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Review

Neuroimaging the effects of smartphone (over-)use on brain function and structure—a review on the current state of MRI-based findings and a roadmap for future research

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Abstract

The smartphone represents a transformative device that dramatically changed our daily lives, including how we communicate, work, entertain ourselves, and navigate through unknown territory. Given its ubiquitous availability and impact on nearly every aspect of our lives, debates on the potential impact of smartphone (over-)use on the brain and whether smartphone use can be "addictive" have increased over the last years. Several studies have used magnetic resonance imaging to characterize associations between individual differences in excessive smartphone use and variations in brain structure or function. Therefore, it is an opportune time to summarize and critically reflect on the available studies. Following this overview, we present a roadmap for future research to improve our understanding of how excessive smartphone use can affect the brain, mental health, and cognitive and affective functions.

Keywords: smartphone; smartphone use disorder; problematic smartphone use; smartphone addiction; internet; internet addiction; MRI; review; brain; fMRI; mental health

Background

At the time of writing, more than six billion smartphone subscriptions have been estimated for the year 2022 (Statista, 2022). This tremendously high number reflects that over the last 15 years—since the inception of the iPhone in 2007 (Macedonia, 2007)—a global mobile digital revolution happened leading to ubiquitously and permanently available smartphone technologies around the world. Smartphones enable us to find our way in unknown territory, to initiate and maintain social communications, to join and provide content for social networks, and find information on whatever we are interested in as long a network signal is available. Due to the numerous applications in occupational and recreational contexts the smartphone has attracted many users around the globe. The gigantic rise of social media over the last 15 years is highly interwoven with the digital mobile revolution (Jurgenson, 2012; Korolija, 2020).

Adverse consequences of excessive smartphone use

Despite the many obvious improvements in our daily life by the smartphone, the scientific and public debates have drawn attention toward potential detrimental effects of smartphone (over-)use on different levels ranging from the societal to the individual level. Initial evidence suggests negative effects of excessive smartphone use on cognitive and affective domains, such that excessive smartphone use has being linked to lower productivity (Duke & Montag, 2017), lower learning outcomes/academic achievements (Sapci *et al.*, 2021; Sunday *et al.*, 2021), and elevated levels of negative emotionality (Elhai *et al.*, 2019; Montag *et al.*, 2016). Moreover, being distracted by the smartphone in the traffic represents a considerable danger on the road (Jannusch *et al.*, 2021; Rosenthal *et al.*, 2022). Although the cross-sectional nature of many of the available studies does not allow to make causal interpretations with respect to the associations—as it is, for example, also conceivable that higher negative emotionality renders individuals at an increased risk to develop escalating smartphone use—the reported associations between excessive smartphone use and adverse outcomes led to scientific and societal debates around the globe. Most of the research endeavors to date have been trying to understand how the digital revolution and the ubiquitous use of digital platforms may affect mental health, daily life functioning, social interactions, and also the brain (Firth *et al.*, 2019; Montag & Diefenbach, 2018). In the context of smartphone use, much research has focused in recent years on the question of how (excessive)

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smartphone use is linked to altered cognition (Liebherr *et al.*, 2020) and whether excessive smartphone use resembles an addictive behavior.

Debate on the medium versus function of smartphones

One critical debate concerns the differentiation of the medium versus function in the discussion on "smartphone addiction." From the perspective of substance addiction, it would clearly be misleading to refer to being addicted to bottles, but reasonably the content of the bottle matters (Kuss & Griffiths, 2017; Panova & Carbonell, 2018). Applying this example to the area of excessive smartphone use or "smartphone addiction," one would need to disentangle which specific contents the smartphone transmits and ultimately which specific needs these contents fulfill. Initial evidence suggests that drivers of excessive smartphone use likely are social media applications (Montag, 2021; Rozgonjuk *et al.*, 2020; Sha *et al.*, 2019) promoted through highly immersive app designs (Montag, Lachmann, *et al.*, 2019). Of note, many social media apps need to be considered in the context of the so-called data business model, which aims to prolong online time to enlarge the digital footprints of their users (Montag & Hegelich, 2020). Other drivers of excessive smartphone use might be video games on the phone (Leung *et al.*, 2020) and other functions such as unregulated access to work-related e-mails (Sadeghi *et al.*, 2022), which in turn might lower well-being (Kushlev & Dunn, 2015). In the context of ongoing debates about the conceptualization of excessive and potentially harmful smartphone use a very recent systematic meta-analysis reported global prevalence rates as high as 26.99% (Meng *et al.*, 2022) and another work mentioned an increase of "smartphone addiction" around the world (Olson *et al.*, 2022). Interestingly, the work by Meng *et al.* (2022) observed that prevalence rates of smartphone addiction are particularly high among adults (26.84%), followed by adolescents (21.62%), and children (15.19%). Males and females did not differ significantly. For a review on antecedents and consequences of smartphone addiction, see a recent overview by Busch & McCarthy (2021).

Is the actual nature of excessive smartphone use "addictive"?

In addition to the need for a more detailed examination with respect to which specific contents on smartphones drive excessive use, a large and growing number of studies (primarily employing self-report questionnaires) has examined excessive smartphone behavior within an addiction framework. Within the addiction framework, one would hypothesize that excessive—and ultimately problematic—use of the smartphone would be characterized by symptoms such as loss of control and preoccupation with use, reflected in, for example, unsuccessful attempts to reduce use or continued use despite negative consequences, as well as social problems and functional impairments in daily life—which represent key diagnostic symptoms of both substance and behavioral addictions (e.g. see also the new Gaming Disorder criteria by the WHO; Montag, Schivinski *et al.*, 2021). Of note, the duration of use, so spending a considerable amount of time on the smartphone, is not a distinct criterion per se. On the one hand, not everyone who spends much time on the smartphone shows problematic smartphone use behavior (for instance, the time could reflect constant job-related smartphone use); however, on the other hand, those using the smartphone in an "addictive" way will inherently spend much of their time on the smartphone. The most prominent self-report measures to assess problematic use of the smartphone are currently perhaps Kwon's Smartphone Addiction Scale (SAS) (Kwon *et al.*, 2013) and the Korean Smartphone Addiction Proneness Scale (SAPS) (D. Kim *et al.*, 2014). This notion is also supported by their use in many of the brain imaging studies discussed in the present review.

