

Systematic Review

Neural Mechanisms of Smartphone Addiction: A Systematic Review of Neuroimaging and Related Neurophysiological/Neurostimulation Studies

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Abstract

Background: The rapid integration of smartphones into daily life has undeniably brought immense convenience, but it has also introduced challenges, particularly in the form of problematic smartphone use (often referred to as smartphone addiction). This form of behavioral dependence has been linked to significant impairments in physiological, psychological, and social domains. **Methods:** In this systematic review, we investigated the neural underpinnings of smartphone addiction through various brain imaging techniques, with a particular emphasis on studies employing functional near-infrared spectroscopy (fNIRS), electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and complementary neurostimulation as well as neurophysiological methods. Relevant data were retrieved from major academic databases—including CNKI, PubMed, and Web of Science—using a thorough keyword-based search strategy. A total of 41 studies were analyzed and categorized according to their research methods, participant characteristics, targeted populations, and key findings. **Results:** We identified a consistent association between smartphone addiction and alterations in brain structure and activity, as well as its co-occurrence with a range of mental health challenges. **Conclusion:** These findings collectively underscore the pressing need for further research into the neurobiological mechanisms of smartphone addiction and the development of targeted interventions to mitigate its adverse effects. **The PROSPERO Registration:** CRD420261369691, <https://www.crd.york.ac.uk/PROSPERO/view/CRD420261369691>.

Keywords: behavioral addictions; smartphone; neuroimaging; EEG; MRI; fNIRS; tDCS; neurophysiology

1. Introduction

With the rapid advancement of technology and the increasing demands of modern society, smartphones, due to their portability and multifunctionality, have become indispensable tools for communication and daily life. While they provide significant convenience, overreliance on smartphones has also led to a range of challenges, particularly those concerning physical and mental health [1]. Among these challenges, smartphone addiction has emerged as a critical issue, one characterized by excessive and uncontrollable use that disrupts physical, psychological, and social well-being [2,3]. Key symptoms of smartphone addiction include compulsive usage, tolerance, withdrawal symptoms, continued use despite negative consequences, as well as neglect of essential social activities [4].

1.1 Conceptual Controversies in Smartphone Addiction

There remains significant conceptual debate surrounding “smartphone addiction” that extends beyond mere terminology inconsistency. Critics argue that smartphones are multifunctional devices, and that problematic use often stems from excessive engagement with specific applications rather than the device itself. For example, many studies now distinguish between social media addiction, gam-

ing addiction, and video streaming addiction as distinct subtypes of problematic smartphone use, each of which may be associated with unique neural mechanisms. This perspective acknowledges that the smartphone is primarily a delivery platform for reinforcing content, and that future research should increasingly focus on purpose-specific problematic use patterns rather than treating “smartphone addiction” as a monolithic construct.

Despite its prevalence in the literature, there is no universally accepted definition of smartphone addiction. Terms such as smartphone addiction (SA), problematic mobile phone use (PMPU), pathological smartphone use (PSU), mobile phone dependence (MPD), as well as smartphone dependence (SPD) are often used interchangeably in the literature [5,6]. This condition is typically classified as a form of behavioral addiction, drawing on diagnostic criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) for compulsive behaviors such as gambling and substance abuse.

Critically, the monolithic conceptualization of smartphone addiction has been challenged by recent theoretical advances. A growing body of empirical evidence suggests that smartphone use is not a unitary behavior but rather a conduit for diverse platform-specific activities, including social media engagement, short-form video consump-



tion, as well as gaming (e.g., “YouTube addiction”, “TikTok addiction”, or “Instagram addiction”) [7,8]. These platform-specific behaviors may recruit distinct neural reward and habit-formation circuits, which raises the question of whether “smartphone addiction” should be reconceptualized as an umbrella term for application-specific behavioral addictions. This heterogeneity has significant implications for neuroimaging research, given that neural correlates identified across studies may reflect addiction to specific content types rather than to the device per se. The present review acknowledges this limitation and notes, where possible, the primary usage patterns reported in the included studies.

Existing research highlights that young people, and college students in particular, are particularly vulnerable to smartphone addiction. For instance, one prior study reported that 48% of undergraduate students exhibited signs of addiction [9]. This behavioral dependence is associated with a variety of adverse outcomes, including psychological issues such as depression and anxiety, physical problems such as neck pain and migraines, as well as sleep disturbances such as insomnia [10,11]. These impacts significantly diminish the quality of life of affected individuals, underscoring the urgent need for further research into smartphone addiction.

In recent years, significant progress has been made in the development of assessment tools for smartphone addiction. Widely used scales include the Smartphone Addiction Scale-Short Version (SAS-SV) [12], the Smartphone Addiction Scale for College Students (SAS-C) [13], as well as the Mobile Phone Addiction Tendency Scale (MPATS) [14], among others. These tools provide valuable frameworks for evaluating the severity and broader impact of smartphone addiction across different populations.

1.2 Rationale for Focusing on Neural Mechanisms

While behavioral and psychological studies have documented the prevalence and consequences of smartphone addiction, understanding of its underlying neural mechanisms is critical for three key reasons: (1) It provides objective biological markers that can complement self-report measures, as these measures are prone to response bias; (2) It reveals shared and distinct neural pathways between problematic smartphone use and other behavioral addictions (e.g., gambling disorder) as well as substance use disorders, which in turn informs diagnostic classification; (3) It identifies potential targets for neuromodulation interventions (e.g., transcranial direct current stimulation (tDCS), transcranial magnetic stimulation (TMS)) that could complement traditional psychological treatments. This review fills a critical gap in the literature by synthesizing evidence across multiple neuroimaging and related techniques to provide a comprehensive overview of the neural basis of problematic smartphone use.

The present article aims to provide a comprehensive review of the current state of research on smartphone addiction. It begins by outlining the methodology used for article selection and presenting a statistical overview of the reviewed studies, including their demographic characteristics. The review then examines findings from studies employing various neurophysiological and neuroimaging techniques, such as functional near-infrared spectroscopy (fNIRS), electroencephalography (EEG), structural magnetic resonance imaging (MRI), functional MRI, tDCS, as well as TMS. Finally, the article offers a summary of key insights, discusses limitations of the existing literature and the present review, before outlining potential directions for future research.

2. Methods

2.1 Protocol Registration

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (**PRISMA checklist of the Supplementary Material**) [15]. The review protocol was retrospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO; registration number CRD420261369691). We note for transparency that registration was completed after the literature search had been performed (the systematic literature search was conducted on 1 April 2025; the review protocol was submitted to and registered in PROSPERO on 15 April 2026), and the protocol is accordingly reported as a retrospective registration.

2.2 Eligibility Criteria (PICOS Framework)

Study selection was performed based on the PICOS (Population, Intervention/Exposure, Comparator, Outcome, Study design) framework:

Population (P): Human participants of any age or gender who exhibit smartphone addiction, problematic smartphone use, pathological smartphone use, mobile phone dependence, or excessive smartphone use, as defined by validated psychometric instruments.

Exposure/Intervention (I): Studies examining neural correlates, neurophysiological responses, as well as neuromodulatory effects associated with smartphone addiction. Neuroimaging modalities included fNIRS, EEG, functional magnetic resonance imaging (fMRI), as well as structural MRI (sMRI). Neuromodulatory techniques included tDCS and TMS. Psychophysiological measures included skin conductance response (SCR).

