Reduced brain activity and functional connectivity during creative idea generation in individuals with smartphone addiction

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Abstract

Since the coronavirus disease 2019 outbreak, the frequency of smartphone use has surged, which has caused an increase in smartphone addiction among individuals. Smartphone addiction can impair various cognitive abilities. However, to date, the impact of smartphone addiction on creative cognition remains unclear. The current functional near-infrared spectroscopy study compared neural differences between smartphone addiction tendency (SAT) and healthy control (HC) individuals during creative idea generation. In particular, by manipulating a key component of creative cognition, that is, overcoming semantic constraints, we explored whether SAT individuals could overcome semantic constraints. Both the SAT and HC groups completed the alternate uses task (AUT) in semantic constraint and unconstraint conditions. The results indicated that the prefrontal cortex (PFC) and temporal regions were less active during AUT in the SAT group than in the HC group. In the SAT group, the PFC was less active under constraint than unconstraint conditions. Moreover, both task-related and resting-state functional connectivity analyses indicated weaker coupling between the PFC and temporal regions in the SAT than in the HC group. Furthermore, the left dorsolateral PFC mediated the effect of smartphone addiction on creative performance. These findings provide unprecedented neuroimaging evidence on the negative impact of smartphone addiction on creative cognition.

Key words: smartphone addiction; creative cognition; functional near-infrared spectroscopy; functional connectivity

Introduction

The use of smartphones has become an increasingly popular behaviour in people's lives. However, an increased number of people find it difficult to minimise the use of smartphones, leading to the emergence of smartphone-addictive behaviours (Panova and Carbonell, 2018; Busch and McCarthy, 2021). In particular, the rapid spread of coronavirus disease 2019 around the world has led to a dramatic increase in the number of smartphone addicts due to home isolation (Caponnetto *et al.*, 2021). Smartphone addiction is an emerging behavioural addiction, which refers to excessive dependence on and abuse of smartphones by individuals (Kwon *et al.*, 2013; Billieux *et al.*, 2015). Notably, smartphone addiction has been reported to have negative impacts on individuals' cognitive functions, such as attention (Choi *et al.*, 2021; Lee *et al.*, 2021), perception (Dong *et al.*, 2014) and memory (Hartanto and Yang, 2016; Tanil *et al.*, 2020). Nevertheless, the influence of smartphone addiction on individuals' advanced

cognition is still unclear. Smartphone addiction may impair flexible cognitive processes (Dong *et al.*, 2014), such as those that contribute to creative cognition. However, to our knowledge, the influence of smartphone addiction on creative cognition has not been explored.

Given the negative effects and high incidence of smartphone addiction (Zou *et al.*, 2021), it is essential to uncover the underlying mechanisms, especially the neural mechanisms, by which smartphone addiction affects creative cognition. Creative cognition is defined as the ability to generate original and useful products (Sternberg and Lubart, 1999). It is a core cognitive element that allows for daily flexible problem solving and the generation of new ideas. The main components of creative cognition are (i) overcoming the semantic constraints of existing knowledge, which involves goal-directed behaviour through cognitive control, and (ii) building unusual associations to expand the existing structure of knowledge, which involves the spontaneous and unconstrained

generation of novel associations (Ward *et al.*, 1997; Abraham, 2014; Marron and Faust, 2019).

According to the problematic mobile phone use model (Billieux *et al.*, 2015), the lack of planning or reduced cognitive control is a crucial contributor to smartphone addiction behaviour. Previous studies have also indicated that impaired cognitive control is a prominent feature of smartphone addicts, characterised by an inability to focus on task-related information and an inability to suppress dominant, automatic responses (Van Deursen *et al.*, 2015; Li *et al.*, 2021). In fact, previous studies have emphasised the contribution of cognitive control to the generation of creative ideas (Beaty *et al.*, 2016; Benedek and Fink, 2019). During creative idea generation, known ideas are often initially retrieved, which acts as a source of interference allowing the retrieval process to focus on familiar and dominant ideas (Abraham, 2014). In this context, cognitive control is needed to drive the retrieval process of novel and remote information. In particular, the overcoming semantic constraints component of creative cognition is mainly achieved by cognitive control, which appears to mitigate the constraint effect during novel idea retrieval by abandoning dominant ideas and overcoming interference of irrelevant stimuli (Beaty *et al.*, 2017). Therefore, smartphone addiction may affect the overcoming semantic constraints component. However, several studies have overlooked this crucial cognitive process. Thus, it is necessary to explore whether smartphone addiction could influence creative cognition, especially whether it could influence the overcoming of semantic constraints.

Emerging studies (Wilmer *et al.*, 2019; Horvath *et al.*, 2020; Ahn *et al.*, 2021; Lee *et al.*, 2021) using neuroimaging methods have demonstrated that the structural and functional abnormalities of smartphone addicts are predominantly in the prefrontal cortex (PFC). The PFC region is a key node of the executive control network (ECN) and is responsible for self-control and cognitive control (Diamond, 2013; Yuan and Raz, 2014). For instance, smartphone addiction is associated with reduced grey matter volumes (GMVs) in the superior frontal gyrus and inferior frontal gyrus (IFG) (Wang *et al.*, 2016). Moreover, a recent study reported that smartphone addicts had aberrant cortical activations in the frontoparietal and temporoparietal areas during cognitive conflict tasks, indicating impaired attentional control of task-irrelevant stimuli (Choi *et al.*, 2021). In addition, the functional connectivity between seeds of PFC was weaker in smartphone addicts than that in controls, indicating abnormal connectivities between the PFC and other regions (Chun *et al.*, 2018; Lee *et al.*, 2021).

Studies on creative cognition have reported the critical role of the PFC and temporal cortex in the generation of original ideas (Gonen-Yaacovi *et al.*, 2013; Wu *et al.*, 2015). The PFC is involved in top-down control during the formation of novel associations (Neubauer and Fink, 2009; Lu and Hao, 2019). In addition, the temporal cortex is closely associated with the semantic association process of novel ideas (Shen *et al.*, 2017). Specifically, the temporoparietal junction (TPJ) is the core of the default mode network (DMN), and its activation contributes to the attentional focus during creative idea generation (Ritter *et al.*, 2014). The superior temporal gyrus (STG) and the middle temporal gyrus (MTG) are engaged in the construction of novel semantic associations (Shen *et al.*, 2017; Chen *et al.*, 2018). Notably, emerging studies on resting-state and task-based functional connectivity also provide trait and state evidence for brain activity patterns of creative cognition (Finn *et al.*, 2015; Beaty *et al.*, 2018), although combined evidence for resting-state and task-based functional connectivity is lacking. Some studies (Beaty *et al.*, 2014, 2015; Wei *et al.*, 2014; Shi *et al.*, 2018) suggested that creative cognition was identified

with unique features of functional connectivity, with the cooperation of ECN and DMN might support both the suppressions of dominant ideas and retrieval of novel information. Therefore, we chose the PFC and temporal cortex as the regions of interest (ROIs).

