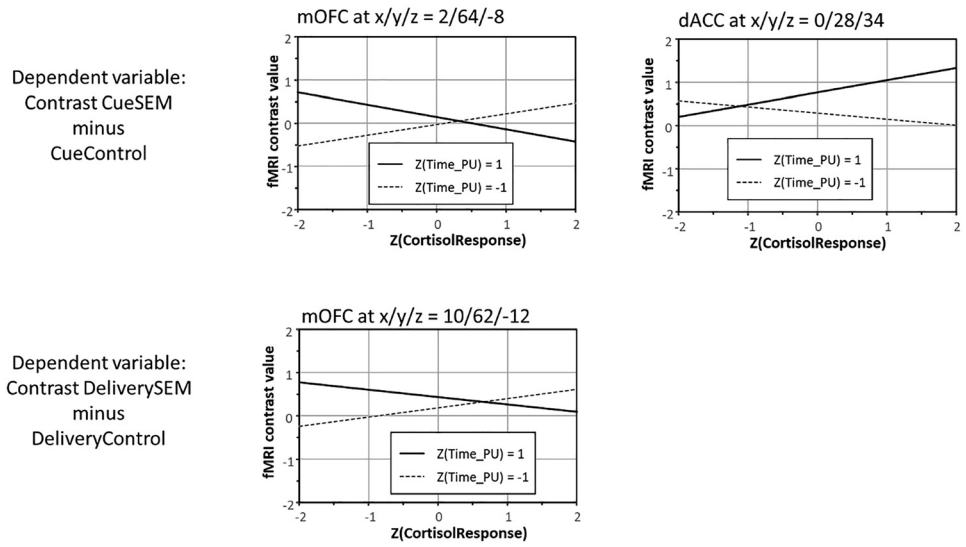

Fig. 4. Moderation of the regression of fMRI contrasts on cortisol response by average time spent on of pornography use per month.
Note. Solid lines show the regression of fMRI contrasts on CortisolResponse if time spent on pornography use (Time_PU) is one *SD* above mean, dashed lines if Time_PU is one *SD* below mean. x/y/z = MNI coordinates; mOFC = medial orbitofrontal cortex; dACC = dorsal anterior cingulate cortex.

shares underlying pathomechanisms with addiction, we hypothesized that changes in the reward system occur due to dysregulation of the stress system during the transition from recreational to addictive behavior as it has been shown in addiction research (Koob & Schulkin, 2019; Piazza & Deroche-Gamonet, 2013; Wemm et al., 2020).

Our experimental setup passed a manipulation check since the sexual incentive delay task (SIDT) resulted in activation of the reward system during the anticipatory and delivery phase as demonstrated in former studies (Gola et al., 2017; Markert et al., 2021; Sescousse, Li, & Dreher, 2015; Stark et al., 2019) and the Trier Social Stress Test (Kirschbaum et al., 1993) resulted in increased cortisol levels and heightened negative mood ratings.

Effect of stress induction and cortisol release on processing of SEM cues and SEM

The effect of stress was analyzed using two approaches. First, we compared the behavioral, subjective and neural responses of the Stress and NoStress group. Using this approach, stress induction did not result in altered behavior (reaction times in the SIDT) or different subjective ratings of the SEM (valence and sexual arousal), but watching sexual film clips (SEM) resulted in higher activation of dACC under stress induction. Second, we analyzed the effect of stress by taking the individual cortisol response to stress into account. We correlated individual cortisol responses to the experimental conditions on one side with the behavioral, subjective rating, and with neural responses of the reward system on the other side. In these analyses, we found that the higher the cortisol response during the experiment, the higher the ratings of sexual arousal for the applied sexual stimuli. At the neural level, the cortisol response was positively correlated with neural responses in the NAcc and dACC to SEM cues but not to SEM. Taking these results of group and correlation approaches together, both suggest that stress increases the motivational salience of stimuli announcing SEM (SEM cues) and SEM. This is in contrast to several studies showing that stress induction/cortisol release result in a decrease of salience indicated by decreased neural activation in the reward system to reward cues and rewarding stimuli (Berghorst et al., 2013; Bogdan & Pizzagalli, 2006; Kinner et al., 2016; Ossewaarde et al., 2011; Porcelli et al., 2012). However, the significance of these studies for the interpretation of the present data might be limited in this respect, since most of these studies used monetary, secondary rewards instead of SEM, which are primary, biologically salient rewards (Georgiadis et al., 2012). Among the few studies on effects of stress on the processing of SEM, the study by Oei et al. (2014) is important for the interpretation of our data, since they also used the TSST (Kirschbaum et al., 1993) for stress induction, but in contrast to the present study subliminally presented, masked sexual pictures. In correspondence with our results, they found that NAcc activation in response to masked SEM was positively correlated with the cortisol response to the TSST. Thus, our study suggests that the individual cortisol stress response in particular is positively related to the salience of SEM indicated by the activation in the reward system. This implies that the use of pornography is not generally rewarding in stress situations but may be for individuals who react with a high cortisol response to stress situations. Following this interpretation, individuals with high cortisol responsivity to stress might be motivated to use pornography not only to distract themselves from the negative mood resulting from stress (negative reinforcement learning) but may experience SEM as particular rewarding in cortisol releasing stress situations. Further research is strongly recommended because this could be a neurobiological risk factor for developing problematic pornography use. Another pointer in this direction might be

the results of Chatzittofis et al. (2016), showing dysregulation of the HPA axis in hypersexual disorder.