Comparator (C): Healthy controls, non-addicted users, as well as within-subject baseline conditions.

Outcome (O): Neural activation patterns, structural brain alterations, functional connectivity, event-related potentials (ERPs), neurochemical concentrations, as well as behavioral outcomes following neuromodulation.

Study design (S): Peer-reviewed empirical studies, including cross-sectional, longitudinal, and intervention studies, published in English. Reviews, conference abstracts, case reports, editorials, as well as non-human studies were excluded.

Exclusion Criteria: (i) studies that did not employ neuroimaging, neuromodulation, or psychophysiological measurement; (ii) studies focusing exclusively on substance use disorders or gambling disorder, with no smartphone addiction dimension addressed; (iii) studies in which smartphone addiction was not the primary focus of neural analysis; (iv) publications in languages other than English.

2.3 Search Strategy

A systematic literature search was conducted across three major electronic databases: China National Knowledge Infrastructure (CNKI, <https://www.cnki.net/>), PubMed (MEDLINE, <https://pubmed.ncbi.nlm.nih.gov/>), as well as Web of Science Core Collection (<https://webofscience.com/>). The search was conducted on 1 April 2025, with publication coverage from January 2000 to the search date. No initial restrictions were placed on publication type; however, only peer-reviewed journal articles were ultimately retained for analysis.

The search strategy was constructed by combining keywords related to smartphone addiction and neurobiological measurement, using standard Boolean operators. The full search string for each database were as follows: PubMed: (“smartphone addiction” OR “problematic mobile phone use” OR “pathological smartphone use” OR “mobile phone dependence” OR “smartphone dependence” OR “excessive smartphone use”)[Title/Abstract] AND (“functional near-infrared spectroscopy”[MeSH] OR “fNIRS”[Title/Abstract] OR “electroencephalography”[MeSH] OR “EEG”[Title/Abstract] OR “magnetic resonance imaging”[MeSH] OR “fMRI”[Title/Abstract] OR “transcranial direct current stimulation”[MeSH] OR “tDCS”[Title/Abstract] OR “transcranial magnetic stimulation”[MeSH] OR “TMS”[Title/Abstract] OR “skin conductance”[Title/Abstract]); filters: English, Human, 2000–2025; Web of Science: TS=(smartphone addiction terms) AND TS=(neuroimaging terms); LA=English; Timespan: 2000–2025; Indexes: SCI-EXPANDED, SSCI; CNKI: 主题=(手机成瘾相关术语) AND 主题=(神经影像相关术语); 来源类别: SCI/EI/核心期刊; 时间: 2000–2025.

2.4 Study Screening and Data Extraction

All records retrieved from the search were imported into EndNote X9 (Clarivate Analytics, Philadelphia, PA, USA) for the removal of duplicates. Two reviewers (H.L. and R.H.) independently completed screening at both the title/abstract and full-text stages. Following the criteria of Landis & Koch (1977) [16], Cohen’s κ values indicated substantial and almost perfect agreement for the two stages, respectively ($\kappa = 0.79$, 95% CI 0.70–0.88; $\kappa = 0.81$, 95% CI

0.71–0.91). All discrepancies were resolved through consensus discussion or arbitration by a third reviewer (X.L.).

2.5 Quality Assessment

The methodological quality of included studies was assessed using the JBI Critical Appraisal Checklist for cross-sectional studies ($n = 38$), the Newcastle-Ottawa Scale for longitudinal studies ($n = 3$), as well as the Cochrane Risk of Bias 2.0 tool for randomized controlled trials. Quality assessment was performed independently by two reviewers, and any discrepancies were resolved through consensus discussion. Full results of the quality assessment are provided in **Supplementary Table 1** of the **Supplementary Material**.

The initial search yielded 268 records. Following duplicate removal, 186 unique records were retained for subsequent evaluation. A thorough review of titles and abstracts was then conducted, after which 101 records that did not meet the inclusion criteria were excluded. To refine the analytical focus, only studies employing brain imaging techniques were retained, narrowing the final sample to 41 studies. This final corpus comprised 4 fNIRS studies, 9 EEG studies, as well as 26 fMRI studies, with two articles incorporating both EEG and TMS methodologies. The search and screening process, designed to ensure methodological rigor, is visually summarized in a PRISMA flowchart (Fig. 1).

2.6 Summary Statistics and Trends

With growing societal concerns surrounding excessive smartphone use, alongside the integration of cutting-edge neuroimaging technologies, research on smartphone addiction has seen remarkable progress in recent years. In 2021 alone, nine neuroimaging studies that focused on smartphone addiction were published, as presented in Fig. 2. Over the past two years, the annual publication count has consistently remained at least seven, which reflects sustained research interest and advancement in this field. Although behavioral and questionnaire-based research on smartphone addiction remains more prevalent, the ongoing maturation of neuroimaging technologies and the increasing prominence of this research area suggest that significant growth is imminent.

3. Neuroimaging Technologies: Methods and Applications

The key neuroimaging modalities used in smartphone addiction studies include fNIRS, EEG, as well as MRI. Each technology offers distinct advantages and limitations. For instance, fNIRS is portable and enables monitoring of cortical hemodynamic changes; however, it is constrained by low spatial resolution and limited penetration depth, which restricts assessment to superficial cortical regions. Meanwhile, EEG offers high temporal resolution and is highly sensitive to dynamic neural activity, yet it is lim-

