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Editorial

Going digital: how technology use may influence human brains and behavior

Margret R. Hoehe, MD, PhD – Issue Coordinator
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The digital revolution has changed, and continues to change, our world and our lives. Currently, major aspects of our lives have moved online due to the coronavirus pandemic, and social distancing has necessitated virtual togetherness. In a synopsis of 10 articles we present ample evidence that the use of digital technology may influence human brains and behavior in both negative and positive ways. For instance, brain imaging techniques show concrete morphological alterations in early childhood and during adolescence that are associated with intensive digital media use. Technology use apparently affects brain functions, for example visual perception, language, and cognition. Extensive studies could not confirm common concerns that excessive screen time is linked to mental health problems, or the deterioration of well-being. Nevertheless, it is important to use digital technology consciously, creatively, and sensibly to improve personal and professional relationships. Digital technology has great potential for mental health assessment and treatment, and the improvement of personal mental performance.

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Keywords: digital revolution; digital media; screen time; brain change; brain imaging; brain function; developmental change; mental health, well-being, mental health assessment, diagnostics, virtual therapy; web-based intervention

The “Digital Revolution”: remaking the world

Within a few decades, digital technology has transformed our lives. At any time, we can access almost unlimited amounts of information just as we can produce, process, and store colossal amounts of data. We can constantly interact, and connect, with each other by use of digital devices and social media. Coping with the daily demands of life as well as pursuing pleasure in recreational activities appears inconceivable without the use of smartphones, tablets, computers, and access to Internet platforms. Presently, over 4.57 billion people, 59% of the world population, use the Internet according to recent estimates (December 31st, 2019), ranging between 39% (Africa) and 95% (North America).1 People are spending an enormous, “insane” amount of time online, according to the latest Digital 2019 report compiled by Ofcom2: on average 6 hours and 42 minutes (06:42) each day (between 03:45 in Japan and 10:02 in the Philippines), half of that on mobile devices, on average equating to more than 100 days per year for every Internet user. According to a landmark report on the impact of the “decade of the smartphone,”3 the average person in the UK spends 24 hours a week online, with 20% of all adults spending as much as 40 hours, and those aged 16 to 24 on average 34.3 hours a week. Britons are checking their smartphones on average every 12 minutes. In the US, teen screen time averages over 7 hours a day, excluding time for homework. Digital technology has become ubiquitous and entwined with our
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modern lives. As Richard Hodson in the *Nature Outlook* on “Digital Revolution,” 2018, concluded, “an explosion in information technology is remaking the world, leaving few aspects of society untouched. In the space of 50 years, the digital world has grown to become crucial to the functioning of society.” This period of societal transformation has been considered “the most recent long wave of humanity’s socio-economic evolution.” As a “meta-paradigm of societal modernization based on technological change” induced by the transformation of information, it supersedes earlier periods of technological revolution based on the transformation of material and energy, respectively, spanning over 2 million years altogether (Hilbert, p 189 in this issue).

In particular, the excessive use of digital technology during adolescence has given rise to grave concerns that this technology is harmful and damages the (developing) brain or may even cause mental health problems. Public concern culminated in Jean Twenge’s 2017 article “Have Phones Destroyed a Generation?,” which linked the rise in suicide, depression, and anxiety among teens after 2012 to the appearance of smartphones. All-too-familiar pictures: parents and children, or couples, or friends, at the table, staring at their phones, texting; colleagues staring at screens, busy with emails; individuals, heads down, hooked on their phones, blind to their surroundings, wherever they are. Individuals interacting with their devices, not with each other. “The flight from conversation,” which may erode (close) human relationships and with them the capacity for empathy, introspection, creativity, and productivity - ultimately, the social fabric of our communities. Sherry Turkle, who has studied the relationship of humans with technology for decades, has articulated these concerns in *Alone Together and Reclaiming Conversation*. Thus, “life offline” has become a consideration and advice to limit screen time and practice digital minimalism has become popular. The concerns about screen time and efforts to keep us from staring at our devices and detox our digital lives came to a sudden end with the COVID-19 coronavirus pandemic. Almost overnight, nearly our entire personal, professional, educational, cultural, and political activities were moved online. The dictum of social distancing necessitated virtual togetherness.

**Changing human brains and behavior?**

The use of digital technology has changed, and continues to change, our lives. How could this affect human brains and behavior, in both negative and positive ways? Apparently, the ability of the human brain to adapt to any changes plays a key role in generating structural and/or functional changes induced by the usage of digital devices. The most direct evidence for an effect of frequent smart phone use on the brain is provided by the demonstration of changes in cortical activity (Korte, p 101 in this issue). Touching the screen repetitively – the average American user touches it 2176 times a day – induces an increase of the cortical potentials allotted to the tactile receptors on the fingertips, leading to an enlargement, ie, reorganization of the motor and sensory cortex. It remains to be determined whether this reshaping of cortical sensory representation occurs at the expense of other motor coordination skills. Processes of neuroplasticity are particularly active in the developing brain, especially during stages of dynamic brain growth in early childhood. For instance, as demonstrated by functional magnetic resonance imaging (fMRI), extensive childhood experience with the game “Pokémon” influences the organization of the visual cortex, with distinct effects on the perception of visual objects even decades later. Furthermore, as shown by diffusion tensor MRI, early extensive screen-based media use is significantly associated with lower microstructural integrity of brain white matter tracts supporting language and literacy skills in preschoolers. Also, adolescence is a time of significant development, with the brain areas involved in emotional and social behavior undergoing marked changes. Social media use can have a profound effect; eg, the size of an adolescent’s online social network was closely linked to brain anatomy alterations as demonstrated by structural MRI. The impact of digital technology use, both negative and positive, on these and many more brain-related phenomena has been elaborated in the review by Korte, who provides a comprehensive overview of the field.

