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ATTENTION-DEFICIT DISORDER (A ROSTAIN, SECTION EDITOR)

The Many Channels of Screen Media Technology in ADHD: a Paradigm for Quantifying Distinct Risks and Potential Benefits

Matthew M. Engelhard[1] · Scott H. Kollins[1]

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Abstract

Purpose of Review Individuals with attention-deficit hyperactivity disorder (ADHD) may be unusually sensitive to screen media technology (SMT), from television to mobile devices. Although an association between ADHD and SMT use has been confirmed, its importance is uncertain partly due to variability in the way SMT has been conceptualized and measured. Here, we identify distinct, quantifiable dimensions of SMT use and review possible links to ADHD to facilitate more precise, reproducible investigation.

Recent Findings Display characteristics, media multitasking, device notifications, SMT addiction, and media content all may uniquely impact the ADHD phenotype. Each can be investigated with a digital health approach and counteracted with device-based interventions. Novel digital therapeutics for ADHD demonstrate that specific forms of SMT can also have positive effects.

Summary Further study should quantify how distinct dimensions of SMT use relate to ADHD. SMT devices themselves can serve as a self-monitoring study platform and deliver digital interventions.

Keywords Attention-deficit hyperactivity disorder · Screen time · Mental health · Mobile health · Digital health · Digital therapeutics

Introduction

The average US adult now spends over 9 h per day using screen media technology (SMT) [1] due largely to rising mobile device use [2, 3], which has surpassed television viewing among younger adults [1, 4]. For the typical American, "screen time" now occupies a majority of waking life: our screens are not just for entertainment but also for work and communication and are deeply integrated in our personal, social, family, and professional activities. In a recent conceptual article, Dr. Adam Gazzaley noted that "every way we interact with our environment, as well as with each other and ourselves, has been radically transformed by technology" [5]. It is natural, then, to be concerned about the effects these technologies may be having on our well-being, and on our minds—particularly the developing minds of children and adolescents, whose media use patterns have shifted most dramatically [1].

Scientific and popular articles have questioned the impact of SMT on mental health, pointing to increasing rates of depression and suicide among adolescents in parallel with growing device use [6•]. Although a statistically significant association between SMT use and well-being has been established, the size of the effect is small, and thus its importance has been debated [6•, 7•, 8]. There has also been growing concern that technology may be affecting our cognition [5, 9], including our ability to control and sustain attention, fueled partly by the rise in diagnosis rates of attention-deficit hyperactivity disorder (ADHD) that has taken place over the past 10 years [10].

ADHD, a neurodevelopmental disorder characterized by deficits in attentional and behavioral control, represents a key, sentinel phenotype that might alert us to the negative impacts of SMT. Due to the nature of the condition, individuals with ADHD may be unusually sensitive to cognitive effects associated with SMT use, whether positive or negative. While the causes of the rise in ADHD diagnosis rates are certainly multifactorial [11], media use has long been suspected as a contributing factor [12•]. Despite a surge of interest in this topic seen in

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✉ Matthew M. Engelhard
m.engelhard@duke.edu

[1] Department of Psychiatry and Behavioral Sciences, Duke University School of Medicine, Lakeview Pavilion, Suite 300, 2608 Erwin Rd, Durham, NC 27705, USA

the scientific literature, evidence for the effect of SMT on attention and other aspects of cognitive functioning has thus far been mixed and inconclusive [13••].

Purpose of Review

We propose a paradigm for conceptualizing and studying the impact of SMT on ADHD and other neurocognitive phenotypes, one focused on isolating the effects of five distinct, quantifiable dimensions of SMT use (see Fig. 1). These include dimensions unique to newer devices that might be examined by leveraging the devices themselves as the primary study platform.