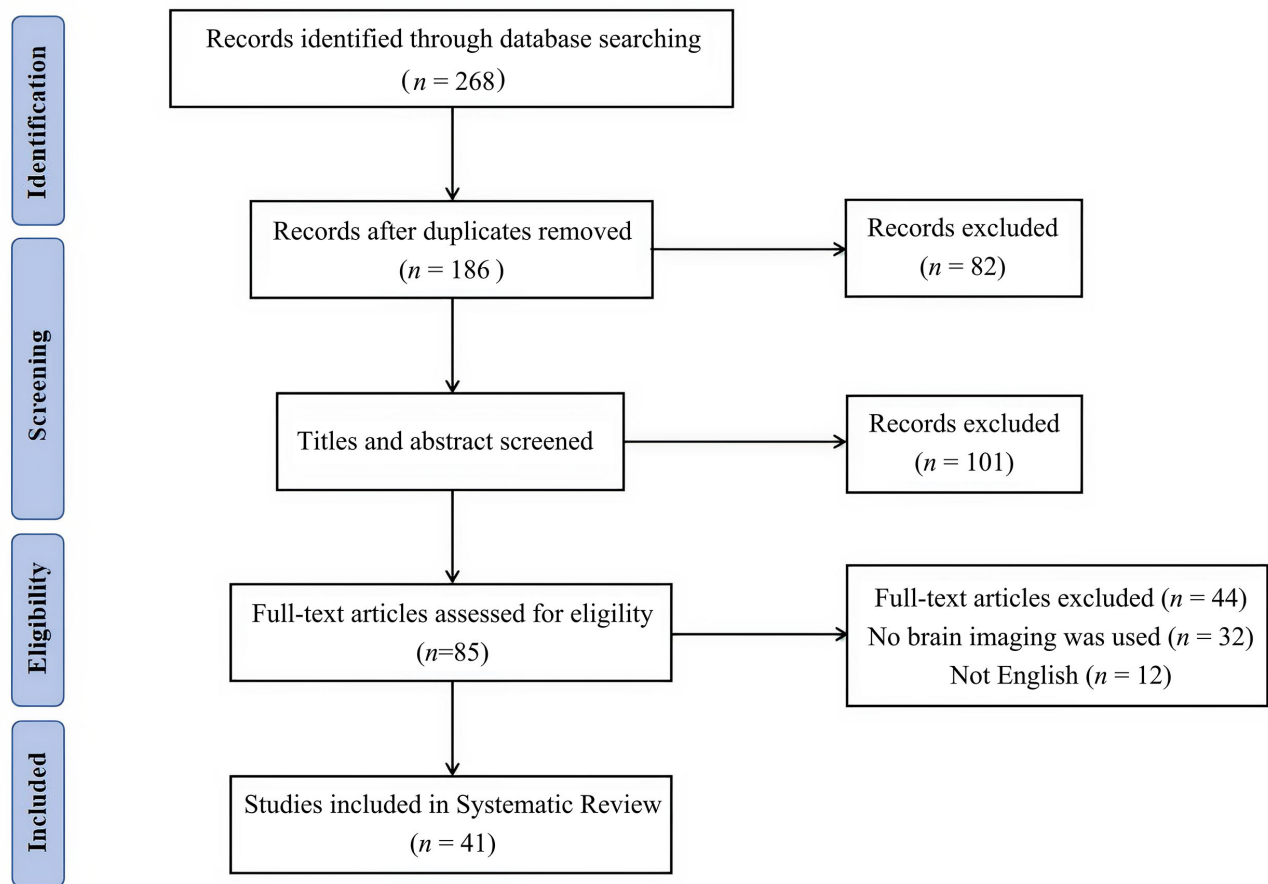


Fig. 1. PRISMA flowchart illustrating paper exclusions, including dual screening. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

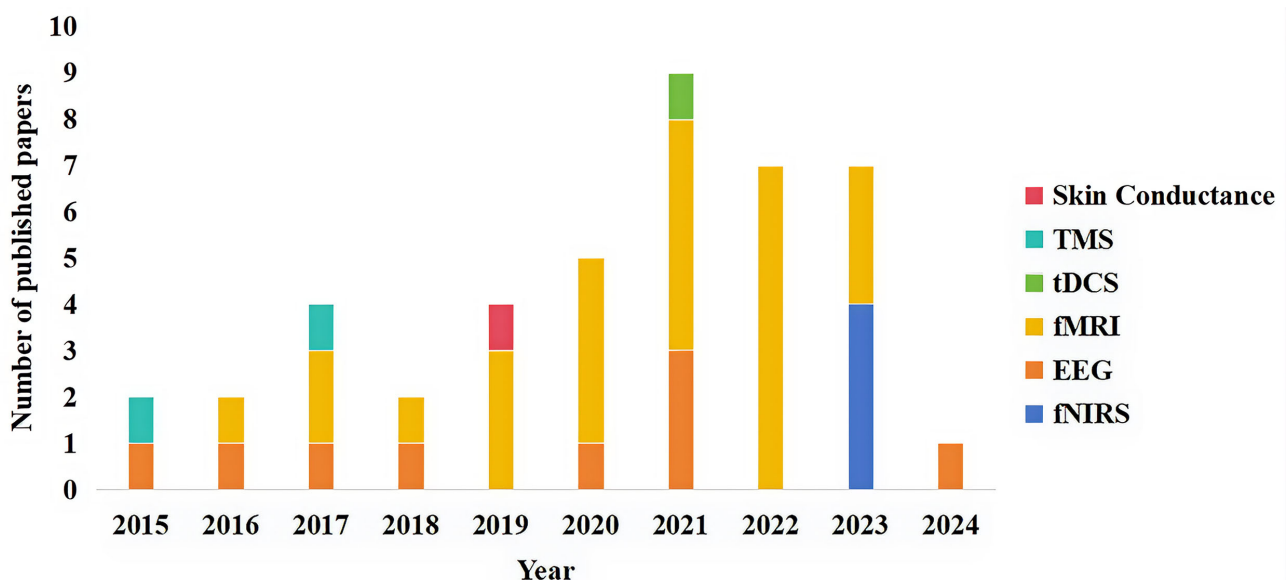


Fig. 2. Annual number of smartphone addiction studies categorized by neuroimaging technique. TMS, transcranial magnetic stimulation; tDCS, transcranial direct current stimulation; fMRI, functional magnetic resonance imaging; EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy.

ited by poor spatial resolution and susceptibility to motion as well as electromagnetic artifacts. MRI, which encom-

passes both sMRI and fMRI, provides the highest spatial resolution among these techniques and the capability to ex-

amine deep brain structures. Although similar to fNIRS and EEG, fMRI can assess task-related brain activity, its superior spatial resolution enables precise localization of neural activity within specific brain regions and subregions. Nevertheless, fMRI is limited by low temporal resolution, pronounced sensitivity to head motion, as well as susceptibility to physiological and scanner-related artifacts.

As depicted in Fig. 2, fMRI has become the predominant neuroimaging tool in problematic smartphone use research since 2017, owing to its ability to study deep brain activity with high spatial precision. Usage of EEG has remained consistent over the years, while fNIRS has seen notable growth since 2023 due to its ease of operation and portability. Despite these advancements, neural intervention techniques such as tDCS and TMS remain underexplored, which signals an area for potential future development. Researchers must carefully evaluate the specific demands of their studies when selecting neuroimaging techniques to ensure that the most suitable technology is deployed.

3.1 Participant Demographics in Smartphone Addiction Studies

As indicated in Fig. 3a, research on smartphone addiction heavily focuses on individuals aged 20–30 years, a figure that accounts for 62% of the included studies. The 10–20 age group, which largely comprises adolescents, represents the second most-studied population. In contrast, research that involves participants over 40 years of age is minimal. Fig. 3b further highlights that young adults aged 20–30 are predominantly university students, while adolescents dominate the 10–20 age range. Strikingly, no neuroimaging studies have specifically targeted smartphone addiction in the elderly, which underscores a significant gap in the existing literature.

3.2 Assessment Tools for Smartphone Addiction

A variety of instruments are employed to evaluate smartphone addiction in research settings, with the most frequently used tools including the SAS-SV by Kwon et al. (2013) [12], the Smartphone Addiction Proneness Scale (SAPS) by Kim et al. (2014) [17], as well as the Smartphone Addiction Inventory (SPAI) by Lin et al. (2014) [18]. Comprehensive usage statistics for these scales are presented in Fig. 3c. These validated instruments play a crucial role in standardizing smartphone addiction assessment across diverse populations and study methodologies.

3.3 Functional Near-Infrared Spectroscopy (fNIRS) Studies on Smartphone Addiction

In recent years, there has been a growing empirical interest in utilizing fNIRS to study smartphone addiction, owing to its ease of use and its capacity for precise localization of brain activity. Through a comprehensive review of the literature, four relevant studies were identified,

for which detailed information is provided in Table 1 (Ref. [19,20,21,22]). This section highlights key findings regarding the role of fNIRS in advancing our understanding of smartphone addiction, particularly its influence on cognitive control as well as related neural mechanisms.