The most direct approach to assess the effect of excessive digital media use on (adolescent) brains presently appears to be the analysis of the neurobiological mechanisms underlying Internet and Gaming Disorder (IGD) (Weinstein and Lejoyeux, p 113 in this issue). The authors thoroughly survey existing brain imaging studies, summarizing the effects of IGD on the resting state, the brain’s gray matter volume and white matter density, cortical thickness, functional connectivity, and brain activations, especially in regions related to reward and decision making, and neurotransmitter systems. Taken together, individuals
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with IGD share many typical neurobiological alterations with other forms of addiction, but also show unique patterns of activation specifically in brain regions which are associated with cognitive, motor, and sensory function. The effects of the Internet on cognition have been comprehensively elaborated by Firth et al.12 Examining psychological, psychiatric, and neuroimaging data, they provide evidence for both acute and sustained alterations in specific areas of cognition, which may reflect structural and functional changes in the brain. These affect: (i) attentional capacities, which are divided between multiple online sources at the loss of sustained concentration on a single task; (ii) memory processes - permanently accessible online information can change the ways in which we retrieve, store, recall and even value knowledge; and (iii) social cognition; the prospects for social interactions and the contexts within which social relationships can happen have dramatically changed. A complementary contribution rounding up these reviews is provided by Small et al (p 179 in this issue). Among the possible harmful “brain health consequences,” these investigators emphasize attention problems and their potential link to symptoms of attention deficit-hyperactivity disorder (ADHD); furthermore the (paradoxical) association of excessive social media use with the perception of social isolation, observable at any age; the impaired emotional and social intelligence, poorer cognitive/language and brain development, and disrupted sleep. A substantial part of this review is devoted to the positive effects benefiting brain health in adults and the elderly, which are referred to below. Independent of ongoing research on the negative and positive implications of digital technology use, there remains a common feeling that there is something about the whole phenomenon that is just not “natural.” “We did not evolve to be staring at a screen for most of our waking hours. We evolved to be interacting with each other face-to-face, using our senses of smell and touch and taste – not just sight and sound… it cannot be healthy to stray so far from the activities for which nature has shaped our brains and our bodies.” Giedd (p 127 in this issue) challenges this notion in his fascinating review on “The natural allure of digital media,” putting the intensive digital media use during adolescence into a grand evolutionary perspective. He argues that the “desire for digital media is in fact exquisitely aligned with the biology of the teen brain and our evolutionary heritage,” with three features of adolescence being particularly relevant to this issue: (i) hunger for human connectedness; (ii) appetite for adventure; and (iii) desire for information.

Screen time: boon or bane?

As with any major innovation that has a profound impact on our lives, finding useful information and orientation means discerning scientific evidence from media narratives. Thus, synthesizing data from recent narrative reviews and meta-analyses including more than 50 studies, Odgers and Jensen (p 143 in this issue) could not confirm a strong linkage between the quantity of adolescents’ digital technology engagement and mental health problems. “There doesn’t seem to be an evidence base that would explain the level of panic and consternation around these issues” said Odgers, in the New York Times.13 The authors point to significant limitations and foundational flaws in the existing knowledge base related to this topic; for instance, the nearly sole reliance on screen time metrics; the disregard of individual differences; the circumstance that almost none of the study designs allowed causal inference. On the other hand, a highly robust finding across multiple studies was that offline vulnerabilities (such as risks present in low-income families, communities, etc) tend to mirror and shape online risks. The observed social and digital divides are presently being magnified through the coronavirus crisis and most likely to increase in the future, further amplifying the existing inequalities in education, mental health, and prospects for youth. The authors strongly advocate the need and opportunities to leverage digital technology to support youth in an increasingly digital, unequal society in an uncertain age; see their suggestions for parents, clinicians, educators, designers and adolescents in Box 1. Similarly, performing an in depth overview of the existing literature, Dienlin and Johannes (p 135 in this issue) could not substantiate the common concerns that digital technology use has a negative impact on young (and adult) peoples’ mental well-being. Their findings imply that the general effects are in the negative spectrum but very small – potentially too small to matter. Importantly, different types of use have different effects: thus, procrastination and passive use were related to more negative effects, and social and active use to more positive effects. Thus, “screen time” has different effects for different people. Digital technology use tends to exert short-term effects on well-being rather than long-lasting effects on life satisfaction. “The dose makes the poison”: both low and excessive use are related to decreased well-being, while moderate use increases well-being. With a strong sense for clear explanation, the authors introduce the concepts, terms, and definitions underlying this complex field, a most
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valuable primer to educate the interested reader, while also addressing the methodological shortcomings that contribute to the overall controversial experimental evidence.