This study aimed to explore different patterns of cortical activation and functional connectivity during a creative task between smartphone addiction tendency (SAT) and healthy control (HC) individuals using functional near-infrared spectroscopy (fNIRS). Specifically, we manipulated the overcoming constraints component to uncover whether SAT individuals could overcome semantic interference. We also compared differences in resting-state and task-based functional connectivity between the two to provide further evidence. Participants in the SAT group (potential smartphone addicts) and the HC group were screened in a nonclinical population. Focusing on the creative cognition of potential smartphone addicts is important because they are more likely to face daily creative problems than the clinical population. The fNIRS is a safe, portable and quiet neuroimaging tool (Ferrari and Quaresima, 2012). It has advantages in creative tasks because it does not require participants to stay in a closed and noisy space, such as functional magnetic resonance imaging (fMRI), which allows individuals to be able to generate novel ideas spontaneously (Schecklmann *et al.*, 2010; Niu and He, 2014). The alternate uses task (AUT) was used to evaluate creative cognition which is a widely used and effective creative task (Gonen-Yaacovi *et al.*, 2013; Wu *et al.*, 2015). In this task, the semantic constraint was achieved by intensifying participants' associations of the common uses for objects in memory before the AUT, which has been proven to be effective (Abraham *et al.*, 2012; Beaty *et al.*, 2017). The recall of common uses to objects can strengthen existing semantic connections in memory, thereby facilitating the potential response tendencies to familiar information when attempting to generate novel ideas. These potential response tendencies can induce semantic constraints in the generation of novel ideas (Beaty *et al.*, 2017). We hypothesised that the SAT and HC groups might exhibit different levels of cortical activation and functional connectivity during the AUT. In particular, the SAT group might exhibit reduced brain activity when semantic constraints exist.

Methods
Participants

A total of 503 students (age = 18–25 years) from Shaanxi Normal University were screened with the Smartphone Addiction Scale (SAS; Kwon *et al.*, 2013). In line with prior studies (Horvath *et al.*, 2020; Lee *et al.*, 2021), students with SAS scores in the upper 27% of the total distribution were classified as the SAT group, and students with SAS scores in the lower 27% of the total distribution were classified as the HC group. We invited students who met these criteria to participate in this experiment, and 48 of them responded to the invitation. Finally, 24 students (16 females and 8 males) were recruited into the SAT group, and 24 students (15 females and 9 males) were recruited into the HC group.

Participants were given the following questionnaires: Raven's Progressive Matrices test (Raven and Court, 1938), the State-Trait Anxiety Inventory-State scale (Spielberger, 1983) and the Beck Depression Scale-II (Beck *et al.*, 1996). There was a significant difference between the SAT and HC groups in the SAS score, t (46) = 25.95, $P < 0.001$ (Table 1). A significant group difference in anxiety state score was also observed, t (46) = 2.63, $P = 0.015$.

Table 1. Demographic information of the SAT and HC groups

	Group			
	SAT, *M* (SD)	HC, *M* (SD)	*t*	*P*-value
Age	19.79 (1.28)	19.42 (1.41)	0.93	0.362
SAS	146.75 (5.38)	70.42 (11.75)	25.95	<0.001[**]
RPM	53.83 (10.02)	53.01 (12.74)	0.39	0.699
BDI	5.04 (1.76)	4.08 (1.35)	1.87	0.074
STAI-S	33.54 (5.86)	30.17 (3.84)	2.63	0.015[*]

Notes. RPM = Raven's Progressive Matrices test; BDI = Beck Depression Inventory-II; STAI-S = State-Trait Anxiety Inventory-State scale.
[*]P < 0.05,
[**]P < 0.001.

Each participant was right-handed and had a normal or corrected-to-normal vision. Participants had no history of psychiatric disorders, had no medications or non-medication that might affect the central nervous system and had no other behavioural addictions (e.g. gambling or food). The study complied with the Declaration of Helsinki and was approved by the local ethics committee of Shaanxi Normal University. Written informed consent was obtained from each participant.

Procedures

Based on previous studies (Fink and Benedek, 2014; Beaty *et al.*, 2017; Kleinmintz *et al.*, 2018), the AUT was used, and the experimental procedure was divided into three stages: the learning stage, consolidation stage and formal experimental stage (Figure 1A).

The purpose of the learning stage was to allow participants to form semantic connections between objects and their common uses. During the learning stage, each object and its two most common uses were listed twice in turn. Participants were required to remember the objects and their common uses. First, a fixation was presented for 1 s. Then an object and its use were presented for 4 s. Participants were instructed to remember the object and its use. There were 6 objects and 12 common uses for learning.

After the learning stage was completed, the consolidation stage began. The purpose of this stage was to strengthen the semantic connections between the objects and common uses by assessing participants' memory for object-use pairs. In this stage, participants were tested on the common uses of the objects learned during the learning stage. First, a fixation was presented for 1 s, followed by an object that the participants had learned during the learning stage for 2 s. Then, a question mark was displayed for 4 s, during which participants were required to recall and speak the common uses of the object. Finally, the correct uses were presented, and participants needed to check whether their answers were correct. They pressed '1' if the answers were correct and '2' if the answers were incorrect or they did not remember the answer. If they pressed '2', the test for that object would start again. This stage ended when the participants correctly reported the common uses of all objects. The fNIRS signals were not recorded online during the learning and consolidation stages.