Liu et al. (2023) [19] investigated decision-making deficits in individuals with smartphone addiction during Sequential Risk-Taking tasks using fNIRS. Their study revealed significant impairments in decision-making under high-risk conditions, which were accompanied by increased activation in the dorsolateral prefrontal cortex (dlPFC) during loss outcome scenarios [19]. Fig. 4 (Ref. [19]) illustrates outcomes related to brain activation patterns that were observed in their experimental framework. Similarly, Li et al. (2023) [20] examined creative processes among problematic smartphone use using the Alternate Uses Task (AUT). Their results indicated reduced activity in both the prefrontal cortex (PFC) and temporal lobe regions, as well as weaker functional connectivity between these areas, which suggests impaired creative performance. Furthermore, research by Xiang et al. (2022) [21] analyzed inhibitory control during the Stroop task and found decreased activation in the left PFC amongst university students with problematic smartphone usage.

Moreover, smartphone addiction may pose significant risks in daily life, which include an increased likelihood of accidents during walking. Mourra et al. (2020) [23] found that smartphone use while walking impairs gait performance and reduces obstacle awareness. Parallel findings were reported by Krasovsky et al. (2022) [24], who used fNIRS to demonstrate elevated PFC activation in individuals who walked while using smartphones, particularly in a head-down posture. However, not all reported results portray solely detrimental effects of smartphone use. Guo et al. (2023) [22] discovered that PSUs exhibited enhanced working memory performance across diverse task materials, which provides an alternative perspective on the implications of smartphone addiction.

In summary, existing fNIRS-based studies highlight abnormal neural activity in the frontal lobe regions of individuals with smartphone addiction [19,20,21]. Given the critical role of the frontal lobe in inhibitory control, cognition, emotion, as well as social abilities [25], such findings suggest that smartphone addiction may impair these functions during tasks that require frontal lobe engagement. Future research should aim to broaden the scope of behavioral and neural investigations of smartphone addiction, with a particular emphasis on identifying distinguishing characteristics within this population. Additionally, research efforts should prioritize the development of more targeted prevention and intervention strategies. Despite its currently limited application within the field, fNIRS holds substantial potential for advancing a more comprehensive understanding of the cognitive as well as neural ramifications of smartphone addiction.

Table 1. Summary of articles using fNIRS to study problematic smartphone use.

Authors	Core focus	Neuroimaging methods	Paradigms	Assessment tool	Sample size	Type of population	Age/Age range	Gender	Type of study	Main discoveries/contributions
Liu et al. (2023) [19]	Investigate the decision making behavior and brain activity of problematic smartphone use under varying risk levels.	8-Source 7-Detector 22-Channel Sampling rate-11 Hz (OFC and dlPFC)	open-box continuous risk decision-making task	SAS-SV	Total = 42 SA Group = 25 Control Group = 17	university students	Male = 21 ± 1.89 Female = 19.5 ± 1.59	Male = 14 Female = 28	Cross-sectional study	In problematic smartphone use group, high-risk levels leading to weaker decision-making ability. And stronger brain activation in the dorsolateral Prefrontal Cortex region for problematic smartphone use under loss outcome conditions.
Li et al. (2023) [20]	The impact of smartphone addiction on creative cognition.	16-Source 16-Detector 43-Channel Sampling rate-12 Hz (PFC and temporal regions)	16- AUT	SAS	Total = 48 SAT Group = 24 Control Group = 24	university students	SAT Group = 19.79 ± 1.28 Control Group = 19.42 ± 1.41	Male = 17 Female = 31	Cross-sectional study	The PFC and temporal regions were less active during AUT and weaker coupling between PFC and temporal regions in the SAT than in the HC group.
Xiang et al. (2022) [21]	The correlation between cortical activation and deficient inhibitory control in PSPU.	8-Source 8-Detector 16-Channel Sampling rate-7.81 Hz (lateral prefrontal)	stroop task	SAS-SV	Total = 110 PSPU Group = 56 Control Group = 54	college students	PSPU Group = 20.46 ± 1.36 Control Group = 20.52 ± 1.03	Male = 57 Female = 53	Cross-sectional study	College students with PSPU may have a deficit in inhibitory control associated with lower cortical activation in the left-dlPFC.
Guo et al. (2023) [22]	Can the WM advantages of PSU group be transferred to other fields?	8-Source 7-Detector 20-Channel Sampling rate-7.8125 Hz (prefrontal lobe)	N-back paradigm	MPPUS	Total = 34 PSU Group = 16 Control Group = 18	unclear	21.63 ± 1.61	unclear	Cross-sectional study	The PSU group has an advantage in WM, transferring from the network-related stimulus to the neutral stimulus. The advantages of network stimulus were related to bidirectional connectivity between frontopolar and right-dlPFC. The left-dlPFC and frontopolar are associated with the cross-material consistency of WM.

Note: SAS, Smartphone Addiction Scale; SAS-SV, Smartphone Addiction Scale-Short Version; MPPUS, Mobile Phone Problem Use Scale; SA, smartphone addiction; HC, healthy control; SAT, smartphone addiction tendency; PSPU, problematic smartphone use; PSU, pathological smartphone use; OFC, orbitofrontal cortex; dlPFC, dorsolateral prefrontal cortex; PFC, prefrontal cortex; WM, working memory; AUT, alternate uses task.