While the introduced scales and several of the current studies refer to smartphone addiction some researchers argue that the term "addiction" should not be simply transferred into the context of smartphone use (Panova & Carbonell, 2018) or propose that the term should be abandoned (Carbonell *et al.*, 2022) "to refocus clinical and research efforts on real disorders" (p. 2). Further, many researchers refer in the context of smartphone addiction research to problematic smartphone use as a more neutral term (Elhai *et al.*, 2017; Fischer-Grote *et al.*, 2019), while others prefer terms such as Smartphone Use Disorder (SmUD) to align the terminology with substance addictions and addictive behaviors in the ICD-11 of the World Health Organization (Gao, Jia, *et al.*, 2020; Gao, Sun, *et al.*, 2020). We currently consider the term SmUD as most suitable as it aligns well with the WHO terminology of Gaming Disorder in the realm of addictive behaviors (Marengo *et al.*, 2020; Montag *et al.*, 2021), but explicitly state that SmUD (or the other terms used) are not officially recognized at the moment and in many studies at best tendencies toward SmUD are investigated. Moreover, we have iterated already on the many problem areas when using terms such as smartphone addiction or SmUD. It is important to not overpathologize everyday behavior, and this is what needs to be kept in mind in this research field (Billieux *et al.*, 2015) until evidence from different areas comes up to understand the actual nature of excessive behavior (Brand *et al.*, 2020)—here, excessive smartphone use. A final thought on the terminology: the umbrella term "Smartphone Use Disorder"—instead of focusing exclusively on excessive use of single app groups such as game apps or social-media apps—might also be relevant, when people show problematic use behavior in several categories on their phones. In this case, the SmUD terminology can summarize the problematic behavior being observed across several apps on the smartphone.

Although research on the detrimental effects of smartphone (over-)use or SmUD has only recently begun, initial studies have employed neuroimaging techniques, in particular magnetic resonance imaging (MRI), to explore associations between excessive smartphone use and individual variations in brain structure and function. These variations may reflect adaptations that neurally underlie excessive use or mediate the association between problematic smartphone use and affective, cognitive, and behavioral dysregulations. The initial yet rapidly growing literature has used different MRI-based approaches to examine variations in the structural organization of the brain using e.g. voxel-based morphometry (VBM) or diffusion tensor imaging (DTI), the functional organization of the brain using resting state functional MRI (fMRI) techniques, and functional alterations during cognitive and affective processes, using task-based fMRI (Ahn *et al.*, 2021; Arató *et al.*, 2023; Cho *et al.*, 2021; Choi *et al.*, 2021; Chun *et al.*, 2017, 2018; Han & Kim, 2022; Hirjak *et al.*, 2022; Horvath *et al.*, 2020; Hu *et al.*, 2017; Kwon *et al.*, 2022; Lee *et al.*, 2019; D. Liu *et al.*, 2022; Lou *et al.*, 2019; Paik *et al.*, 2019; Pyeon *et al.*, 2021; Rashid *et al.*, 2021; Schmitgen *et al.*, 2020, 2022; Tymofiyeva *et al.*, 2020; Wang *et al.*, 2016; Yoo *et al.*, 2021; Zou *et al.*, 2021, 2022). Please note that the papers cited here will be reviewed in the next section of the present work (for a summary, see Tables 1 and 2; see also an overview in Fig. 1).

Meanwhile >20 studies on MRI-neuroimaging and excessive smartphone use or SmUD have been published and the number has strongly increased since 2020. Within this context, it is an opportune time for a review that (i) critically reflects on where

Table 1: Findings from structural MRI studies on smartphone (over-)use (in alphabetic order following the surname of the first author); gray shaded boxes represent DTI studies, the Wang *et al.* (2016) and Zou *et al.* (2021) studies in the table include both a VBM and DTI approach.