We begin by highlighting the challenges of studying SMT, including sources of variability and imprecision that have contributed to the conflicting and inconclusive findings in the literature. We then describe each dimension of SMT use and summarize (a) what is known about its relationship to ADHD, and (b) how it has been, or might be, explored with a digital health study design. In choosing this organizational principle, we hope to encourage further study examining these dimensions individually, leading to interventions designed to counteract specific, hazardous forms of SMT use. Finally, we touch on the emerging field of digital therapeutics, which seeks to develop SMT-based interventions to treat impairments related to ADHD and other dimensions of cognitive and psychosocial functioning. Throughout, current technologies are emphasized not only as a potential hazard but also as a flexible platform for studying that hazard and delivering digital interventions.

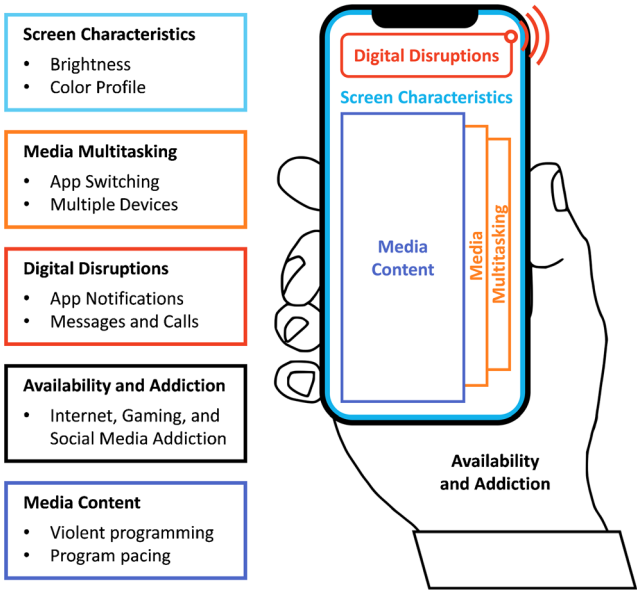

Fig. 1 Overview of distinct dimensions of screen media technology use that may impact the ADHD phenotype

Challenges of Studying SMT

In this section, we identify several challenges inherent in measuring and studying the effects of SMT on ADHD and other phenotypes, then suggest how the field might move forward.

Defining and Measuring Screen Time

An association between well-being and SMT use has been confirmed in large-scale, observational datasets [6•, 7•] and by meta-analysis [8], but effect sizes are small, with SMT use explaining < 1% of the variance in depression and related outcomes [6•, 7•, 8]. Although the statistical findings of these studies have been consistent, interpretations have varied widely. For example, one study emphasized that "new media screen time should be understood as an important modern risk factor for depression and suicide" [6•], whereas another came to the opposite conclusion, stating that "effects of technology might be statistically significant but so minimal that they hold little practical value" [7•].

A similar debate is taking place in the ADHD literature. A recent, 2-year longitudinal study of high school students in Los Angeles County found that higher self-reported digital media use was associated with increased odds of self-reported inattentive and hyperactive-impulsive symptoms at follow-up [14••]. This result corroborated and extended previously identified cross-sectional associations [15], but with a small effect size based entirely on self-report [14••, 16]. Echoing this uncertainty, a recent review found "contradictory and inconclusive" evidence for the impact of SMT on our attentional processes, working memory, and reward seeking [13••]. Findings connecting SMT use to ADHD-related symptoms have been sufficiently robust to prompt valid concern [17•, 18], but too imprecise to provide insight or a way forward short of curbing all device use.

Inconsistency in the methods used to quantify SMT use is partly to blame. With the exception of a limited number of laboratory studies [12•, 19, 20••], assessment of SMT use has relied on ad hoc questionnaires that vary widely in their structure and the breakdown of SMT-related activities. For example, one study asks about the frequency of 14 SMT-related activities spanning multiple devices [14••], whereas another asks about the total duration of only 5 activities [21]. Several validated questionnaires [22, 23] have been used [21, 24•] but have become somewhat outdated with the rapid changes in SMT use patterns that have taken place. Only recently has mobile device use been assessed [25], with studies as few as 5 years ago not including them [26, 27]. Some investigations have explored the differential impact of distinct activities accessed through a single device [19], whereas others have grouped activities and devices together to explore the effect of SMT as a whole [24•]. While it is important to study the full range of SMT use, our understanding of its impact on ADHD has been limited by imprecision and variability in the way SMT has been conceptualized and measured.