The formal experimental stage included the AUT and the recall common use task which served as a control task. The AUT contained two conditions that differed in semantic constraints, the constraint and unconstraint conditions. The constraint condition presented objects that were previously learned in the learning stage, while the unconstraint condition presented objects that had not been previously learned (Beaty *et al.*, 2017). During this stage, after a fixation presented for 8 s, the task instruction ('create original uses' or 'recall common uses') was presented for 3 s. Then an object was presented for 30 s, during which participants completed the task according to the instruction. In the AUT, participants were instructed to speak as many original uses of the object as possible. Although some trials would include objects in the learning stage, they should always try to generate original uses. The recall common use task required participants to report
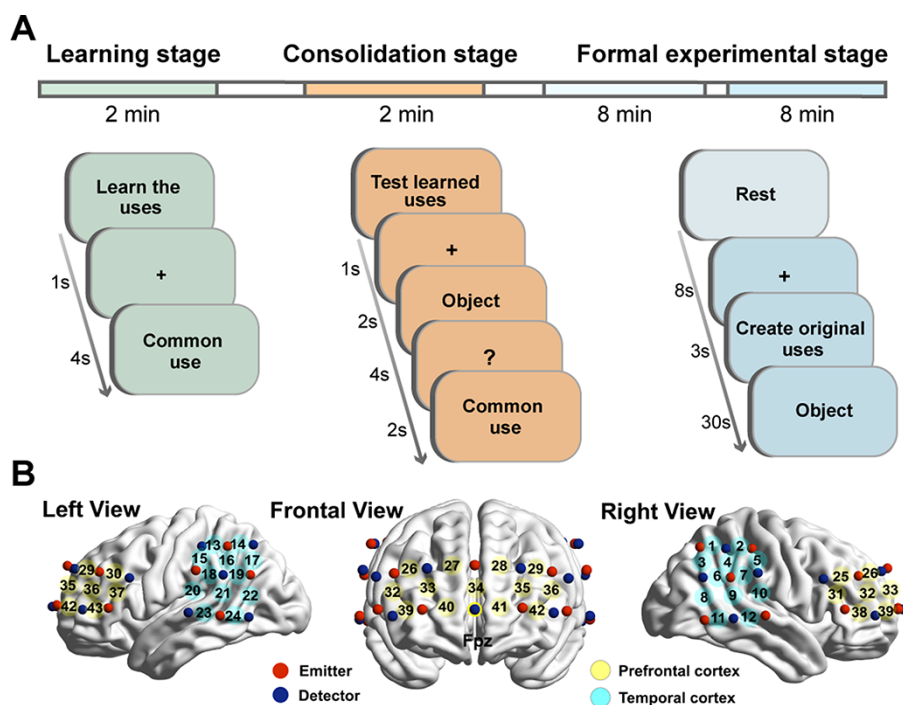

Fig. 1. Experimental procedure and channel locations. (A) The experimental procedure contained the learning stage, consolidation stage and formal experimental stage. (B) Channel locations. The channels covered the PFC and temporal cortex.

the common uses of objects, and the process of this task was the same as that of the AUT.

Participants' verbal responses were recorded online using a voice recorder. There were six learned objects and six unlearned objects in the AUT. Trials were presented randomly in each task. Before the formal experiment, a practice experiment was completed to help participants familiar with the experimental procedure. After the experiment, we evaluated the effectiveness of semantic constraint manipulation (see Supplementary Section 1.1).

Each participant experienced two sessions of fNIRS recordings: the former for the 8 min resting-state session and the latter for the online recordings during the formal experimental stage. For the resting-state fNIRS recording, participants were instructed to close their eyes and try to keep as motionless as possible.

Assessment of performance on AUT task

The AUT performance was evaluated by fluency, flexibility and originality (Runco, 1991; Kaufman *et al.*, 2008). Fluency was defined as the number of responses. Flexibility referred to the number of categories of responses. Originality was assessed through the consensus assessment technique (CAT; Amabile, 1982; Wang *et al.*, 2022). The CAT is an accurate assessment of the level of creativity achieved through a comprehensive evaluation of creative products by experts in a specific field (Batey, 2012). Thus, three experienced experts rated each response using a five-point scale (1 = not novel at all; 5 = very novel). The inter-rater reliability across experts was satisfactory (originality internal consistency coefficient, ICCs = 0.92; flexibility ICCs = 0.91) (Koo and Li, 2016). The scores of the three experts were averaged to obtain a final score for each dimension.

fNIRS data acquisition and analysis
fNIRS data acquisition

The hemodynamic responses were measured by the fNIRS optical topography system (LABNIRS, Shimadzu Corporation, Kyoto, Japan), with a sampling rate of 12 Hz. The fNIRS measurements were conducted with 2×7 (including seven emitters and seven detectors) and two 3×3 (including nine emitters and nine detectors) optode probe sets (Figure 1B). A total of 43 measurement channels (CHs) (inter optode distance = 3 cm) were generated, defined as the area between the pairs of emission–detector probes. The patch was placed according to the International 10–20 system (Xia *et al.*, 2013). The PFC and temporal regions were defined as ROIs (Supplementary Table S1). The exact locations were confirmed by a 3D-digitiser (FASTRAK; Polhemus, USA) and converted into the channel location on an estimated Montreal Neurological Institute coordinate (Singh *et al.*, 2005).

fNIRS data analysis

The offline fNIRS signals were analysed using NIRS_SPM (Ye *et al.*, 2009), with the sampling rate being down to 10 Hz. The fNIRS signals were pre-processed using the hemodynamic response function filter and wavelet minimum description length detrending algorithm (Brigadoi *et al.*, 2014). The concentration values of hemodynamic signals (Maki *et al.*, 1995) were calculated according to the modified Beer–Lambert Law (Cope and Delpy, 1988). The oxygenated haemoglobin (HbO) data were analysed in the present study (Strangman *et al.*, 2002). The general linear model was applied to estimate the intensity of cortical activation. Subsequently, beta values were obtained, representing the intensity of

the hemodynamic response. In line with previous studies (Wang *et al.*, 2019; Li *et al.*, 2022), the beta values in the recall common condition were subtracted from the beta values in each condition, and the final beta values were analysed. Then the group (SAT and HC) × the semantic constraint (constraint and unconstraint) two-way mixed (ANOVA)s Analysis of Variance were performed on the beta values across each channel. All of the following results were controlled using the false discovery rate (FDR).

Time-series analysis

To further investigate the pattern of cortical activity over time between the HC and SAT groups, we performed the time-series analysis of the channels with significant cortical activation in each condition. We compared the time series of pre-processed signals of the first two and last two trials in the AUT. This allowed the comparison of time-based signal changes in HbO concentration between the SAT and HC groups during the early and late stages of the task. First, we superimposed and averaged the time-series signals of the first two trials during the AUT (the first and second trials, six trials in total) as the early stage. We superimposed and averaged the time-series signals of the last two trials during the AUT (the fifth and sixth trials) as the late stage. Thus, we obtained a time series of HbO concentration from 0 to 30 s after object onset for each condition. Next, we divided the 30 s time series into six epochs equally (each 5 s is considered as one epoch). Finally, we performed the task stage (early and late) × the semantic constraint (constraint and unconstraint) repeated measures ANOVA on each epoch in both the SAT and HC groups.

Functional connectivity analysis

The psycho-physiological interaction (PPI) analysis (Friston *et al.*, 1997; O'Reilly *et al.*, 2012) was used to assess task-based functional connectivity. Based on previous studies (Gonen-Yaacovi *et al.*, 2013; Sepede *et al.*, 2016; Sharifat *et al.*, 2018), bilateral dorsolateral prefrontal cortex (DLPFC) was defined as seed regions. The regressor of the experimental design included either the HC group or the SAT group condition versus control condition, respectively. The PPI term was generated, representing the connectivity strength. Subsequently, we conducted the group (SAT and HC) × the semantic constraint (constraint and unconstraint) two-way mixed ANOVAs on connectivity strength.