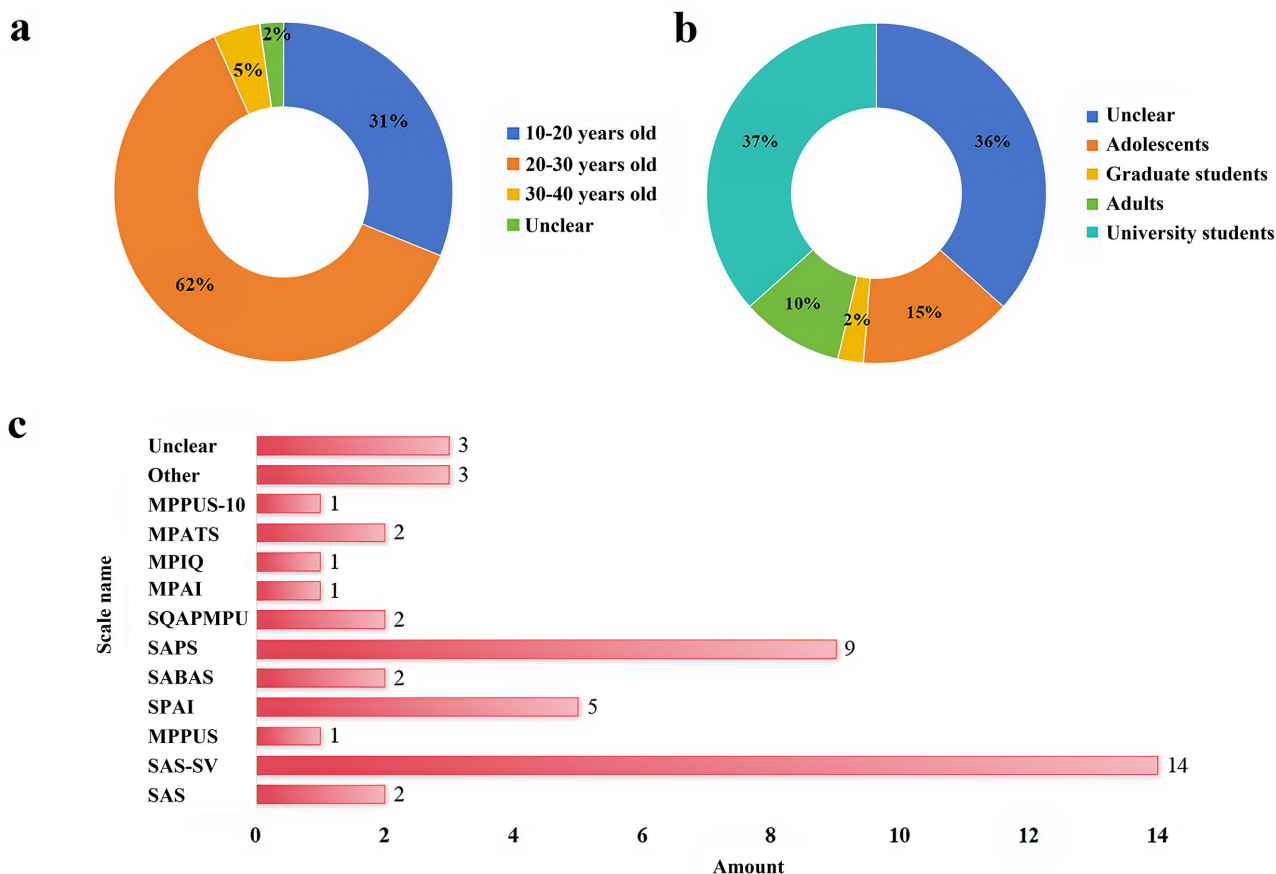


Fig. 3. Participant demographics and assessment tools in smartphone addiction studies. (a) Proportion of participants across different age groups in smartphone addiction research. (b) Proportion of participants from various social groups in smartphone addiction studies. (c) Number of assessment tools used in smartphone addiction research (SAS, Smartphone Addiction Scale; SAS-SV, Smartphone Addiction Scale-Short Version; MPPUS, Mobile Phone Problem Use Scale; SPAI, Smartphone Addiction Inventory; SABAS, Smartphone Application-Based Addiction Scale; SAPS, Smartphone Addiction Proneness Scale; SQAPMPU, Self-rating Questionnaire for Adolescent Problematic Mobile Phone Use; MPAI, Mobile Phone Addiction Index; MPIQ, Mobile Phone Involvement Questionnaire; MPATS, Mobile Phone Addiction Tendency Scale; MPPUS-10, 10-item Mobile Phone Problematic Use Scale).

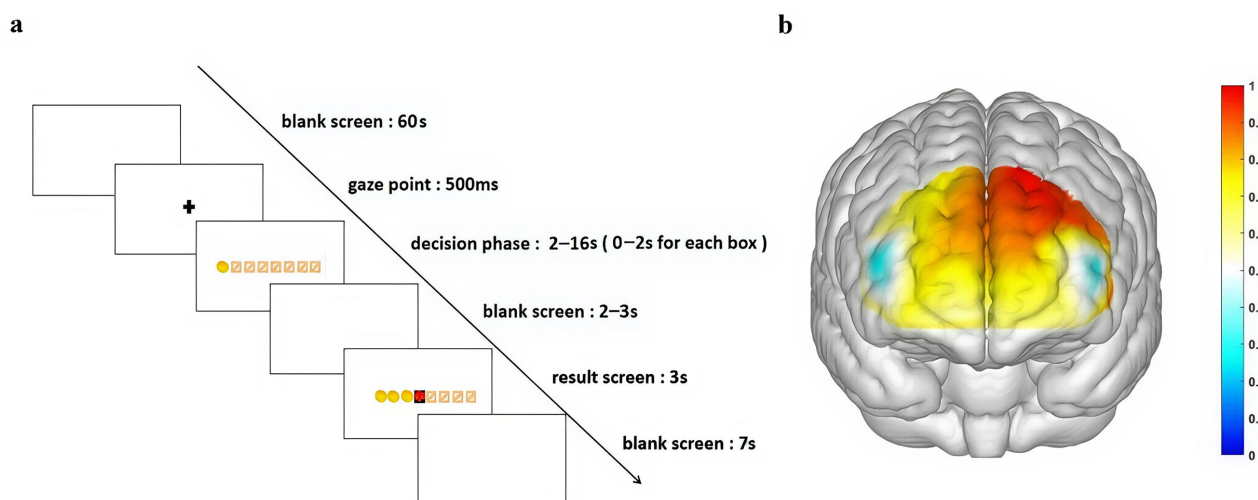


Fig. 4. Task paradigm and associated brain activation maps. (a) The experimental task flowchart. (b) Activation maps of the measured brain regions, specifically the OFC and dlPFC, in the addiction group under high-risk conditions with a loss outcome [19].

3.4 Electroencephalography (EEG) Studies on Smartphone Addiction

Smartphone addiction has garnered significant attention in recent years, particularly since 2020, as researchers have employed EEG to investigate its neurological underpinnings. Current studies have primarily explored dimensions such as negative emotions, inhibitory control, attention, as well as reward processing, which have revealed distinct patterns of abnormal neural activity in the frontal lobe region of individuals prone to smartphone addiction. Table 2 (Ref. [26,27,28]) in the main text presents some of this information, while a comprehensive set of specific information for the included studies is available in **Supplementary Table 2** in the **Supplementary Material**.

Negative emotions have been a focal point of several studies. Yin et al. (2024) [26] employed resting-state EEG (rs-EEG) and minimum spanning tree (MST) methods, which demonstrated that disruptions in alpha- and delta-band brain networks, which are mediated by negative emotions, are linked to smartphone use disorder. Similarly, Kim and Kang (2018) [2] reported heightened emotional instability in risk smartphone users, in whom notable differences were observed in the gamma band. Withdrawal symptoms, which are often accompanied by negative emotions, further reinforce the role of emotional dysregulation in smartphone addiction [29].

Inhibitory control, which represents another key area of inquiry, remains subject to debate. Early findings by Chen et al. (2016) [27] revealed reduced inhibitory control in excessive smartphone users, which was evidenced by a negative N2 event-related potential (ERP) during Go/No Go tasks. However, subsequent studies, such as Gao et al. (2020) [30], suggested that these impairments might only manifest in smartphone-related contexts, which indicates the need for nuanced interpretations within this domain.

Attention deficits have been consistently linked to smartphone addiction across existing studies. Heavy users have been shown to experience impaired attention, diminished numerical processing, as well as heightened impulsivity [28]. Further research strengthens the argument that problematic smartphone use adversely affects attention networks as well as sensory processing [29]. Additionally, reward sensitivity has emerged as a critical factor in this line of inquiry. Deng et al. (2021) [31] reported heightened P3 amplitudes in adolescents with greater smartphone addiction tendencies, a finding that emphasizes their increased sensitivity to social feedback. In contrast, moderate as well as high levels of problematic smartphone use have been associated with ERP attenuation during reward processing [32].