Limitations of Available Study Designs

The vast majority of findings linking SMT to ADHD have been derived from cross-sectional studies, leading to uncertainty about cause versus effect. Results from large-scale, longitudinal studies provide stronger evidence that SMT use may contribute to ADHD-related symptoms, but conclusions remain tentative due to possible unmeasured confounders [14••, 28]. Because SMT is so ubiquitous, identifying large groups of participants who differ only in their SMT use is challenging at best, and finding participants with no exposure is near-impossible [13••].

These concerns could, in principle, be addressed with a randomized study design. Unfortunately, randomizing participants to SMT conditions for a suitable time period is impractical precisely because SMT is so deeply integrated in daily life. Indeed, a recent "24-h challenge" study found it difficult to identify participants willing to constrain their device use for a single day [29]. When randomized controlled trials have been conducted, they have been restricted to time-limited experimental conditions and their immediate effects. For example, several studies have examined the effect of television program pacing on subsequent symptoms of attention and hyperactivity [12•]. However, these short-term designs do not shed light on the longer-term neurocognitive impact of SMT use that has been hypothesized.

Rapidly changing SMT use patterns also strain the slow pace of scientific research. In addition to previously noted challenges in measuring use, rapid changes in SMT adoption may lead the composition of specific groups (e.g., video gamers) to differ systematically between studies.

Replacement Effects

In addition to the direct effects of SMT use on ADHD, a number of studies have emphasized the importance of replacement effects, wherein time using SMT might otherwise be spent engaging in activities with positive impact on ADHD-related symptoms and impairment. For example, both television watching and cell phone use have been linked to poorer cardiovascular health and reduced physical activity [30, 31], thereby reducing the potential benefit of physical activity on ADHD-related symptoms [32].

Importantly, SMT use has been found to reduce sleep in individuals with ADHD, which may in turn contribute to ADHD-related symptoms [21]. Nighttime SMT use has been associated with reduced sleep in older children and adolescents with ADHD [24•], and the mere presence of a television in the bedroom may have a small effect on average sleep duration [27]. However, media use has also been connected to additional sleep problems beyond sleep duration, such as increased sleep onset latency [24•], suggesting that nighttime media use may have a physiological impact on sleep that goes beyond a simple replacement effect. This is later discussed in more detail.

Replacement effects are not a dimension of SMT use itself, and therefore are not included among the quantifiable dimensions we have identified. However, understanding how these effects may mediate the relationship between SMT and ADHD is critical and might be investigated with digital health study designs that quantify sleep and physical activity in addition to SMT use.

Toward Quantifiable SMT Metrics

In light of these challenges, a recent commentary emphasized the need to "go beyond self-report" with apps that record detailed patterns of device use [28]. This approach leverages a key advantage of current technologies, namely that they are capable of self-monitoring. Instead of relying on coarse measures such as total screen time, device-based study platforms can quantify app use and timing, multitasking patterns, and the number and timing of notifications [33]. These observational data might be paired with outcomes of interest to test specific hypotheses that, if validated, would naturally lead to device modifications or non-digital interventions designed to counteract any negative effects identified. For example, if high notification frequency were conclusively linked to increased symptoms of inattention, an intervention might include scheduled periods when the device is placed in "do not disturb" mode (device-based implementation) or left in another room (non-device-based implementation). Intervention effectiveness could then be evaluated using a traditional trial or a range of small-scale, quasi-experimental digital health study designs [34].

Hazards of SMT Use and Options for Mitigating Impact

Having described challenges in studying the effects of SMT on ADHD, we now propose five dimensions of SMT use that might be better isolated going forward to promote a more precise, actionable program of research.

Screen Characteristics

Screen size, brightness, color profile, and other characteristics vary between devices and display technologies (e.g., LCD, OLED) and may pose health risks independent of specific SMT content or activities. For example, prolonged screen viewing is known to cause visual fatigue, with some evidence suggesting that over 50% of the adult US population is affected by symptoms such as blurred vision, eye irritation, or headache [35]. Screen flicker (i.e., oscillating brightness) also has established biological effects [36], but these are less of a concern with current high-frequency, LED-illuminated displays [37].