The resting-state functional connectivity was analysed through a whole-brain correlation analysis approach. The artefacts were removed using the bandpass filter (0.001–0.01 Hz). Subsequently, Pearson's correlation analysis was conducted on the HbO time series and the symmetry matrix (43×43) of the correlation value was obtained, indicating the functional connectivity mapping of the brain regions. The correlation values were then transformed using Fisher's *r-z* (Fisher, 1915; Niu and He, 2014). One-way ANOVAs were performed to compare the differences in functional connectivity between the HC and SAT groups.

Finally, we calculated the correlation between brain neural activity (cortical activation and resting-state functional connectivity) and AUT score through Pearson's correlation analyses. In addition, we also calculated the correlation between brain neural activity and the level of smartphone addiction (SAS score). Subsequently, mediation analyses and multi-group analyses were conducted using (AMOS) Analysis of Moment Structures 23.0 to investigate whether cortical activation would mediate the effect of smartphone addiction on creative performance and whether these mediating effects differ significantly under constraint and
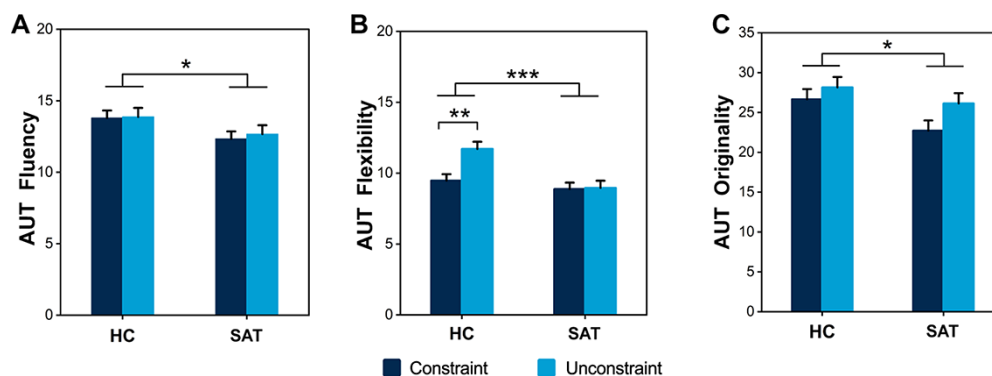
Fig. 2. Behavioural results of AUT in (A) fluency, (B) flexibility and (C) originality. Error bars represent standard errors of the mean. *P < 0.05, **P < 0.01 and ***P < 0.001.

unconstraint conditions. The statistical significance of the mediating effect was checked by the 95% confidence interval (CI) of 5000 bootstrapping samples. Model fit was evaluated by the following indices: chi-squared test (χ^2), comparative fit index (**CFI**), Tucker–Lewis index (**TLI**), root-mean-square error of approximation (**RMSEA**).

Results
Behavioural results
The group (SAT and HC) × the semantic constraint (constraint and unconstraint) two-way mixed ANOVAs were conducted on the fluency, flexibility and originality scores. The results revealed significant main effects of group [fluency: F (1, 46) = 4.394, P = 0.042, η^2_p = 0.087; flexibility: F (1, 46) = 14.97, P < 0.001, η^2_p = 0.245 and originality: F (1, 46) = 4.78, P = 0.034, η^2_p = 0.094], with significantly higher AUT score in the HC group than in the SAT group (Supplementary Table S2). The significant interaction between the group and semantic constraint was observed on flexibility, F (1, 46) = 4.877, P = 0.032, η^2_p = 0.096. Bonferroni-corrected simple effect analysis indicated that in the HC group, flexibility score was significantly higher in the unconstraint condition than in the constraint condition, P < 0.001 (Figure 2).

fNIRS results
Cortical activation
The main effects of the group and the semantic constraint were significant at the right medial prefrontal cortex (MPFC) (BA10; CH33), left DLPFC (BA9/46; CH30 and CH36), left IFG (BA45; CH37), right TPJ (BA40; CH6 and CH7), right STG (BA22; CH9 and CH10) and right MTG (BA21; CH12) (Supplementary Table S3). The beta values in the HC group were significantly higher than those in the SAT group at the right MPFC (CH33, P = 0.005), left DLPFC (CH30, P < 0.001; CH36, P = 0.014), left IFG (CH37, P = 0.009), right TPJ (CH6, P = 0.005), right STG (CH9, P = 0.005; CH10, P < 0.001) and right MTG (CH12, P = 0.006) (Supplementary Table S4). Importantly, the group × semantic constraint interactions were significant at the right MPFC (BA10; CH33), left DLPFC (BA9/46; CH30), left IFG (BA45; CH37) and right TPJ (BA40; CH6). Bonferroni-corrected simple effect analyses revealed that in the SAT group, higher beta values in the unconstraint condition than in the constraint condition at the right MPFC (CH33, P < 0.001), left DLPFC (CH30, P < 0.001), left IFG (CH37, P = 0.001) and right TPJ (CH6, P < 0.001) were observed (Figure 3).

Time-series analysis
The results revealed that in the HC group, the main effect of the task stage was significant on the fourth epoch [16–20 s; F (1, 46) = 4.43, P = 0.047, η^2_p = 0.174] at the right MPFC (CH 33), with significantly higher HbO concentrations in the early stage than in the late stage (Figure 4A). In the SAT group, the main effects of the task stage were significant on the second epoch [6–10 s; F (1, 46) = 4.37, P = 0.049, η^2_p = 0.172] and the third epoch [11–15 s; F (1, 46) = 4.45, P = 0.047, η^2_p = 0.175] at the left DLPFC (CH 30), with significantly higher HbO concentrations in the early stage than in the late stage. In addition, the main effect of the semantic constraint was significant on the fifth epoch [21–25 s; F (1, 46) = 4.43, P = 0.047, η^2_p = 0.174] at the left DLPFC (CH 30), with significantly higher HbO concentrations in the unconstraint condition than in the constraint condition (Figure 4B).