Author name and year	MRI type	Smartphone use assessment	Number of participants	Main findings
Cho *et al.* (2021)	Analysis of T1 images with a focus on brainstem structures, Freesurfer	SAPS	$n = 20$ PSU, $n = 67$ controls	PSU < control group: lower volume in the superior cerebellar peduncle in PSU, negative correlation between volume of the superior cerebellar peduncle and the SAPS score.
Hirjak *et al.* (2022)	Analysis of T1 images, examination of cortical surface indices	SPAI	$n = 19$ PSU, $n = 22$ controls; subsample from Horvath *et al.* (2020)	PSU < control group: lower complexity of cortical folding in the right superior frontal gyrus, in the right caudal and rostral anterior cingulate cortex (ACC). Dimensional approach across 41 participants: complexities of cortical folding of the right caudal ACC was significantly (and negatively) associated with SPAI total score, as well as with distinct SPAI subdimensions and time spent with the device.
Horvath *et al.* (2020)	Analysis of T1 images, DARTEL VBM	SAS-SV/SPAI	$n = 22$ PSU, $n = 26$ controls	PSU < controls: lower gray matter volume in the following brain areas—left anterior insula, inferior temporal, and parahippocampal cortex. Further: negative association between SPAI and ACC volume, negative association between SPAI and left orbitofrontal GMV.
Hu *et al.* (2017)	TBSS analysis of DTI data	Mobile Phone Addiction Tendency Scale	$n = 25$ PSU, $n = 24$ controls	PSU < controls: PSU associated with lower white matter integrity in superior longitudinal fasciculus, superior corona radiata, internal capsule, external capsule, sagittal stratum, fornix/stria terminalis, and midbrain structures. Further: fractional anisotropy of internal capsule/stria terminalis were negatively correlated with the Mobile Phone Addiction Tendency Scale in PSU.
Lee *et al.* (2019)	T1 images, DARTEL VBM analysis; region of interest analysis with focus on fronto-cingulate region	SAPS	$n = 39$ PSU (detail: with excessive use of social networking platforms via smartphone), $n = 49$ controls	PSU < controls: lower gray matter volume in the right lateral orbitofrontal cortex (OFC); further: negative correlations between gray matter volume in the right lateral OFC and SAPS (including the SAPS tolerance facet) in PSU sample.
Rashid *et al.* (2021)	T1 images, VBM analysis	SAS, Malay version	$n = 20$ PSU, $n = 20$ controls	Controls > PSU: decreased gray matter density in PSU in the inferior parietal lobe. PSU > controls: increased gray matter density in the insula in PSU (see Table 2 in the paper). Total sample: negative correlation between the precuneus gray matter density and the SAS-M scores. Please note that the information provided regarding the brain regions is not consistent across the paper.
Tymofiyeva *et al.* (2020)	DTI analysis	SAS-SV	$n = 19$ participants	Positive correlations between the node centrality of the right amygdala and SAS-SV.
Wang *et al.* (2016)	Brain structural assessments, including T1 and DTI, using TBSS and VBM analyses	Mobile Phone Addiction Index (MPAI)	$n = 34$ belonging to the Mobile Phone dependent group (MPD) and $n = 34$ controls	PSU < controls: among others lower gray matter volume in right superior frontal gyrus, right inferior frontal gyrus, and thalamus (bilateral). In the PSU (MPD group): negative correlation between gray matter and MPAI scores in the mentioned areas. TBSS analysis: fractional anisotropy and axial diffusivity lower in PSU (MPD) compared to control in the bilateral hippocampal cingulum bundle fibers. Within the PSU (MPD) group: negative correlations in the mentioned fiber tract with MPAI.

Table 1: Continued

Author name and year	MRI type	Smartphone use assessment	Number of participants	Main findings
Yoo *et al.* (2021)	T1 images, volume-based analysis in Freesurfer	SAPS	$n = 20$ with higher scores in the SAPS vs. 68 with lower scores on the SAPS	PSU < controls: lower caudate volumes. Left caudate volume was negatively associated with SAPS scores (to us it is unclear whether this is true for the entire sample or just the higher score participants).
Zou *et al.* (2021)	Brain structural assessments, including T1 and DTI, using TBSS and VBM analyses	Questionnaire for Adolescent Problematic Mobile Phone Use	$n = 266$ participants	Higher GMV of the anterior cingulate gyrus and right fusiform gyrus (FFG) was associated with lower PSU. TBSS analysis: fractional anisotropy in the body of the corpus callosum was negatively correlated with PSU.

GMV = gray matter volume, SPA = smartphone addiction, PSU = problematic smartphone use (smartphone use disorder tendencies), SPAI = Smartphone Addiction Inventory, TBSS = tract-based spatial statistics, SAS-SV = SAS-Short Version, MPAI = Mobile Phone Addiction Index, MPD = Mobile Phone Dependent group.

the field stands and how strong the evidence is for smartphone-use associated brain changes, and (ii) provides a roadmap that outlines critical issues in the field and next steps that can help to shed light on the cognitive, affective, and neurobiological basis of smartphone (over-)use.

Neuroimaging of SmUD

The last few years have seen a strong increase in studies investigating individual differences in SmUD and associated brain variations by means of MRI. As depicted in Fig. 1, the studies encompass structural MRI focusing on use-associated variations in gray and white matter as well as functional MRI studies examining associations with the intrinsic functional organization of the brain or during engagement in cognitive and affective tasks.

Associations between SmUD and the structural organization of the brain have been examined on the level of gray and white matter. Further, different methodological strategies including the use of individual differences association designs (e.g. examining linear relationships between the level of SmUD and brain structural variations) as well as between group designs aiming to examine brain structural differences between groups of individuals with high and low SmUD levels have been implemented. Differences in the gray matter organization of the brain are commonly examined by means of voxel based morphometry of T1 images [Ashburner & Friston (2000); for recent methodological aspects see the work by Zhou *et al.* (2022) and for information on cortical thickness or cortical folding patterns the work by Chen *et al.* (2013); additional insights can be derived from the work by Jiang *et al.* (2022)]. Investigations on the level of the white matter tract organization are for instance examined using DTI (and the application of tract based spatial statistics: Bach *et al.*, 2014). While structural brain imaging provides insights into the structural brain architecture, fMRI is applied to study the intrinsic functional organization of the brain (resting state fMRI) or the engagement of specific brain regions during cognitive or affective task paradigms (task-based fMRI). To better understand individual differences in SmUD tendencies both task-based fMRI and resting state fMRI have been applied. During task-based fMRI studies, the individuals engage into specific cognitive or affective processes of interest, e.g. viewing a smartphone stimulus that can trigger "cue-reactivity." Cue-reactivity is a process during which a stimulus that is frequently paired with the addictive substance or the addictive behavior gains strong incentive salience (e.g. Yu *et al.*, 2020; X. Zhou *et al.*, 2019). In contrast, resting state fMRI aims to gain insights into the intrinsic functional architecture of the brain ("at rest") while the participants do not engage in a specific mental operation ("do not think of something in particular") (Gonzalez-Castillo *et al.*, 2021; Markett *et al.*, 2018).

The structural and functional MRI-approaches have been extensively used—either separately or in combination—to determine the brain basis of substance-related and (established) behavioral addictions (for quantitative and qualitative reviews, see also Klugah-Brown *et al.*, 2021; Taebi *et al.*, 2022; Tolomeo & Yu, 2022; and Zilverstand *et al.*, 2018 for examples). The combination of the different imaging approaches can allow a more holistic evaluation at different levels and allow to examine different research questions with respect to potential addiction-related changes. The present review aims to provide a brief overview on the smartphone-(over-)use MRI literature, and is divided in both structural and functional MRI sections summarizing the results of the current literature (Fig. 1). Next, the review presents a roadmap for future studies in the field of SmUD and associated brain changes.