In ADHD, the negative impact of nighttime media use may be exacerbated by the bright artificial light emitted by SMT, which increases arousal and suppresses melatonin production [38, 39]. In a crossover study comparing nighttime use of an e-reader to a printed book, e-reader use was associated with increased sleep onset latency, reduced evening melatonin secretion, and reduced next-morning alertness [40]. Newer, LED-based technologies may have greatest impact due to their higher blue-light activity, which suppresses melatonin production and shifts the circadian cycle more effectively than other parts of the spectrum [41, 42]. Compared to red-enriched light, exposure to a blue-enriched light environment reduces reaction time variability and increases sleep onset latency [43].

These effects are particularly concerning among adolescents given the critical importance of sleep on adolescent neural development [44] and high nighttime SMT use in this group [24•]. Some evidence has suggested that effects of light on melatonin suppression may be stronger in early adolescence [45], and nighttime media use has been linked to reduced, poor sleep in adolescents with ADHD [24•].

Device-based interventions include f.lux [46] and Apple's Night Shift, which appear to reduce melatonin suppression by limiting brightness and blue light in the evening hours [47–49], but were not found to impact sleep onset latency or sleep quality [50]. Alternatively, external filters can reduce screen brightness and/or blue light. In one study, blue-light-reducing eyewear reduced sleep latency and melatonin suppression, but results may have been confounded by unintended effects of the eyewear on vision sharpness [51]. A second study found that combining a blue-light filter with the removal of personally relevant social media content improved sleep quality, whereas either intervention alone did not [52]. However, these interventions have not yet been tested in ADHD or other populations particularly vulnerable to the effects of SMT.

Media Multitasking

In their seminal 2009 paper, Ophir et al. examined the relationship between self-reported media multitasking, defined as using several forms of SMT at once, and experimental tasks measuring cognitive control. Paradoxically, participants who multitasked more often seemed to be poorer at it: they were slower to classify a stimulus after a task-switching condition than other participants. Further, the heavy multitasking group performed worse on a working memory task in the presence of distracting, irrelevant stimuli, suggesting that participants' multitasking behaviors were driven not by an ability to effectively multitask but an inability to attend to a single task when distractions are present [53]. This in turn underscored a possible relationship to inattention, distractibility, and ADHD.

Subsequent results strengthened this interpretation [54], including an fMRI study that connected multitasking behaviors to distractibility and differential activation of brain areas related to attentional control [55]. Multitasking behaviors and preference were found to be associated with symptoms of inattention and hyperactivity-impulsivity [56], making the connection to ADHD explicit, and heavier multitasking has also been linked to poorer achievement test scores [57]. The evidence seemed to point conclusively to an association between simultaneous use of multiple media streams and deficits in attentional and inhibitory control.

However, two recent studies failed to replicate the effects reported by Ophir et al. [58, 59], and recent reviews have drawn attention to conflicting findings [60, 61•]. Other researchers have observed non-monotonic relationships between executive functioning and media multitasking, suggesting that multitasking behaviors should be divided into more than two groups [62, 63]. When interpreting the evidence, it must be noted that technology and media use patterns changed dramatically in the time between Ophir and colleagues' original study and more recent studies that failed to replicate it. Current SMT facilitates multitasking and encourages it through notifications; therefore, the composition of the heavy multitasking groups may have changed substantially between 2009 and 2018.

Device-based studies of multitasking have found that most participants use a large range of apps (> 50), and a substantial portion of app use is very brief (< 15 s) [64, 65•]; therefore, self-reported measures may not be sufficiently precise or detailed to adequately capture variability in current multitasking behaviors. Moreover, multitasking is heavily impacted by device notifications, discussed in the next section, which frequently elicit app-switching but have little impact on total device use [66]. Further study is needed to explore app-switching behaviors in the context of ADHD.