Functional connectivity analysis
When the bilateral DLPFC were the seed regions, the ANOVAs results revealed that there were significant main effects of the group between left DLPFC seed and left IFG [F (1, 46) = 4.11, P = 0.048, η^2_p = 0.082] (Figure 5A), right DLPFC seed and right TPJ [F (1, 46) = 4.21, P = 0.046, η^2_p = 0.084] (Figure 5B), with the stronger connectivity strengths in the HC group than in the SAT group. Importantly, we observed the significant group × semantic constraint interactions between left DLPFC seed and right MTG [F (1, 46) = 4.177, P = 0.047, $\eta 2p$ = 0.083], left DLPFC seed and right IFG [F (1, 46) = 5.273, P = 0.026, $\eta 2p$ = 0.103]. Bonferroni-corrected simple effect analyses revealed that the connectivity strengths in the unconstraint condition were stronger than in the constraint condition in the SAT group between left DLPFC seed and right MTG (P = 0.002), left DLPFC seed and right IFG (P = 0.007).

In addition, the results of resting-state functional connectivity revealed that the connectivity strengths in the HC group were stronger than in the SAT group within the temporal region (right TPJ–left MTG and right TPJ–right MTG) and between the PFC and temporal regions (left IFG–right MTG, left IFG–left MTG, left MPFC–right TPJ and left MPFC–left TPJ) (Figure 5C; Supplementary Table S5).

Correlation and mediation analysis
The correlation analysis between cortical activation and AUT score revealed that in the SAT group, originality scores and
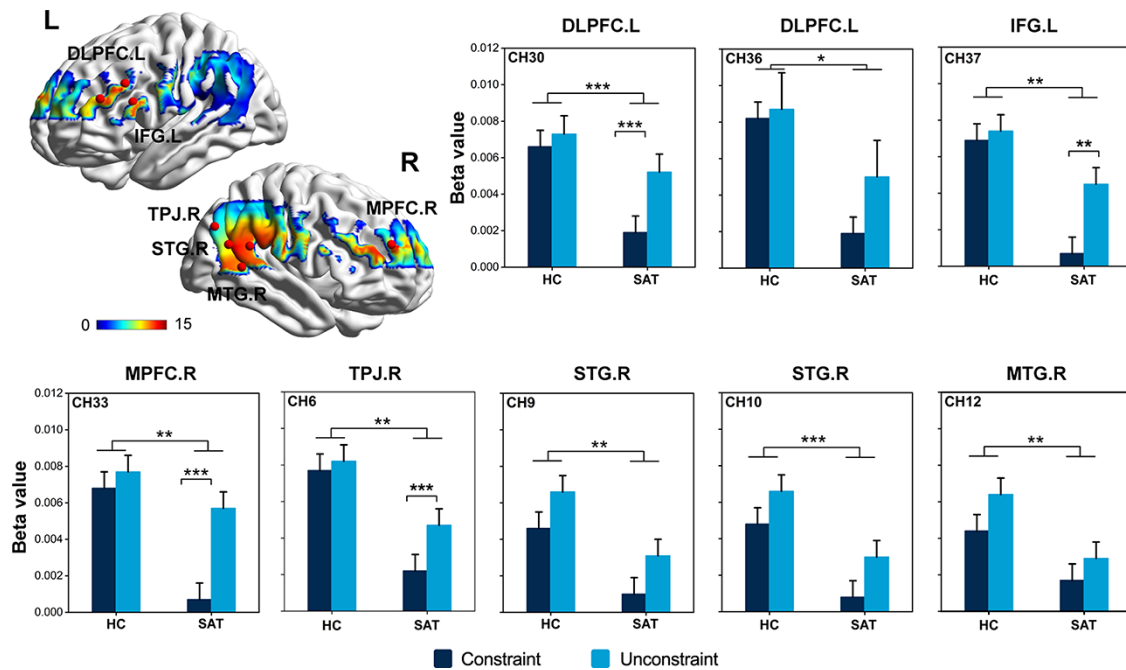
Fig. 3. Cortical activation results obtained during AUT. L, left hemisphere; R, right hemisphere. Error bars represent standard errors of the mean. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$ and FDR corrected.
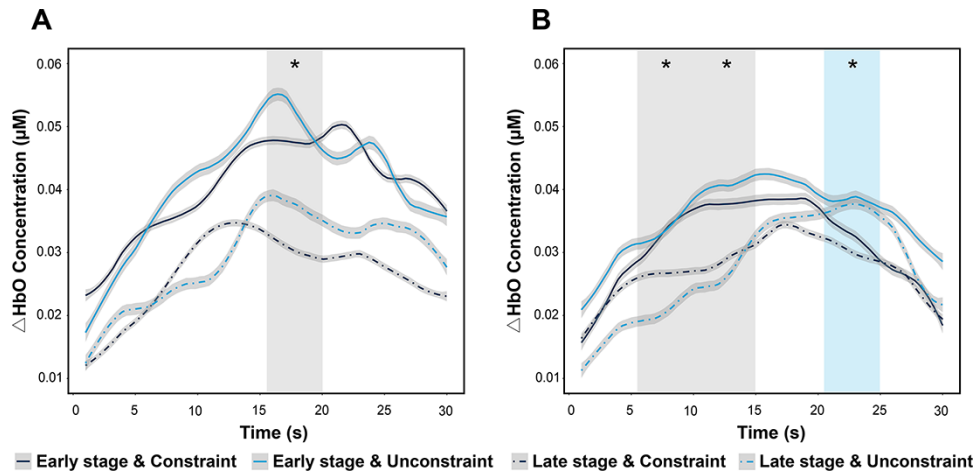

Fig. 4. Time series of the HbO concentration during creative idea generation in each group. (A) Time series of the HbO concentration in the HC group at the right MPFC. (B) Time series of the HbO concentration in the SAT group at the left DLPFC. The ribbons of the lines represent the 95% CIs. *$P < 0.05$.

beta values were positively correlated in the unconstraint (right STG: $r = 0.449$, $P = 0.041$; left DLPFC: $r = 0.547$, $P = 0.015$; left IFG: $r = 0.42$, $P = 0.043$) and constraint (right STG: $r = 0.416$, $P = 0.043$; left DLPFC: $r = 0.656$, $P = 0.005$) conditions (Figure 6A). The correlation analysis between cortical activation and SAS score revealed that in the SAT group, the SAS scores were negatively correlated with beta values at left DLPFC (constraint: $r = -0.591$, $P = 0.005$; unconstraint: $r = -0.463$, $P = 0.023$) (Figure 6B).

In addition, the correlation analysis between resting-state functional connectivity and AUT score revealed that in the SAT group, connectivity strengths were positively correlated with originality scores in both the unconstraint (left MPFC–right TPJ, $r = 0.675$, $P < 0.001$) and constraint (left IFG–left TPJ, $r = 0.431$, $P = 0.043$) conditions (Figure 6C). Moreover, in the HC group, connectivity strength was positively correlated with flexibility score

in the constraint (right TPJ–right MTG, $r = 0.579$, $P = 0.016$) condition (Figure 6D). The correlation analysis between resting-state functional connectivity and SAS score revealed that in the SAT group, the SAS scores were negatively correlated with connectivity strength in the right TPJ–left MTG ($r = -0.573$, $P = 0.007$) and the left MPFC–left TPJ ($r = -0.562$, $P = 0.008$) (Figure 6E).