Smartphone (over-)use and brain structure (structural MRI studies)

As becomes apparent in Table 1, several studies examined differences in gray matter brain volumes in the context of SmUD tendencies. Overall deriving a consistent picture of SmUD tendency associated variations in brain structure is currently limited by the use of varying SmUD assessments in these studies. Moreover, differences in MRI analysis strategy may further limit direct comparisons. In this context, recent studies have shown that the specific brain structural variations that are identified may strongly depend on the choice of processing pipeline (see Zhou *et al.*, 2022 for a methodological evaluation of the effects of choice of processing pipeline on brain structural analyses). Moreover, some of the identified studies focused in their analysis on specific hypothesis-driven brain regions such as the brain stem (Cho *et al.*, 2021) or specifically on striatal morphology (Yoo *et al.*, 2021), whereas other studies used whole-brain analytic approaches (Horvath *et al.*, 2020; Rashid *et al.*, 2021). Further complicating matters is the use of different rigor in the brain analysis and in the level of description of the analyses used, such that for several studies the exact multiple comparisons approach used remains unclear.

An initial overview of the reported associations between brain volume and SmUD tendencies mostly suggests an association of inverse nature (such that higher SmUD tendencies associated with lower volumes in specific brain regions, e.g. Wang *et al.*,

Table 2: Findings from functional MRI studies on smartphone (over-)use (in alphabetic order following the surname of the first author); gray colored parts of the table represent task-based fMRI studies, the remaining studies represent resting state fMRI studies.

Author name and year	MRI type	Smartphone use assessment	Number of participants	Main findings
Ahn *et al.* (2021)	Resting state fMRI	SAPS	$n = 44$ PSU, $n = 54$ control participants	PSU > controls: enhanced functional connectivity between the salience and default mode network and within the salience network. Controls > PSU: decreased functional connectivity between the salience and central executive network in PSU.
Arató *et al.* (2023)	Task-based fMRI: Facial Emotion Recognition Paradigm	Smartphone application–based addiction scale (SABAS)	$n = 65$	Positive associations between functional connections related to emotional cognitive control/social brain networks and SABAS scores were presented; please note that also problematic Internet use was assessed in the study.
Choi *et al.* (2021)	Task-based fMRI: modified cognitive conflict task	SAPS	$n = 33$ PSU, $n = 33$ controls	PSU < controls: lower performance in PSU that was accompanied by enhanced (but not differentiated) activation in fronto-parietal brain regions, this was observed for all conditions, and distractor saliency did not matter here. PSU < controls: decreased functional connectivity between the right inferior parietal lobule and the right superior temporal gyrus in the attention-demanding condition relative to the easiest condition of the experiment; this was associated with SAPS scores.
Chun *et al.* (2017)	Task-based fMRI: facial emotion processing	SAPS	$N = 25$ PSU, $n = 27$ controls	PSU < controls: lower activity (neural deactivation) in the dorsolateral prefrontal cortex and dorsal ACC during processing of an angry face and emotional transition compared to the controls. PSU < controls: lower activity (neural deactivation) of the superior temporal sulcus and temporo-parietal junction related to social interaction during emotional transition.
Chun *et al.* (2018)	Resting state fMRI	SAPS	$n = 38$ PSU, $n = 42$ controls	PSU < controls: lower functional connectivity between the right OFC and NAcc, lower functional connectivity between the left OFC and midcingulate cortex. PSU > controls: higher functional connectivity between the midcingulate cortex and Nucleus Accumbens (NAcc).
Han & Kim (2022)	Task-based fMRI: odd-ball-task	SAS	43 adults	PSU < controls: lower levels of activation in the frontopolar cortex; moreover, PSU worse in filtering out distractor stimuli.
Horvath *et al.* (2020)	Amplitude of low frequency fluctuations (ALFF)	SAS-SV/SPAI	$n = 22$ PSU, $n = 26$ controls	PSU < controls: lower intrinsic activity in the (right) ACC. For the total sample: negative association between SPAI and ACC activity.
Kwon *et al.* (2022)	Resting state fMRI	SAPS	$n = 30$ PSU, $n = 35$ controls	PSU > controls: larger functional connectivity of the dorsal ACC with the ventral attention network and with the default mode network. Complete sample: dorsal ACC-ventral attention network functional connectivity correlated negatively with the SAPS total scores; the same was observed for the dorsal ACC-default mode network activity.
Liu *et al.* (2022)	Resting state fMRI	SAS-SV	$n = 29$ PSU, $n = 22$ controls	Total sample, dimensional approach analysis: SAS-SV score was positively correlated with global efficiency/local efficiency of static brain networks; negative associations appeared between SAS-SV and the temporal variability using the dynamic brain network model. Large-scale subnetwork analyses in the total sample: a higher SAS-SV scores were linked to higher strengths of static functional connectivity within the frontoparietal and cinguloopercular subnetworks, moreover higher SAS-scores went along with lower temporal variability of dynamic functional connectivity patterns within the attention subnetwork. See also Figure 3 and 4 for illustrations in the article. PSU and controls did not differ in the resting state fMRI analysis.
Lou *et al.* (2019)	Resting state fMRI	MPAI and SPAI	$n = 24$ PSU, $n = 16$ controls	PSU > controls: functional connectivity with posterior cingulate cortex was higher with the brain regions anterior cingulate, bilateral middle frontal gyrus, bilateral inferior frontal gyrus, right middle temporal gyrus, and right inferior temporal gyrus.