Although its impacts remain uncertain, several interventions to curb multitasking have been developed. Interventions have focused on awareness of multitasking behaviors, mindfulness, or device restrictions [67], any of which might be implemented using a device-based approach. Although positive effects on attention have been reported [68], a majority of interventions have been brief (i.e., occurring in a single session), and evidence supporting their effectiveness is inconclusive [67].

Digital Disruptions

Although device notifications initiated by e-mail, messaging, and other apps encourage multitasking behaviors [13••, 66], they also represent a distinct, modifiable hazard of SMT use that has been directly connected to symptoms of ADHD.

Disruptions from mobile phones impair performance on attention-related tasks by causing post-disruption commission errors [69], also called "resumption errors" [13••], which can be mitigated by a brief "resumption lag" to recover from the

interruption [70]. However, individuals with deficits in attention may be more vulnerable to resumption errors, as they have established deficits in post-error slowing, an adaptive behavior similar to resumption lag that is thought to improve post-error performance [71].

Recently, notifications were directly linked to ADHD-related symptoms in a crossover study of 221 university students, who maximized and minimized notifications, respectively, in two different weeks. Notification levels self-reported at baseline were significantly associated with both inattention ($r = 0.30$) and hyperactivity ($r = 0.31$), and maximizing notifications led to a medium-sized increase in both types of symptoms. Perhaps most interestingly, mediation analysis revealed that participants with higher inattention scores reported greater reduction in productivity, environmental mastery, social connectedness, perceived choice, and meaning in life when notifications were maximized [72••].

Moreover, the negative impact of disruptions is not limited to times when they occur, but instead leads to a "checking habit" that persistently undermines productivity [73]. Indeed, the mere presence of a cell phone on a participant's desk was found to reduce performance on complex cognitive tasks [74]. While the long-term impact is unknown, evidence suggests that individuals with ADHD, particularly those with prominent inattentive symptoms, are unusually sensitive to the negative effects of SMT-related disruptions.

Device-based strategies for managing notifications include "do not disturb" functions as well as e-mail and messaging apps that reduce alerts by filtering low-priority messages. Participants in a "24-h challenge" to eliminate notifications reported that they were more productive during the challenge period but also more anxious and lonely [29]. These negative symptoms may be more extreme in participants with ADHD, who have a greater need for social connection and assurance [75]. However, limiting social media use over a longer, 3-week period reduced loneliness and depression among college students [76], implying that the negative effects observed in the 24-h challenge may be short-lived. This underscores the importance of a longer trial window when exploring notification-related interventions in ADHD populations.

Availability and Addiction

Persistent, compulsive use of SMT—including social media, video games, and the internet—has been connected to impairment and therefore labeled as a form of behavioral addiction. This expanding view of addiction is reflected by the inclusion of gambling addiction in the 5th Edition of the Diagnostic and Statistical Manual [77]. Although SMT can have positive effects, excessive or compulsive use has negative effects on physical and psychosocial health, as observed in gaming addiction [78] and internet addiction [79]. Individuals with ADHD are at greater risk for several addictive behaviors, including smoking and illicit drug use [80], suggesting they may also be at greater risk for SMT-related addictions.

Recent studies have confirmed this hypothesis. In a cross-sectional study of 263 participants with online gaming addiction and 153 controls, the ADHD rating scale was the strongest predictor of gaming addiction among a range of demographic and psychosocial factors [81]. This finding has been reproduced and does not depend on the type of video game [82]. Similarly, ADHD symptoms were the best predictor of social media addiction in a large cross-sectional study of adults [83•] and have been linked to Facebook addiction in adolescents [84]. A moderate association between ADHD and internet addiction has been demonstrated by meta-analysis [85], and the link between addictions and ADHD is stronger than links between distinct forms of addiction [86]. As with other addictive behaviors, therefore, the ADHD phenotype is uniquely predisposed to addictive use of SMT.

Because SMTs have become so pervasive and integrated in daily life, SMT-related addictions may be particularly difficult to overcome. Unlike substance use, abstaining from SMT may not be feasible due to work or social obligations, which often require access to an internet-connected device. With a device always in reach, overcoming SMT addiction might be compared to quitting smoking while holding a lit cigarette, surrounded by smokers. Moreover, current technologies are deliberately designed to maximize engagement through habit-forming "features" such as infinite scroll [87] and intermittent reinforcement schedules known to lead to more persistent behaviors [88].