Moderating effect of indices of problematic pornography use

A second goal of the study was to examine whether the effect of stress changes when problems regarding pornography use arise. In our cross-sectional study, time spent on pornography use and self-reported problems concerning pornography use were used as dimensional estimates for arising problems. The moderator analyses revealed that time spent on pornography use indeed moderated the effect of cortisol on the activity of the reward system but not self-reported problems concerning pornography use. The differential influence of the two indicators suggests that it is not so much problems with pornography use but rather habitual use that may moderate the effect of stress on SEM processing. Therefore, the results in this healthy sample should not be interpreted in the framework of addiction since not loss of control but habitual use only moderated the effect of cortisol. We observed that more time spent on pornography use in combination with a high cortisol response was associated with diminished processing of SEM cues and SEM in the mOFC. The mOFC activity reflects the subjective positive value of stimuli (Bartra, McGuire, & Kable, 2013; Klein et al., 2020; Kuehn & Gallinat, 2012). This can be interpreted as follows: sexual cues have high positive value among low intensity pornography users under high cortisol levels and a low positive value among high intensity pornography users under high cortisol level. The decrease of subjective value in intense pornography users may be traced back to habituation effects in that these users likely had often used pornography as a coping strategy in stressful, cortisol releasing situations. For dACC, an opposite pattern was observed: The activation of the dACC was highest in high intensity pornography users under high cortisol levels. The dACC is an important part of the reward system as an interface between reward evaluation and action (Bush et al., 2002; Chau, Jarvis, Law, & Chong, 2018). The opposite activation pattern of the mOFC and the dACC might seem contradictory at first glance. However, the dACC seems to be an action-outcome predictor (Alexander & Brown, 2011) and codes reward history (Kolling et al., 2016). Using this interpretation of dACC activity, a frequent pornography use to cope with stress in the past of high intensity pornography users might have built up action-reward expectations resulting in high dACC activity. Summarizing this interpretation, the frequent use of pornography in stress situations might lead to devaluation of SEM in this situation (coded in the mOFC) but high reward expectations (coded in the dACC) due to former experiences in which pornography use often was highly rewarded by masturbation and orgasm (Solano, Eaton, & O'Leary, 2020).

Our results suggest that stress and especially the accompanied cortisol release heightened the neural response of the reward system to cues announcing sexual stimuli as well as sexual stimuli. A higher activation of the reward system might indicate that the motivational impact and the subjective salience of sexual stimuli is increased under stress. With regard to our initial research question, why stress is often claimed as a reason for pornography use (Bőthe et al., 2021; Reid, Li, Gilliland, Stein, & Fong, 2011), it can be stated that not only negative reinforcement learning motivates the use of pornography but likely also a higher subjective value of sexual stimuli under stress. Thus, not only distraction from the stress accompanied negative mood, but also higher motivational salience of sexual stimuli under stress could favor pornography use which may then become the preferred stress coping strategy for some individuals. From our study, individuals with high stress related cortisol response might be especially at risk to develop habitual pornography use and maybe a problematic pornography use later down the line. Therefore, to prevent this development these potentially at-risk individuals should be supported to foster other strategies than pornography use to cope with stress like relaxation techniques, meditation, or sport activities. It is important to remember that we investigated healthy individuals without clinical levels of problematic pornography use. Thus, our results tell less about the effect of stress in problematic pornography users with clinically relevant symptoms. Assuming that problematic pornography use shares etiological commonalities with addictions (Brand et al., 2022; Kraus, Voon, Kor, & Potenza, 2016; Stark et al., 2018) one would expect that stress increases cue reactivity, craving, and triggers relapses (alcohol: Cooney, Litt, Morse, Bauer, & Gaupp, 1997; cocaine: Potenza et al., 2012; Sinha, Fuse, Aubin, & O'Malley, 2000; nicotine dependency: McKee et al., 2011; opioid dependency: Saraiya et al., 2021), although also decreased craving was reported (gambling disorder: Wemm et al., 2020). Therefore, it is highly warranted to expand studies of stress on cue reactivity to patients suffering from problematic pornography use to gain further insights in the interplay between stress and pornography craving. This might foster treatment strategies, which specifically address stress management especially in individuals with anomalies in the interplay between the stress and the reward system.

Limitations

Our findings must be interpreted in the light of some limitations. As a first limitation, we have studied only heterosexual men. This was done, because the prevalence of CSBD in men is higher than in women and we wanted to homogenize the sample. Second, we included in our sample only men without clinically relevant problematic pornography use. Therefore, we could not draw direct conclusions to a clinical sample. Third, we used the same sexual material for all participants. Maybe the results would be even clearer if we had used individualized stimuli, considering more adequately the individual pornography use history.

Conclusions

Taken all results together, our results show that stress induction and especially the concomitant cortisol response

enhanced the neural activation in the reward system to sexual cues. Cortisol responses were associated with increased incentive value of sexual cues, which may help to explain why stress could be a risk factor for developing problematic pornography use.

Founding sources: The work was funded by an individual project grant of the German Research Foundation (DFG, STA 475/16-1).

Authors' contribution: RS mainly planned the study concept and design, supervised the data collection and the data analyses, and wrote the manuscript. OK also contributed to study concept. SK, OK, CM, and JS were involved in the setup of the study, analysis and interpretation of the data, and finalizing the manuscript. BW was involved in the statistical analyses and interpreting the results.

Conflict of interest: All authors report no financial or other relationship relevant to the subject of this article.

SUPPLEMENTARY MATERIALS

Supplementary data to this article can be found online at https://doi.org/10.1556/2006.2022.00037.

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