Table 2: Continued

Author name and year	MRI type	Smartphone use assessment	Number of participants	Main findings
Paik *et al.* (2019)	Resting state fMRI of the insula	SAPS	$n = 90$ adults	Total sample: SAPS scores were positively associated with connectivity between the right putamen and left insula.
Pyeon *et al.* (2021)	Resting state fMRI	SAPS	$n = 47$ PSU, $n = 46$ controls	PSU < controls: reduction in resting state functional connectivity between the right inferior frontal gyrus and limbic areas. Total sample: lower fronto-limbic resting state functional connectivity was associated with higher SAPS scores and amount of time on the smartphone.
Rashid *et al.* (2021)	Resting state fMRI	SAS, Malay version, 33 items	$n = 20$ PSU, $n = 20$ controls	PSU > controls: higher activity among others in left fusiform gyrus, right superior frontal gyrus, right precuneus, right superior motor area, and left superior parietal lobe.
Schmitgen *et al.* (2020)	Task based fMRI; a modified cue reactivity task	SAS-SV/SPAI	$n = 21$ PSU, $n = 21$ controls; subsample from Horvath *et al.* (2020)	Contrast smartphone vs. neutral stimuli: group differences in several areas were found between both investigated groups (medial prefrontal, occipital, temporal, and anterior cingulate cortices: moreover, in temporoparietal regions, and cerebellum). Contrast active vs. inactive smartphones: group differences were observed in several brain areas (frontal operculum/anterior insula and precentral gyrus). Negative associations were found - among others - in brain areas such as medial prefrontal cortex and ACC and specific subscores of the SPAI.
Schmitgen *et al.* (2022)	Parallel independent component analysis	SAS-SV/SPAI	$n = 20$ PSU, $n = 24$ controls; subsample of Horvath *et al.* (2020)	PSU > controls: medial/dorsolateral prefrontal component showed increased activation in PSU. PSU < controls: parietal cortical/cerebellar component showed decreased activation in PSU (see Figure 1 in the paper).
Zou *et al.* (2022)	Resting state fMRI	Self-rating Questionnaire for Adolescent Problematic Mobile Phone Use	$n = 76$ PSU, $n = 162$ controls	PSU > controls: higher intrinsic functional connectivity of left inferior frontal gyrus to left occipital gyrus, left parahippocampal gyrus to right middle temporal gyrus, and right orbital gyrus to left occipital gyrus.

2016; Zou *et al.*, 2021). Accordingly, between-group designs comparing participants with high versus low SmUD often revealed decreased regional brain volumes in the group of excessive smartphone users compared to control individuals (e.g. Lee *et al.*, 2019; Yoo *et al.*, 2021). With respect to the volumetric gray matter approach, studies reported lower gray matter volume in regions such as the anterior cingulate cortex (ACC), orbitofrontal cortex (OFC), fusiform gyrus, parahippocampal regions, and the striatum (caudate). These regions partly resemble regions that have been identified in previous works examining brain volumetric alterations in substance and behavioral addictions (e.g. see the following studies: Klugah-Brown *et al.*, 2021; Koester *et al.*, 2012; Qin *et al.*, 2020; Yu *et al.*, 2022; Zhang *et al.*, 2021). However, none of the regions consistently replicated across SmUD studies and, together with the lack of standardized SmUD assessments and brain structural analyses strategies, the previous studies currently do not allow to draw clear conclusions with respect to the specific regions that might show brain structural alterations associated with excessive smartphone use. While the lack of consistently reported regions and the methodological limitations do not allow a clear interpretation of the underlying brain structural variations, previous studies in behavioral addictions have associated volumetric decreases in some of the mentioned regions with, for example, the severity of problematic online gaming or social media engagement (Montag *et al.*, 2018; F. Zhou *et al.*, 2019) or higher impulsivity in cocaine dependent individuals (Moreno-López *et al.*, 2012), which may suggest an association with key features of addiction. For details on the specific regions reported in the SmUD studies, please see also Table 1.

Although the reviewed number of structural studies - from our perspective - is currently too small and heterogenous to support an overarching picture, we further refer to studies that examined either white matter tract integrity (Hu *et al.*, 2017; Tymofiyeva *et al.*, 2020; Zou *et al.*, 2021) or variations in cortical folding (Hirjak *et al.*, 2022) in the context of SmUD tendencies.

Smartphone (over-)use and functional MRI

Table 2 shows studies investigating the neural correlates of SmUD tendencies using fMRI. Most previous studies employed a resting state fMRI approach examining associations between SmUD tendencies and the intrinsic functional organization of the brain (Ahn *et al.*, 2021; Chun *et al.*, 2018; Horvath *et al.*, 2020; Kwon *et al.*, 2022; D. Liu *et al.*, 2022; Lou *et al.*, 2019; Paik *et al.*, 2019; Pyeon *et al.*, 2021; Rashid *et al.*, 2021; Schmitgen *et al.*, 2022; Zou *et al.*, 2022). A direct comparison between the studies is hindered by differences in the methodological approaches, ranging from different preprocessing methods to different network analytic strategies. The studies reported potential associations between SmUD tendencies and variations in the intrinsic architecture of a number of brain systems and large-scale networks, including for instance altered connectivity of striatal, limbic, and frontal regions (e.g. Pyeon *et al.*, 2021; Zou *et al.*, 2022; Chun *et al.*, 2018; Paik *et al.*, 2019), as well as altered functional interaction between and within large scale networks including the default mode network and the salience network (Ahn *et al.*, 2021; Kwon *et al.*, 2022). While the different approaches employed in these studies and the methodological limitations prevent clear conclusions at the present stage, the identified pathways partly overlap with the intrinsic pathways