In conclusion, EEG studies on smartphone addiction reinforce the presence of abnormal frontal lobe activity and offer valuable insights across multiple domains, including emotion regulation, cognitive control, as well as reward processing. However, despite these advancements, the field

remains constrained by a scarcity of empirical research as well as a lack of consensus. Many studies rely on limited research paradigms, which raises concerns about their specificity to smartphone addiction. Moving forward, future research should prioritize the development of more robust as well as comprehensive experimental designs to establish unified conclusions and deepen our understanding of the neural mechanisms that underlie smartphone addiction.

3.5 Magnetic Resonance Imaging (MRI) Studies on Smartphone Addiction

fMRI and sMRI have established themselves as critical tools for studying brain mechanisms that underlie smartphone addiction, which surpass alternative neuroimaging techniques such as fNIRS and EEG. Unlike fNIRS and EEG, which are primarily employed to record behavioral responses and brain activity during task execution, fMRI and sMRI offer a superior capability to examine internal brain structures and anatomy independent of specific experimental paradigms. This unique advantage has contributed to their widespread use in investigating the neural correlates of smartphone addiction. Table 3 (Ref. [33,34,35,36]) displays a portion of the relevant data. For a complete set of detailed information, readers may consult **Supplementary Table 3** in the **Supplementary Material**.

3.5.1 Structural MRI (sMRI) Findings

Numerous studies have observed brain gray matter volume (GMV) reductions in problematic smartphone use, particularly in regions such as the anterior insula, inferior temporal cortex, parahippocampal cortex, anterior cingulate cortex (ACC), as well as the lateral orbitofrontal cortex [37,38]. The right superior frontal gyrus (sFG) and bilateral thalamus (Thal) also demonstrate negative correlations with the severity of smartphone addiction [6]. Notably, existing research suggests that GMV in the ACC may mediate the relationship between PMPU and depression [39].

Investigations of white matter integrity underscore significant structural alterations that are linked to behavioral changes in smartphone addiction. For instance, abnormalities in white matter structures, including those in the brainstem, have been associated with mobile phone dependence [6,33]. These findings highlight potential neurobiological mechanisms that underlie problematic smartphone use (PSU).

3.5.2 Functional MRI (fMRI) Findings

Among the most extensive areas of research is the analysis of functional connectivity (FC). However, findings on FC alterations in individuals with PSU remain complex and, at times, contradictory. Some studies suggest a reduction in FC within critical brain networks. For instance, Áfra et al. (2024) [34] reported decreased within-network FC in the executive control network as well as the

Table 2. Summary of articles using EEG to study problematic smartphone use.

Authors	Core focus	Neuroimaging methods	Paradigms	Assessment tool	Sample size	Type of population	Age/Age range	Gender	Type of study	Main discoveries/contributions
Yin et al. (2024) [26]	Examine the relationship between the topology of the resting-state electroencephalography (rs-EEG) brain network and smartphone use disorder using minimum spanning tree analysis.	64 Ag/AgCl sintered electrodes sampling rate: 500 Hz	unclear	SAS-SV	Total = 113	university students	20.87 ± 2.42	Male = 53 Female = 60	Cross-sectional study	The findings suggest that excessive scale-free alpha- and delta-band brain networks contribute to the emergence of smartphone use disorder. Negative emotions play a mediating role in the association between topological deviations and smartphone use disorder.
Chen et al. (2016) [27]	Whether there is an inhibitory deficit in excessive smartphone users.	32 scalp sites	modified Go/No-Go task	SPAI	Total = 38 Excessive users Group = 19 Control Group = 19	local university community	Analysis: Excessive users Group = 19.56 ± 1.25 Control Group = 19.78 ± 1.21	Analysis: Male = 17 Female = 19	Cross-sectional study	In the early stage of inhibition processing, excessive smartphone users experience more conflicts and show a general deficit that does not depend on smartphone-related cues.
Hadar et al. (2017) [28]	Determine whether excessive usage is accompanied by measurable neural, cognitive and behavioral changes.	64 electrodes (right prefrontal cortex)	Speeded numerical processing task Memory task Stop signal task	SAS MPIQ	First phase: Total = 51 SU = 16 NU = 35 Second phase: Total = 25 NUco = 14 NUsp = 11	university students	First phase: SU = 24 ± 2.5 NU = 25 ± 3.8 Second phase: NUco = 24.9 ± 2.2 NUsp = 24.7 ± 2	First phase: Male = 23 Female = 28 Second phase: Male = 10 Female = 15	Longitudinal study	Heavy usage was found to be associated with impaired attention, reduced numerical processing capacity, changes in social cognition, and reduced right prefrontal cortex (rPFC) excitability.

Note: SAS, Smartphone Addiction Scale; SAS-SV, Smartphone Addiction Scale-Short Version; SPAI, Smartphone Addiction Inventory; MPIQ, Mobile Phone Involvement Questionnaire; SU, heavy smartphone users; NU, nonusers; NUsp, NU participants receive smartphone devices for a 3-month period; NUco, NU participants served as matched controls.

Table 3. Summary of articles using fMRI to study problematic smartphone use.

Authors	Core focus	Neuroimaging methods	Paradigms	Assessment tool (SA)	Sample size	Type of population	Age/Age range	Gender	Type of study	Main discoveries/contributions
Áfra et al., (2024) [34]	The neurobiological background of Internet-related behavioral addictions.	3T fMRI 20-channel head/neck coil	unclear	SABAS	Total = 59	unclear	24.69 ± 3.23	Male = 29 Female = 30	Cross-sectional study	Smartphone and social media addictions lead to decreased FC in visual and language networks. Additionally, the executive control network and the frontoparietal network showed decreased within-network FC in people with high levels of smartphone addiction. Problematic smartphone and social media use are associated with sensory processing and higher cognitive functioning.
Henemann et al., (2023) [36]	Aimed at identifying neurochemical pathways that are related to excessive smartphone use.	3T fMRI 32-channel head coil	cue-reactivity task	SAS-SV	Total = 42 ESU Group = 21 n-ESU Group = 21	unclear	ESU Group = 22.57 ± 3.04 n-ESU Group = 22.52 ± 3.01	Male = 12 Female = 30	Cross-sectional study	The MOR system is a neurochemical pathway associated with ESU. The MOR system is closely linked to the reward system.
Liu et al., (2022) [35]	Investigate the possible associations between problematic smartphone use and brain functions in terms of both static and dynamic functional connectivity patterns.	3T fMRI	unclear	SAS-SV	Total = 51	young healthy adults	21.51 ± 1.55	Male = 16 Female = 35	Cross-sectional study	At the global network level, the SAS-SV score was found to be significantly positively correlated with the global efficiency and local efficiency of static brain networks, and negatively correlated with the temporal variability using the dynamic brain network model.
Cho et al., (2021) [33]	Examine the difference in the volume of brainstem substructures among adolescents with and without PSU.	3T fMRI 16-channel head coil	unclear	SAPS	Total = 87 PSU = 20 TDC = 67	adolescents aged 12–18 years	PSU = 16.20 ± 1.11 TDC = 15.27 ± 1.69	Male = 56 Female = 31	Cross-sectional study	The PSU group showed a significantly smaller volume of the SCP than the control group. The volume of the SCP and the SAPS score were negatively correlated.