The results of mediation analysis indicated that the left DLPFC had significant indirect effects on the association between smartphone addiction and originality both in the constraint [$\beta = -0.369$, $P = 0.007$, 95% CI (−0.725, −0.096)] and unconstraint ($\beta = -0.279$, $P = 0.012$, 95% CI (−0.676, −0.024)] conditions. Subsequent multi-group analysis indicated that the differences in fit indices between the models were not all less than 0.01 (ΔCFI $= -0.142$, ΔTLI $= 0.024$ and ΔRMSEA $= -0.012$), indicating that the mediating effect of the left DLPFC between the constraint and unconstraint conditions was not significantly different (Figure 7). In addition, the model
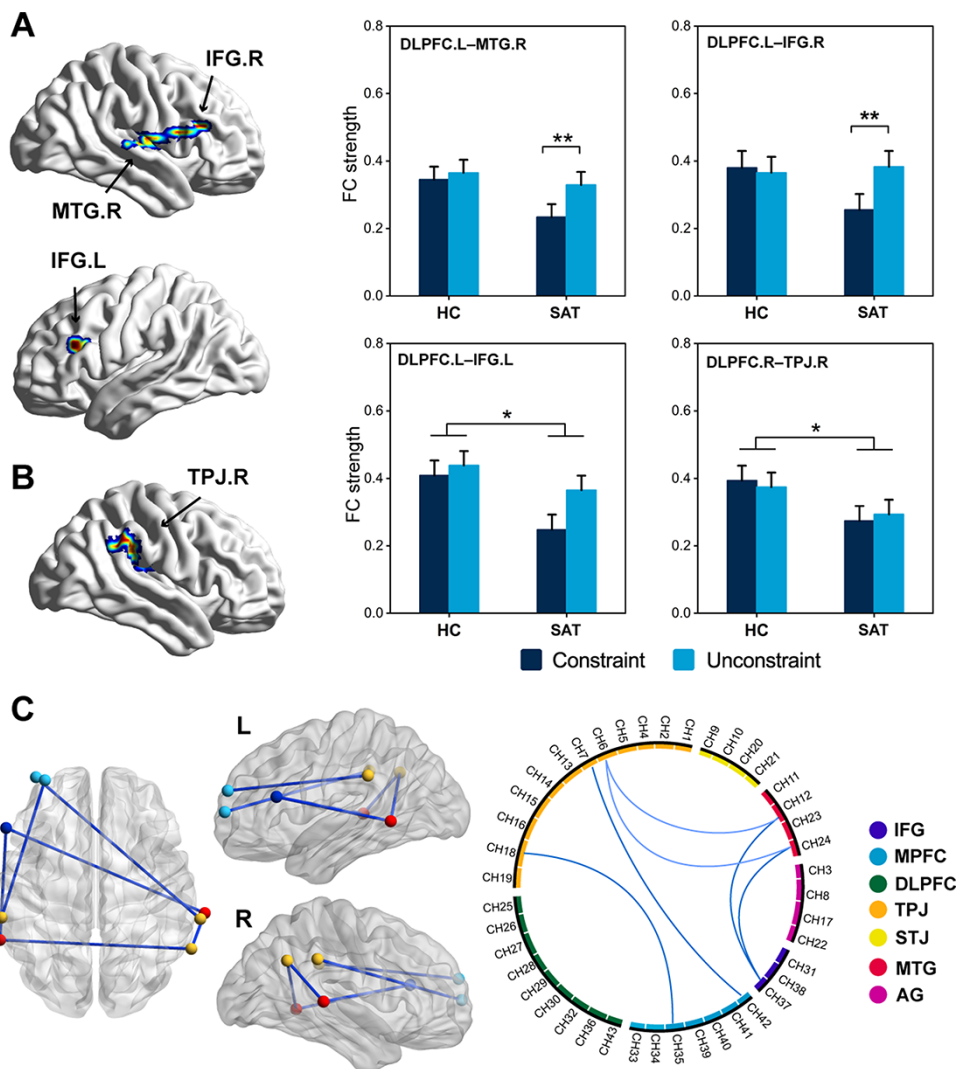
Fig. 5. Functional connectivity results. (A) The significant difference of tasked-based functional connectivity in each condition with the seed at the left DLPFC. (B) The significant difference of tasked-based functional connectivity in each condition with the seed at the right DLPFC. (C) Group difference of resting-state functional connectivity in ROI pairs. L, left hemisphere; R, right hemisphere; AG, angular gyrus. Error bars represent standard errors of the mean. *P < 0.05, **P < 0.01, ***P < 0.001 and FDR corrected.

fit revealed a good fit, $\chi^2/df = 1.78$, **CFI** $= 0.954$, **TLI** $= 0.903$ and **RMSEA** $= 0.078$.

Discussion

This study aimed to compare the neural differences in creative cognition between smartphone addiction tendencies and healthy individuals, especially whether individuals with smartphone addiction tendencies could overcome semantic constraints. To our knowledge, this study was the first attempt to uncover the neural mechanism underlying the influence of smartphone addiction on creative idea generation. We found that smartphone addiction had a negative impact on creative cognition, which was reflected in cortical activities and functional connectivity patterns in the PFC and temporal regions.

Specifically, behavioural results revealed that the SAT group performed worse than the HC group on fluency, flexibility and originality dimensions. Previous studies indicated that the interaction between the inhibition of stereotypical automatic ideas and the generation of original associations would facilitate creative idea generation (Abraham, 2014; Marron and Faust, 2019).

However, smartphone addiction has been reported to impair individuals' executive function and cognitive flexibility, as reflected by impaired inhibition of automatic responses and difficulty in switching between conceptual categories which is not conducive to flexible retrieval of novel information (Dong *et al.*, 2014; Billieux *et al.*, 2015; Chen *et al.*, 2016). Therefore, the lower creative performance of the SAT group than the HC group may be due to their reduced retrieval of novel and remote information. In addition, on the flexibility dimension, the flexibility scores under the constraint condition were significantly lower than those under the unconstraint condition in the HC group. This finding is consistent with previous studies (Beaty *et al.*, 2017; Frith *et al.*, 2022), indicating that semantic constraint could inhibit the process of suppressing salient responses to retrieve the original information. This could make it difficult for individuals to retrieve multiple categories of concepts.