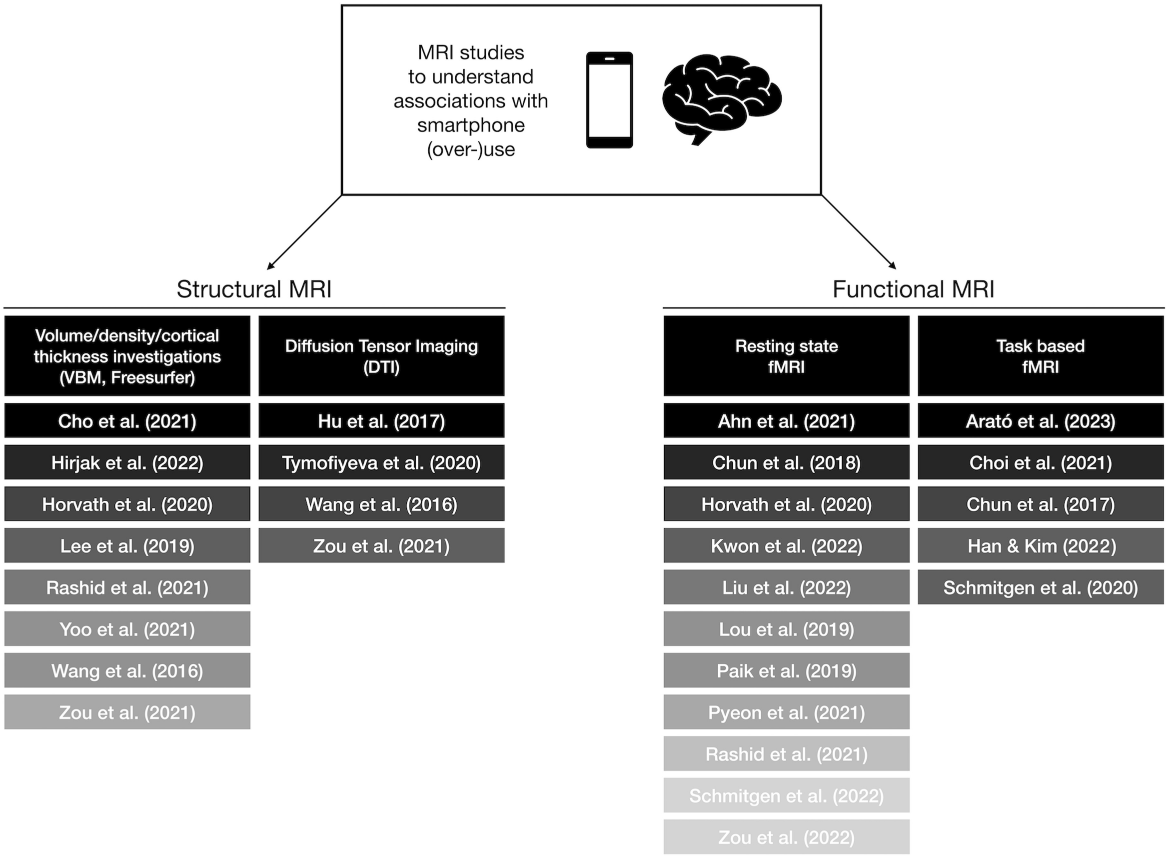

Figure 1: Structural and functional MRI studies on SmUD tendencies (also known as smartphone addiction or problematic smartphone use) as reviewed in the present work.

and networks that have been identified in substance and behavioral addictions (Zhou *et al.*, 2018; Taebi *et al.*, 2022; Tolomeo & Yu, 2022; Yan *et al.*, 2021; Zimmermann *et al.*, 2018). Within the context of the previous literature on the role of dysregulations in the intrinsic functional organization of the brain in addiction, it is conceivable that alterations in specific systems may promote different symptomatic features. Alterations in salience and executive control systems may, for instance, underly dysregulations in several affective and cognitive domains, while alterations in the striato-frontal organization may reflect the development of compulsive behavior and alterations in the default mode network may promote dysfunctional self-related decision-making (Taebi *et al.*, 2022; Tolomeo & Yu, 2022; Yan *et al.*, 2021; Yu *et al.*, 2022; Zhang & Volkow, 2019; X. Zhou *et al.*, 2019; Zimmermann *et al.*, 2018). However, clear conclusions with respect to consistent and robust effects of excessive smartphone use or SmUD on the functional architecture of the brain remain to be determined.

Five studies investigated the neural basis of altered cognitive and affective behaviors related to SmUD tendencies by means of task-based functional MRI (Arató *et al.*, 2023; Choi *et al.*, 2021; Chun *et al.*, 2017; Han & Kim, 2022; Schmitgen *et al.*, 2020). An early study by Chun *et al.* (2017) examined facial emotion processing alterations in participants with high SmUD versus participants with low SmUD and found that the high SmUD group displayed decreased activiation in the dorsolateral prefrontal cortex and dorsal ACC during the presentation of angry faces. Schmitgen *et al.* (2020) used a cue reactivity paradigm during which participants were presented with smartphone or neutral images and reported group differences between participants with high and low SmUD tendencies in several regions including anterior cingulate, medial prefrontal, and temporal regions. Choi *et al.* (2021) used a modified version of a cognitive conflict task and reported that participants with high SmUD exhibited lower task performance accompanied by enhanced recruitment of fronto-parietal regions. Han and Kim (2022) used a modified oddball task in participants with high versus low risk for SmUD and observed attention filtering impairments and a lower engagement of the frontopolar cortex in participants at high risk for SmUD. The most current study by Arató *et al.* (2023) applied a facial emotion recognition paradigm, where higher scores in the smartphone application-based addiction scale were associated with higher functional connectivity among brain regions related to emotional/cognitive control. While these findings may reflect that (social) cognitive and addiction-related changes in SmUD are accompanied by changes in corresponding brain systems, the low number of available studies and some other methodological limitations, such as the comparably small samples and lack of replication designs, do not allow to draw conclusions at present with respect to robust task-based brain functional alterations related to excessive smartphone use. Please note that two studies are not listed in Table 2 as they did not investigate SmUD tendencies, but either directly investigated links between objective smartphone use measures and resting state fMRI (Huckins *et al.*, 2019) or applied a general screen time self-report measure/time spent on reading to investigate functional connectivity in children (Horowitz-Kraus & Hutton, 2018).