Note: SAS-SV, Smartphone Addiction Scale-Short Version; SABAS, Smartphone Application-Based Addiction Scale; SAPS, Smartphone Addiction Proneness Scale; ESU, excessive smartphone use; n-ESU, non-ESU (controls); PSU, problematic smartphone users; TDC, typically developing children; SCP, superior cerebellar peduncle; MOR, mu-opioid receptor.

frontoparietal network among individuals with high levels of smartphone addiction. Conversely, other research highlights enhanced FC in problematic smartphone use, such as stronger connectivity between the dorsal anterior cingulate cortex (dACC) and networks like the default mode network (DMN) as well as the ventral attention network (VAN) [40]. These seemingly contradictory findings have been attributed to the pathological brain's need for greater cognitive effort to compensate for inefficiencies, which may explain the observed FC enhancements [41].

Dynamic functional connectivity (dFC) has emerged as an important complement to traditional static FC (sFC) analyses. Unlike sFC, which provides a snapshot of connectivity, dFC captures the temporal variability of brain network interactions. For example, Liu et al. (2022) [35] found that excessive smartphone use was positively correlated with the global and local efficiency of static brain networks, while it was negatively associated with the temporal variability of dynamic brain networks. This finding underscores the importance of adopting dynamic models to capture the evolving nature of brain connectivity in smartphone addiction.

Beyond connectivity, neurochemical studies have provided additional layers of understanding. The mu-opioid receptor (MOR) system has been implicated in excessive smartphone use [36]. Similarly, elevated γ -aminobutyric acid (GABA) levels in the ACC have been linked to smartphone and internet addiction, for which normalization has been observed following cognitive behavioral therapy [42]. These findings highlight the interplay between neurochemical pathways and behavioral addictions, which offer potential biomarkers for intervention.

Overall, fMRI research has significantly advanced our understanding of the neural and structural abnormalities that are associated with smartphone addiction. In particular, abnormalities in the frontal lobe have been consistently observed, which supports the hypothesis of frontal lobe dysfunction in problematic smartphone use. Additionally, studies have expanded their focus to include gray matter volume, white matter integrity, dynamic connectivity, as well as neurochemical pathways. Gender differences have also been acknowledged, as some studies have opted to examine fixed-gender cohorts to account for neurobiological variability [40]. However, compared to other neuroimaging techniques, such as fNIRS and EEG, fMRI studies have been less exploratory in employing experimental paradigms. Given the dynamic nature of brain connectivity, future research should prioritize experimental designs that capture the temporal evolution of brain changes in smartphone addiction.

4. Neuromodulation and Psychophysiological Studies on Smartphone Addiction

Recent studies have explored the application of various neurostimulation and physiological measurement tech-

niques to better understand as well as address smartphone addiction. Comprehensive study data are concisely summarized in Table 4 (Ref. [28,43,44,45]).

Among neuromodulatory approaches, tDCS has shown promise as an intervention tool, with findings that indicate its potential to reduce smartphone addiction rates in adults [43]. Similarly, research that employs TMS has revealed a correlation between inattention problems and TMS-evoked potentials in the right prefrontal cortex [28].

Despite these advances, research on the application of tDCS, TMS, as well as skin conductance in populations with smartphone addiction remains limited. Existing evidence suggests that techniques such as tDCS [46], transcranial alternating current stimulation (tACS) [47], as well as TMS [48] yield effective outcomes in neural stimulation and behavioral interventions. Future studies should leverage these methods to investigate changes in behavior and neural activity that occur following intervention in smartphone addiction groups. Furthermore, the integration of these techniques with neural imaging tools such as fNIRS and EEG could provide deeper insights into brain activation patterns that emerge post-stimulation. Such interdisciplinary approaches could significantly enhance our understanding of the neural mechanisms that underlie smartphone addiction and pave the way for more effective intervention as well as treatment strategies.

Skin conductance, which serves as a measure of autonomic nervous system arousal, provides complementary insights into emotional and reward processing in problematic smartphone use. Khoury et al. (2019) [44] used the Game of Dice Task (GDT) and Iowa Gambling Task (IGT) to examine decision-making under risk and ambiguity in 50 problematic smartphone users and 50 healthy controls. They found that problematic smartphone users exhibited impaired decision-making under ambiguity, difficulty recognizing disadvantageous alternatives, high sensitivity to rewards, as well as low sensitivity to punishments. These behavioral differences were accompanied by altered skin conductance responses, which indicate dysregulated autonomic arousal during decision-making.

Future research, by combining advanced neurostimulation techniques with innovative imaging technologies, holds the potential to address the growing challenge of smartphone addiction with greater precision as well as efficacy.

5. Future Directions

The present review synthesizes evidence from 41 neuroimaging studies that examine the neural correlates of smartphone addiction. Converging findings suggest that excessive smartphone use is associated with altered activation patterns in prefrontal-striatal circuits, as well as structural variations in regions that are implicated in reward processing and cognitive control. These observations align with theoretical models of addiction that emphasize dysreg-

Table 4. Summary of articles using tDCS, TMS and Skin Conductance to study problematic smartphone use.

Authors	Core focus	Paradigms	Assessment tool (SA)	Sample size	Type of population	Age/Age range	Gender	Type of study	Main discoveries/contributions
Lee (2021) [43]	Investigate the effect of tDCS on smartphone addiction solution and stress reduction.	unclear	unclear	Total = 41 tDCS Group = 21 Control Group = 20	college adults	22.95 ± 2.76	Male = 18 Female = 23	Longitudinal study	The use of tDCS will reduce the addiction rate of adults and reduce stress.
Hadar et al., (2015) [45]	To establish whether smartphone usage may cause measurable changes in cognitive capacities, behavioral tendencies and relevant prefrontal neural activity.	timed arithmetic, response inhibition and monetary delay tasks	unclear	Total = 55 nonusers = 38 heavy users = 17	unclear	unclear	unclear	Longitudinal study	Heavy smartphone usage is associated with increased impulsivity and decreased information processing capacity as measured in simple arithmetic tasks. Lower prefrontal LICI in heavy users group as compared with nonusers.
Hadar et al., (2017) [28]	Determine whether smartphone excessive usage is accompanied by measurable neural, cognitive and behavioral changes.	Speeded numerical processing task Memory task Stop signal task	SAS MPIQ	First phase: Total = 51 SU = 16 NU = 35 Second phase: Total = 25 NUco = 14 NUsp = 11	university students	First phase: SU = 24 ± 2.5 NU = 25 ± 3.8 Second phase: NUco = 24.9 ± 2.2 NUsp = 24.7 ± 2	First phase: Male = 23 Female = 28 Second phase: Male = 10 Female = 15	Longitudinal study	Heavy usage was found to be associated with impaired attention, reduced numerical processing capacity, changes in social cognition, and reduced right prefrontal cortex (rPFC) excitability.
Khoury et al., (2019) [44]	Evaluate the decision-making process under risk and under ambiguity in individuals with SA and to measure the physiological parameters that accompany this process.	GDT IGT	SPAI-BR	Total = 100 SA Group = 50 HC Group = 50	graduate students	18–25	Male = 43 Female = 47 (Considering a possible loss of 20%, 100 individuals were recruited to participate in the study. At the endpoint, 10 subjects were excluded from the sample: four individuals interrupted the questionnaire during the procedure, and six failed to measure SCR. Of the 90 individuals composing the final sample, 47 (52.22%) were female and 43 (47.77%) were male.)	Cross-sectional study	Smartphone dependents presented a profile of impairment in decision-making under ambiguity, without impairment in decision-making under risk. And difficulty in recognizing disadvantageous alternatives, high sensitivity to rewards, and low sensitivity to punishments.