To understand and combat SMT addiction, we can begin to identify frequent or repetitive use patterns associated with self-reported addiction and impairment [89]. Apps such as Moment [90] and Apple's Screen Time are beginning to provide such data, and Moment has been used to identify patterns connected to depression and emotion regulation [91]. Development of research-oriented apps such as MyCap [92] may provide greater customization and data granularity needed to rigorously study the relationship between SMT addiction and ADHD.

Media Content

Video programming, games, internet and social media, and a range of other content can be accessed with any smartphone. Some content types have been studied for years (e.g., television programs), whereas others are unique to newer devices (e.g., augmented reality apps). Exposure to specific content, such as fast-paced and violent programming, has long been hypothesized to contribute to the development of ADHD-related symptoms and behaviors. In both cases, the balance of evidence has been inconclusive [12•, 17•], partly due to the ethical and practical limitations of studying the effects of SMT in children [20••].

However, a controlled, blinded study of "excessive sensory stimulation" in juvenile mice demonstrated that learning and memory were decreased, and risk-taking and motor activity were increased, in animals exposed nightly to simulated television viewing compared to control animals [20••]. Further, a recent study of 2- and 3-year old children found that an interactive, tablet-based app improved measures of both hot and cold executive functioning compared to non-interactive educational content, suggesting that interactivity may be a key factor [19]. These results highlight the importance, but also the difficulty, of investigating the effects of specific forms of media content.

With newer technologies, detailed app usage statistics can be used to approximate exposure to specific forms of content, such as social media or video programming [65•]. Given the shift toward mobile devices [3] and other smart technologies, device-based monitoring is an increasingly important alternative to older measures of exposure when studying the effects of media content on individuals with ADHD.

Digital Therapeutics—Beyond Counteracting Negative Effects

Amid concerns about the impact of SMT, a wave of FDA-regulated "digital therapeutics" has also emerged [93]. This new treatment category consists of apps and other software that incorporate evidence-based principles and might be prescribed to treat specific medical or psychiatric conditions following clinical trials. Their development rests on the assumption that SMT effects are not uniformly positive or negative but vary by content type and mode of interaction.

A trial of a digital therapeutic for ADHD, an app designed to improve attentional control and resistance to distractions, has demonstrated differential benefit on working memory and the Test of Variables of Attention (TOVA) among children with ADHD, including a high-severity group, compared to children without [94•]. This app, a game called *Project: EVO*, was based on an earlier app found to improve cognitive control in older adults [95], and it also appears to be effective in children with co-occurring ADHD and autism spectrum disorder [96]. Other digital therapeutics designed for ADHD include a "Decoder" game that improved visual attention in adult participants compared to a non-app-based control group [97], and a smartglasses intervention that improved ADHD symptoms in a small pilot study of children with autism spectrum disorder [98].

These results, while promising, should be interpreted with a degree of caution. A recent meta-analysis found that video game training has negligible effect on cognition in the general population, and studies have repeatedly demonstrated that learned cognitive skills tend to generalize poorly between domains [99]. Consistent with these general principles, *Project: EVO* was found to improve performance only in children with ADHD, and not control children with no psychiatric diagnoses [94•]. Continued study is needed to determine whether novel digital therapeutics can complement other device-based interventions to shift the net effects of SMT from negative to positive.

Conclusions

We have proposed a novel paradigm for conceptualizing and studying the effects of SMT despite varied, shifting usage patterns. Our review identified five distinct dimensions of SMT use whose effects might be isolated, for instance by leveraging SMT itself as a study platform. There is evidence that the ADHD phenotype may be unusually sensitive to each of these dimensions, but further study is needed to directly investigate potential effects and motivate interventions. Although some forms of SMT use appear to be hazardous, the emergence of effective digital therapeutics for ADHD implies that others are likely to be beneficial.

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