Summary of the current status and a roadmap for future research

From the literature review, it becomes apparent that although the smartphone technology has now been available for over 15 years and the detrimental consequences of excessive smartphone use have been increasingly debated, the present knowledge about how smartphone use affects our neurobiology or is linked to variations in brain structure and function still is very limited. The available literature—although growing—does currently not allow us to draw firm conclusions with respect to potential effects of excessive smartphone use on the brain. This is partly because no consensus exists on which inventories to best use to assess smartphone (over-)use and a lack of studies including "objective" tracked smartphone data in the available MRI literature (see exceptions in studies such as those by Huckins *et al.*, 2019 and Montag *et al.*, 2017). While the conventional (neuroimaging) studies in this field employ a combination of self-report data for determining the severity or the extent of smartphone (over-)use with respect to symptoms or actual duration of use, "objective" in this context refers to tracked behavior on smartphones providing quantifiable and precise data of actual use, including, for example, how often a person checks the phone, what apps are used in particular, etc. (for a tracking app, see Montag, Baumeister, *et al.*, 2019). This approach is often described as digital phenotyping or mobile sensing in the literature (Baumeister & Montag, 2023). In this context, it is of importance to mention that SmUD tendencies not necessarily need to strongly overlap with time spent on the phone ["not everyone spending much time on the phone is addicted"; see also lack of association between fear of missing out (FOMO) with actual phone behavior (Rozgonjuk *et al.*, 2021)]. With respect to the design of the studies, several of the studies cited here are underpowered for determining robust brain alterations in SmUD and some studies do not adhere to multiple correction procedures, which are the current standard in the field. Finally, the predominance of retrospective cross-sectional study designs limits the conclusions that can be drawn with respect to disentangling predisposing brain variations from effects that are directly linked to smartphone (over-)usage.

Nevertheless, the available literature suggests a potential association between smartphone (over-)use and variations in brain structure and function that may mediate cognitive and behavioral changes, as well as detrimental effects on mental health and probably even addictive usage. Going forward, it will be essential to apply strategies and experimental designs that have been evaluated in the context of other mental disorders to disentangle the potential impact of different factors and thus to describe potential smartphone (over-)use associated brain changes. In contrast to other fields of research on the neurobiological basis of addiction, i.e. substance addiction, animal models for SmUD have not been developed and it will be challenging—or even impossible—to develop corresponding mechanistic animal models. Within this context, neuroimaging potential brain changes in humans will be even more important as a strategy to determine the underlying neurobiological and potentially neuropathological pathways. Based on the present overview, we outline the following key questions and strategies as a roadmap on the way forward to determining brain changes associated with smartphone (over-)use.

(i) SmUD (or smartphone addiction/problematic smartphone use) consists of many symptoms such as loss of control, functional impairments due to excessive use of the smartphone, and preoccupation with the smartphone, etc. Therefore, it is of importance to not only understand how overall SmUD scores are linked to brain structure and function, but also the different symptoms/facets. Initial studies have begun to determine separable and common brain alterations associated with different facets of general internet gaming behavior (e.g. Yu *et al.*, 2022). Within the SmUD context similar approaches may allow to better describe associations between specific symptomatic and behavioral dysregulations and associated brain changes. Moreover, we mention that several studies are hard to compare because different inventories to assess SmUD have been applied, as no agreement exists regarding a conceptual framework (but see Billieux's framework to understand problematic smartphone use; Billieux, 2012). Beyond this, it will be vital to disentangle brain changes that are specifically associated with SmUD and to separate these from other psychological processes that might be associated with or even inherently linked with SmUD. The construct fear of missing out (FOMO) for instance has gained increasing interest in the field of digital addictions (Elhai, Yang, Montag, *et al.*, 2020; Elhai, Yang, Rozgonjuk, *et al.*, 2020) and has been associated with individual variations in brain morphology (Wang *et al.*, 2022). Moreover, it will be critical to further separate brain changes related to specific or unspecific pathology relevant domains such as depression and anxiety—which have been related to brain structural and functional variations (X. Liu *et al.*, 2021, 2022; Serra-Blasco *et al.*, 2021; Wise *et al.*, 2017)—from variations that specifically associate with SmUD.

(ii) The literature search demonstrated (see also Fig. 1), that only few studies applied task-based fMRI methods in the field of SmUD. While resting state and brain structural approaches may allow to determine variations in the intrinsic architecture of the brain, task-based fMRI studies will further allow to determine the neural alterations that underlie dysregulations in domains that have been found to be disrupted across other addictive disorders. Promising underlying domains in this respect may be to examine whether: (a) smartphone-associated stimuli have gained an increased salience or even engage habit and compulsive use associated circuits during cue reactivity paradigms (for substance related addictions, see e.g. Vollstädt-Klein *et al.*, 2010; X. Zhou *et al.*, 2019; for behavioral addictions, see e.g. L. Liu *et al.*, 2017; for SmUD see Schmitgen *et al.*, 2020); (b) whether cognitive functions, in particular executive functions and the underlying fronto-parietal networks, show alterations in SmUD (for studies in other addictions please see Klugah-Brown *et al.*, 2021; Zheng *et al.*, 2019); and whether brain systems involved in (c) emotion and stress reactivity; or (d) natural reward processing are affected by SmUD (for studies in other addictions see e.g. Luijten *et al.*, 2017; J. Zhang *et al.*, 2020; Zhao et al., 2020).

(iii) Aside from self-reported SmUD tendencies, more studies need to correlate objective tracked smartphone use with brain data to add a further data layer to the neuroscientific study on smartphone use (Montag, Elhai, *et al.*, 2021b). Meanwhile, it became clear that humans have problems in correctly assessing their technology use, in particular regarding the quantity of technology use (Parry *et al.*, 2021).

(iv) To our knowledge no study in the field investigated potential changes of the brain due to smartphone use in term of structure and function with repeated MRI measures. This will be of particular importance within prospective longitudinal designs that hold the promise to separate predisposing brain alterations that render participants at an increased risk of developing SmUD from effects that are rather a consequence of escalating smartphone use or develop in association with the transition to addictive use (for prospective longitudinal designs in substance addiction research, see also the following studies: Becker *et al.*, 2013, 2015; Jager *et al.*, 2007). The implementation of prospective longitudinal designs would allow to draw stronger conclusions with respect to whether and how the smartphone technology affects human neurobiology (for comparable approaches in the field of behavioral addictions, see also previous studies: Gleich *et al.*, 2017; Kühn *et al.*, 2018; Yu *et al.*, 2020; Zhou *et al.*, 2019).