However, on the originality dimension, we did not find a significant interaction between the group and the semantic constraint, although we observed that in the SAT group, the originality scores in the constraint condition were lower than those
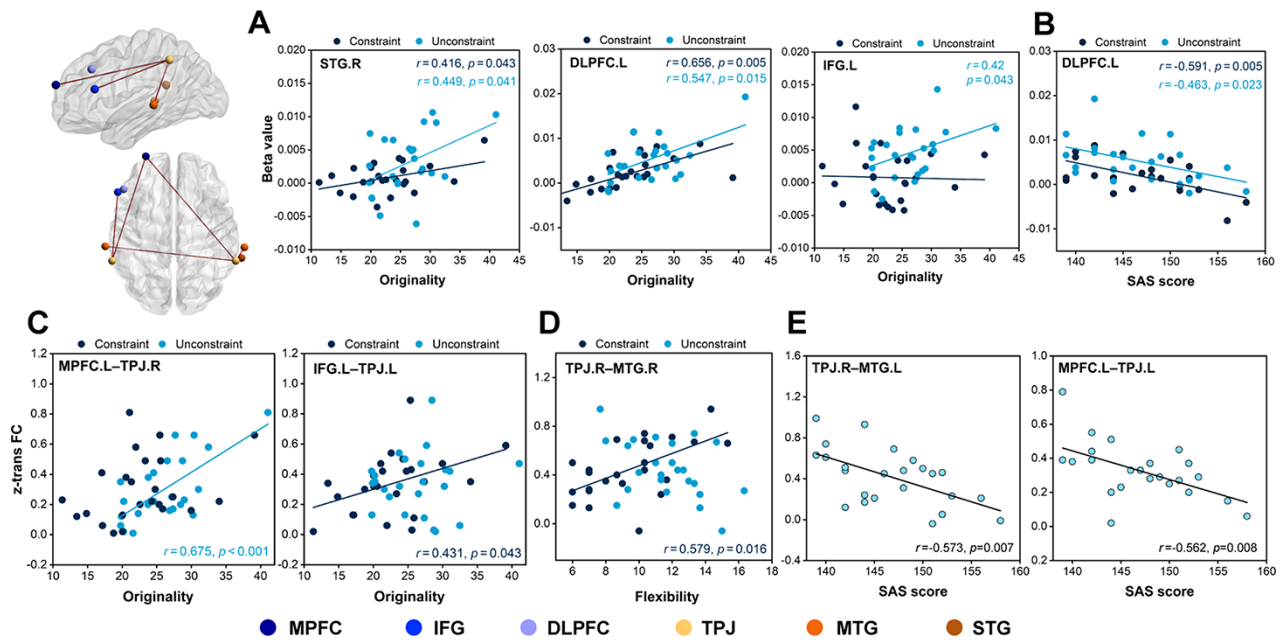
Fig. 6. Scatter plots of the significant correlations between behavioural and fNIRS results. (A) Correlation between beta value and originality score. (B) Correlation between beta value and SAS score. (C) Correlation between resting-state functional connectivity strength and originality score in the SAT group. (D) Correlation between resting-state functional connectivity strength and flexibility score in the HC group. (E) Correlation between resting-state functional connectivity strength and SAS score. L, left hemisphere; R, right hemisphere.
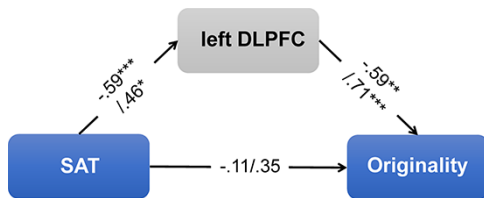

Fig. 7. Mediation analysis of beta value in the left DLPFC on the association between the SAT group and originality performance (constraint/unconstraint). All path coefficients are standardised. *$P < 0.05$, **$P < 0.01$ and ***$P < 0.001$.

in the unconstraint condition. This result might be related to the duration of object presentation in this study. The duration of each object presentation was 30 s, which was referenced from relevant neuroimaging studies (Beaty *et al.*, 2017; Wang *et al.*, 2022). However, studies have found the serial order effects in the generation of creative ideas, with individuals generating increasingly original and highly creative ideas across time (Christensen *et al.*, 1957; Beaty and Silvia, 2012). Creative ideas come from activating and connecting remote information in the semantic network. Proximal semantic nodes would be activated first, eliciting highly accessible but original nodes; activation would require more time to reach more remote and more original nodes. This implies that the average originality of ideas should increase over time, and differences in the originality of ideas may also increase across conditions (Reinig and Briggs, 2008). Therefore, we speculate that this insignificant tendency of interaction effect may be due to the short duration of object presentation in the present study. Nevertheless, the interaction between the group and the semantic constraint was observed at the neural level.

At the neural level, the cortical activation results indicated that the SAT group exhibited weaker activation in the left DLPFC, right MPFC and left IFG compared to the HC group. Particularly, in the SAT group, weaker activations were observed in

these regions in the constraint than the unconstraint conditions. The left DLPFC mediated the effect of smartphone addiction on originality performance. The PFC plays an essential role in cognitive control and behavioural monitoring (Aziz-Zadeh *et al.*, 2013; Gonen-Yaacovi *et al.*, 2013). For example, DLPFC is engaged in automatic response selection and allocation of attentional resources based on target stimuli (Chen *et al.*, 2018; Adnan *et al.*, 2019); IFG is related to top-down suppression control and monitoring of information retrieval (Badre and Wagner, 2007; Wu *et al.*, 2015). This finding indicated that the SAT group exhibited diminished cognitive control during creative idea generation. Indeed, previous studies indicated that compared with HCs, smartphone addicts exhibited lower activation in the PFC, which was related to reduced inhibition of interfering stimuli and suppression of familiar information (Horvath *et al.*, 2020; Choi *et al.*, 2021). However, during the generation of novel ideas, the recall of the common uses could lead to semantic constraints in which individuals need to abandon familiar responses to focus on potential remote information (Beaty *et al.*, 2017; Marron and Faust, 2019). Therefore, this finding implies that individuals with smartphone addiction tendencies may be unable to abandon familiar information and focus on potentially novel information through cognitive control during creative idea generation. Furthermore, the activation in the left DLPFC was negatively correlated with the SAS score in the constraint condition, suggesting that higher degrees of SAT are accompanied by weaker activity in the left DLPFC during creative idea generation. This result supports our findings, indicating that altered PFC activity in the SAT group may be a key role in influencing creative cognition.