Note: SAS, Smartphone Addiction Scale; MPIQ, Mobile Phone Involvement Questionnaire; SPAI-BR, Brazilian version of the Smartphone Addiction Inventory; SA, smartphone addiction; HC, healthy control; SU, heavy smartphone users; NU, nonusers; NUsp, NU participants receive smartphone devices for a 3 months period; NUco, NU participants served as matched controls; tDCS, Transcranial Direct Current Stimulation; LICI, long intracortical inhibition; GDT, Game of Dice Task; IGT, Iowa Gambling Task.

ulated incentive salience attribution as well as compromised executive function. Nevertheless, substantial methodological heterogeneity across existing studies complicates efforts to distill a coherent neurobiological signature.

This heterogeneity is perhaps most evident within the assessment domain. The included studies employed eleven distinct self-report instruments, each of which operationalizes smartphone addiction through different conceptual lenses, ranging from compulsive usage patterns to withdrawal symptoms as well as functional impairment. Divergent cut-off scores and dimensional assumptions introduce measurement noise that likely obscures true neural effect sizes. From a psychometric standpoint, this variability raises questions about whether current instruments capture a unitary construct or merely index correlated facets of problematic digital behavior. Future work would benefit from adopting consensus-based diagnostic frameworks, which may integrate dimensional severity gradients rather than relying on dichotomous classifications. Whether “smartphone addiction” constitutes a unified nosological entity or represents an umbrella term for platform-specific behavioral addictions, each with potentially distinct neural substrates, remains an open empirical question that carries direct implications for assessment design.

Methodological refinement in neuroimaging protocols represents another key priority. While fMRI offers superior spatial resolution for localizing structural and functional abnormalities, its temporal resolution limits the capture of rapid neural dynamics that underlie compulsive checking behavior. Conversely, EEG provides millisecond-level temporal precision but suffers from poor spatial localization. fNIRS occupies a middle ground with reasonable spatial coverage and acceptable temporal resolution, as well as practical advantages for ecological research settings. Integrating these modalities, for instance through simultaneous EEG-fMRI or hybrid fNIRS-EEG designs, would allow researchers to model both where and when neural deviations occur. Such approaches are particularly relevant for the development of closed-loop brain-computer interface systems that might support real-time intervention delivery.

Non-invasive neuromodulation techniques, including tDCS as well as tACS, have emerged as potential adjunctive interventions. Preliminary evidence suggests that these methods can modulate cortical excitability in regions that are associated with craving and cognitive control. However, the therapeutic value of such approaches for smartphone addiction remains speculative. Critical unknowns include optimal stimulation parameters, target site selection based on individual neuroimaging profiles, and, most importantly, whether observed neuromodulatory effects translate into sustained behavioral change. Longitudinal randomized trials with repeated stimulation sessions, which are ideally coupled with concurrent neuroimaging to monitor neural plasticity indices, are needed before these tools can be considered evidence-based treatment components.

Sample characteristics in the existing literature also warrant careful scrutiny. The preponderance of college student samples introduces age-related confounds and limits generalizability to broader population strata. Smartphone use patterns differ markedly across the lifespan; older adults, for instance, exhibit distinct usage motivations and platform preferences that may engage partially overlapping but non-identical neural circuits. The rising prevalence of problematic smartphone use among middle-aged as well as elderly populations renders this demographic gap particularly problematic. Similarly, although biological sex has been recognized as a moderator in substance addiction research, gender-stratified analyses remain rare within the smartphone addiction literature. Given documented sex differences in prefrontal-limbic connectivity as well as reward sensitivity, ignoring gender as an analytical variable may mask important neural phenotypes.

Perhaps the most pressing measurement concern involves the near-exclusive reliance on self-report instruments for participant classification. Self-reported addiction severity correlates only modestly with objective usage metrics, and recall biases may distort estimates of actual behavior. The integration of digital phenotyping, or passive sensing of screen time, app-specific engagement, unlock frequency, as well as circadian usage patterns via smartphone-native Application Programming Interfaces (APIs) or dedicated applications, would anchor neuroimaging findings to ecologically valid behavioral anchors. Such objective metrics would enable more precise severity stratification and could serve as proximal outcomes in intervention trials, which bridges the gap between neural markers and real-world behavior change.

The social ecology of smartphone addiction has received insufficient attention within neuroimaging research. Hyperscanning methodologies, which capture inter-brain synchronization during social interaction, offer a promising avenue for examining how problematic use spreads through dyadic and group-level processes. Whether in physical co-presence or virtual environments, analyzing inter-subject neural correlations may reveal mechanisms of social contagion as well as normative influence that self-report methods cannot access. This perspective shifts the analytical unit from the isolated individual to the interacting dyad or network, which may inform intervention designs that target social systems rather than individual users alone.

6. Limitations

Several limitations of the present review should be acknowledged. The restriction to English-language publications may have excluded relevant studies from non-English journals, particularly given the high prevalence of smartphone addiction research in East Asian contexts. The diversity of neuroimaging protocols, analytical strategies, as well as reporting standards precluded quantitative meta-analysis of neural effect sizes. The cross-sectional design

that dominates the primary literature limits causal inference; observed neural alterations may represent premorbid vulnerability markers, consequences of chronic use, or both. Additionally, the rapid evolution of mobile technology means that studies that were conducted even five years ago may not capture neural responses to contemporary usage patterns such as short-form video consumption or algorithmic content delivery. The absence of standardized risk-of-bias tools that are tailored for neuroimaging research necessitated adapted quality appraisal, which may not fully reflect the methodological nuances of specific imaging paradigms. In addition, the protocol was registered retrospectively rather than before the search. Although the eligibility criteria and analysis plan were not modified after the search, the absence of prospective registration provides weaker protection against selective reporting and is acknowledged here in line with PRISMA 2020.

7. Conclusion

In sum, while neuroimaging research has begun to map the neural correlates of excessive smartphone use, the field remains in an early descriptive phase overall. Progress will depend on resolving fundamental construct validity questions, embracing multimodal and ecologically valid measurement strategies, diversifying samples, as well as integrating social-neuroscience perspectives. Addressing these challenges will be essential for the translation of neural findings into theoretically grounded, clinically actionable intervention strategies.

Availability of Data and Materials

This review does not include/use any original data or code. For any data/code contained in any studies referenced, please refer to the original article for further information.

Author Contributions

HL conceptualized the review framework, designed the search strategy, wrote the original draft, and supervised the overall project. TL and RH performed the formal analysis and investigation, and contributed to the data extraction and interpretation of the results. PY participated in the literature screening, data extraction, and formal analysis. YL and XL participated in the literature acquisition and screening, contributed to the data extraction and analysis of the findings, and provided critical revisions to the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

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Conflicts of Interest

The authors declare no conflicts of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at <https://doi.org/10.31083/JIN52647>.

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