(v) The scientific works available in the field usually study the different MRI sources in an independent fashion, hence they correlate the smartphone behavior or SmUD scores with the brain data without shedding light on what differences in structure mean for functionality of the brain when studying smartphone use. Bringing these different brain sources together in a meaningful fashion would open interesting research avenues.

(vi) As already mentioned, to understand how smartphone (over-)use affects human neurobiology, a closer look needs to be taken on what smartphone applications humans use in what intensity and in what context. A taxonomy of different smartphone use patterns will be needed to be taken into account to better grasp the nature of smartphone (over-)use and potential brain changes (Marengo *et al.*, 2021; Montag *et al.*, 2021). Generalized views on overusing the smartphone might be helpful to get a bird's eye view on the topic, but consuming different contents might lead to different results when one is trying to understand the neurobiology of smartphone (over-)use. See also exemplary research in related areas investigating general social media (over-)use, specific social media (over-)use or e-mail (over-)use (He *et al.*, 2017; Lee *et al.*, 2021; Montag *et al.*, 2017, 2018; Nasser *et al.*, 2020; Sadeghi *et al.*, 2022; Sherman *et al.*, 2016; Turel *et al.*, 2014, 2018), which at best would directly be also put in the context of smartphone (over-)use research (seldom done at the moment). We also mention highly interesting work investigating smartphone touchscreen use and the brain (Balerna & Ghosh, 2018; Gindrat *et al.*, 2015).

(vii) Finally, the present review showed that most studies (to our knowledge) focused on the study of SmUD or related topics by means of MRI. There is so much else to be studied in the context of smartphone use—which likely will result in the study of so called digital biomarkers (Montag, Elhai, *et al.*, 2021a). By this, we mean that the digital footprints left on smartphones (and other devices of the Internet of Things) can help us to get insights into the neurobiology of a person (Montag, Elhai, *et al.*, 2021b). Given that the smartphone is our companion with whom we interact in many everyday life situations, it is not surprising that the smartphone can provide a detailled characterization of behavioral, cognitive and affective domains and this could inform not only psychological but also neuroscientific approaches.

(viii) An increasing number of studies suggests sex differences in the brain correlates of addiction (see e.g. Grace *et al.*, 2021) and going forward it will be important to explore potential differences in the effects of smartphone (over-)use in men and women. Moreover, it will be important to determine the effects of smartphone (over-)use on the brain over the life span, it is e.g. conceivable that in particular developing brains are more sensitive to the impact of excessive usage (but see interesting opposing prevalence numbers as mentioned above; Meng *et al.*, 2022).

(ix) In terms of a general challenge of the MRI-based research field it will be vital to better address and enhance the replicability of MRI research (see e.g. Klugah-Brown *et al.* (2022) for an example of replicable brain structural markers in behavioral addictions), employing designs that extend the view of the traditional case-control designs in neuroimaging of mental disorders (Etkin, 2019), and implement transparent data and code sharing as well as preregistration of studies that allow an a priori specification of brain-based hypotheses (see also Nichols *et al.*, 2017; Poldrack *et al.*, 2017).

Conclusions

The present paper provides an initial overview on research examining potential brain changes related to smartphone (over-) use from studies applying MRI techniques (studies are of cross-sectional nature though). While many studies observed functional and structural differences and associations with SmUD in brain systems spanning cortical and subcortical regions involved in reward/motivational processes, affective and cognitive domains, and the development of addictive behavior, the current evidence remains patchy and overarching neuroscientific frameworks uniquely touching on smartphone (over-)use are lacking. The studies do not allow us to determine whether the observed brain characteristics are a result of a certain kind of smartphone use or merely represent a predisposition to use the smartphone in a certain kind of way. Many study findings are based on small study populations. In this context, prospective longitudinal designs and replication studies are needed soon to determine the direction of the associations and the robustness of the findings. Finally, MRI, although being a powerful tool to understand the human brain, comes with technical limitations—among others a limited temporal resolution. Therefore, multimodal assessments that integrate the advantages of different brain imaging methods are warranted. Within this context, we shortly hint toward already existing literature investigating the present smartphone use complex with means of electroencephalography (S.-K. Kim *et al.*, 2015; Weon, 2017), fNIRS (Li *et al.*, 2022; Xiang *et al.*, 2023) as well as positron emission tomography (Westbrook *et al.*, 2021). The combination of advanced prospective study designs with different neuroscientific techniques (also hormones and genetics) can promote a better and more complete understanding of the neurobiological changes related to smartphone (over-)use.

Conflict of interest

The author B.B. is editorial-board member of *Psychoradiology*. He was blinded from the review process and making decisions on the manuscript.

C.M. reports no conflict of interest. Nevertheless, for reasons of transparency, C.M. mentions that he has received (to Ulm University and earlier University of Bonn) grants from agencies such as the German Research Foundation (DFG). C.M. has performed grant reviews for several agencies; has edited journal sections and articles; has given academic lectures in clinical or scientific venues or companies; and has generated books or book chapters for publishers of mental health texts. For some of these activities he received royalties, but never from the gaming or social media industry. C.M. was part of a discussion circle (Digitalität und Verantwortung: https://about.fb.com/de/news/h/gespraechskreis-digitalitaet-und-verantwortung/) debating ethical questions linked to social media, digitalization, and society/democracy at Meta. In this context, he received no salary for his activities. C.M. currently functions as independent scientist on the scientific advisory board of the Nymphenburg group (Munich, Germany). This activity is financially compensated. Further, he is on the scientific advisory board of Applied Cognition (Redwood City, CA, USA), an activity that is also compensated.

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