The results of the time-series analysis added further insights. We analysed the patterns of cortical activity over time in each group at early and late stages throughout the task. The result indicated that in the HC group, the HbO concentration of the right MPFC was significantly lower in the late stage than in the early stage at 16–20 s after object presentation. This finding suggested

that the activity of the PFC was reduced in the HC group during the late stage of the task. This might be caused by the exhausted resources of cognitive control in the late stage of the task due to continuous executive control through the PFC. This finding further supports the importance of PFC in the generation of creative ideas. In the SAT group, significantly the lower HbO concentration of the left DLPFC was also found at 6–15 s after object presentation in the late stage compared to the early stage during the task. Interestingly, the time point of exhausted resources of cognitive control in the SAT group was earlier than that in the HC group, and the duration of exhausted resources of cognitive control in the SAT group was longer than that in the HC group. This finding might support the results of the cortical activation, indicating that the SAT group exhibited altered PFC activity during creative idea generation. Furthermore, in the SAT group, the lower HbO concentration of PFC was observed in the constraint condition at 21–25 s after object presentation than in the unconstraint condition. A previous study indicated that the induced semantic constraint could trap individuals in close semantic networks that limit remote associations, in which cognitive control was needed to suppress salient information and focus on original information (Beaty *et al.*, 2017). Therefore, this finding also supports the cortical activation results, suggesting that the SAT group may have difficulty overcoming underlying semantic constraints through cognitive control when semantic constraints are available.

In addition, the SAT group exhibited weaker activation of the right TPJ, right STG and right MTG compared to the HC group. Moreover, in the SAT group, participants exhibited weaker activation of the right TPJ in the constraint condition than in the unconstraint condition. The TPJ is involved in the suppression of irrelevant cognitive processes and attentional control of target orientation (Zilverstand *et al.*, 2018). The STG and MTG are related to semantic processing, and they were associated with the retrieval and integration of semantic information related to novel concepts (Wu *et al.*, 2015; Shen *et al.*, 2017). Therefore, this finding suggested that the SAT group exhibited reduced inhibition of irrelevant information and integration of novel information. In the current study, the activated common semantic information of the objects was a precursor to generating semantic stereotypes. In this context, the SAT group might not be able to abandon the semantic stereotypes and focus on potentially novel concepts compared to the HC group. This finding is consistent with previous research, which suggested that the damaged parietal–temporal region was associated with worse performance in overcoming knowledge constraints (Abraham *et al.*, 2012). In addition, studies on smartphone addiction have found that the GMV of smartphone addicts is reduced in the temporal cortex, which is associated with semantic processing and altered memory (Horvath *et al.*, 2020). Moreover, smartphone addiction has been found to negatively affect retrieval ability, which may impair fluent retrieval of unfamiliar information and novelty associations (Thornton *et al.*, 2014). Thus, the weakened activation in the temporal cortex with SAT individuals might indicate the reduced retrieval and integration of novel concepts. Furthermore, the originality performance was positively correlated with cortical activation in the left DLPFC, left IFG and right STG, indicating that the low creative performance of the SAT group may be due to the reduced activation of these regions. Taken together, these findings suggest that SAT may negatively affect the generation of creative ideas through reduced cognitive control and novel information processing.

Notably, the findings of functional connectivity during the AUT provided further evidence. We found that the SAT group has weakened functional connectivity strengths between the DLPFC seed (a component of the ECN) and left IFG (a component of the ECN), the DLPFC seed and right TPJ (a component of the DMN) than the HC group during AUT. In particular, in the SAT group, participants exhibited weaker functional connectivity strengths between the left DLPFC and right MTG (a component of the DMN), the left DLPFC and right IFG in the constraint condition than in the unconstraint condition. According to previous studies, enhanced coupling between the ECN and DMN may support both goal-directed information retrieval and the suppression of familiar ideas (Beaty *et al.*, 2015, 2016). The DMN engages in enhanced spontaneous thinking involving forming novel associations and rapid retrieval of information from memory (Fox *et al.*, 2015). The ECN is responsible for selective retrieval and inhibition of inappropriate information (Niendam *et al.*, 2012). Thus, these findings suggest the inhibitory effect of SAT on the functional connectivity of brain networks during creative idea generation.

The findings of resting-state functional connectivity analyses further support our notion. The results indicated that the SAT group exhibited weakened connectivity strengths in the temporal region (within the DMN; right TPJ–left MTG and right TPJ–right MTG) and between the PFC and temporal regions (connectivities between DMN and ECN; left IFG–right MTG, left IFG–left MTG, left MPFC–right TPJ and left MPFC–left TPJ) than the HC group, and stronger connectivity strengths between the PFC and temporal regions (left MPFC–right TPJ, left IFG–left TPJ and right TPJ–right MTG) were correlated with better AUT performance in both the HC and SAT groups. Meanwhile, the connectivity strengths between the PFC and temporal regions (right TPJ–left MTG and left MPFC–left TPJ) were negatively correlated with the degree of SAT. Previous research has indicated that smartphone addiction can alter connectivity within the DMN and interact abnormally with brain regions related to executive function, memory and emotion, which may reflect reduced spontaneous thinking and craving responses (Zhang and Volkow, 2019). Moreover, connectivity within the DMN may influence the retrieval of dominant information and the recall of the optimum response (Euston *et al.*, 2012). Therefore, this finding indicates that the decreased originality in the SAT group may be mediated by the abnormal functional connectivity between intrinsic networks. Overall, the functional connectivity findings in both task and resting states suggest that the SAT group exhibited weaker functional connectivity strengths between DMN and ECN than the HC group, which may imply that the SAT group has more difficulty in overcoming constrained information and forming novel associations.

Some limitations need to be considered. First, we did not distinguish categories of smartphone addiction, such as mobile game addiction and social network addiction. In the future, the types of smartphone addiction can be carefully divided. Secondly, we focused only on the process of creative idea generation. However, creative cognition also includes insight problem solving (Runco and Pritzker, 2020). Future research should consider different processes of creative cognition to supplement the current findings. Finally, fNIRS cannot detect activation in the deep brain areas. Some deep brain areas have been found to be highly involved in the generation of creative ideas, such as the hippocampus (Luo and Niki, 2003) and the precuneus (Jauk *et al.*, 2015). Therefore, future studies can apply high spatial resolution neuroimaging devices, such as fMRI, to extend the findings of this study.

Conclusions

The current study provides the first neuroimaging evidence that uncovered the negative impact of SAT on creative cognition. In particular, by manipulating the semantic constraints, we found that the SAT individuals exhibited reduced cortical activations and functional connectivities in the PFC and temporal cortex, making it difficult to overcome semantic constraints and establish original associations during creative idea generation. This finding has positive implications for revealing the deleterious effects of smartphone addiction on individuals' advanced cognitive abilities.

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Conflict of interest

The authors declared that they had no conflict of interest with respect to their authorship or the publication of this article.

Supplementary data

Supplementary data are available at SCAN online.

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