Thus, against common concerns, digital technology as such does not affect mental health or deteriorate well-being. Its use can have both negative and positive consequences. Technology simply does not “happen” to people. Individuals can shape the experiences they have with technologies and the results of those experiences. Thus, it is important to shift the focus towards an active, conscious use of this technology, with the intention to improve our lives and meaningfully connect with each other. This has become, more than ever, important now: “There is increased urgency, due to coronavirus, to use technology in ways that strengthen our relationships. Much of the world has been working, educating, and socializing online for months, and many important activities will remain virtual for the foreseeable future. This period of physical distancing has shed light on what we need from technology and each other… “ Morris (p 151 in this issue) introduces her article addressing the enhancement of relationships through technology in the most timely manner with a preface on “Connecting during COVID-19 and Beyond.” In this synopsis, she sums up five directions to “build on as we connect during and after the pandemic.” Furthermore, in her review, she examines how technology can be shaped in positive ways by parents, caregivers, romantic partners, and clinicians and illustrates with real life examples creative and sensible ways to adapt technology to personal and relational goals (see also ref 14). Highlighting the importance of context, motivation, and the nuances of use, this review encourages people to understand how technologies can be optimally used to improve personal and clinical relationships.

Digital tools in diagnosis and therapy

The use of digital tools for practical clinical applications and improvement of mental health conditions is gaining increasing acceptance, especially due to smartphone accessibility. This could fill at least in part the treatment gap and lack of access to specialized (psychotherapeutic) care, particularly in developing countries. Even in countries with well-developed health care systems, only a minority of patients receives treatment in line with the recommendations provided by evidence-based treatment guidelines. Thus, as elaborated in a thorough, comprehensive review by Hegerl and Oehler (p 161 in this issue), web-based interventions, especially in the case of Major Depression (MD), a highly prevalent and severe disorder, promise to be a method that provides resource-efficient and widespread access to psychotherapeutic support. The authors provide detailed information on available tools for digital intervention and their core principles; these are mostly based on principles of cognitive behavioral therapy, but also include elements of other psychotherapeutic approaches. As evident from meta-analyses summarizing studies that use face-to-face psychotherapy as a comparator, digital interventions can have equivalent antidepressant efficacy. Importantly, web-based interventions are most efficient when accompanied by adequate professional guidance and, if well designed, can be successfully integrated into routine care. The authors also address carefully the risks and limitations as well as unwanted effects of available digital interventions. Another powerful digital technology is gaining importance as a clinical tool in mental health research and practice, virtual reality (VR). According to Valmaggia and collaborators (p 169 in this issue), “At any time or place, individuals can be transported into immersive and interactive virtual worlds that are in full control of the researcher or clinician. This capability is central to recent interest in how VR might be harnessed in both treatment and assessment of mental health conditions.” To date, VR exposure treatments have proven effective across a range of disorders including schizophrenia, anxiety, and panic disorders. In their review, the authors summarize comprehensively the advantages of using VR as a clinical assessment tool, which could “radically transform the landscape of assessment in mental health.” Thus, VR may overcome many of the limitations concerning the diagnosis of psychological phenomena through its ability to generate highly controlled environments, that is, real-world experiences. In addition to increasing ecological validity, VR enhances personalization, that is, VR experiences can be tailored to match individual needs, abilities, or preferences. Furthermore, VR enhances an individual’s engagement with the test or assessment. Additional advantages include the capture of real-time, automated data in real-world contexts. In sum, the authors have thoroughly addressed the opportunities and challenges of VR in any relevant aspect. Finally, to complement the applications of digital technology to improve mental health, Small et al (p 179 in this issue) provide, in the second part of their review, rich information about specific programs, videogames, and other online tools, particularly for the
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aging brain. These may provide mental exercises that activate neural circuitry, improve cognitive functioning, reduce anxiety, increase restful sleep, and offer many other brain health benefits.

Emerging key messages

Several key messages emerge from these reviews, which cover a substantial amount of studies: first of all, scientific evidence does not support the common concerns that excessive use of digital technology causes mental health problems and a deterioration of well-being. There is increasing consensus that the methodological foundation is weak in many studies, in part explaining the controversial results and small effect sizes obtained to date. Above all, it appears absurd to collapse, as was common practice, the highly complex interaction between “machine and man” into a uniform quantitative screen time measure. Research, public policies, and interventions need to focus on the user, and not the extent of usage of technology. Who spends time and in what form with the digital devices is what is important. This leads us to what should be the main subject of interest, but has mostly — conceptually and factually — been disregarded: the human “individual” with its motivation, intentions, goals, needs, predispositions, familial, educational and social background, and support systems, or lack thereof. Needless to say, this calls for the consideration of individual differences in all aspects of research and application. Thus, digital technology is not intrinsically good or bad: it depends on the uses it is being put to by the user, and it can be utilized by individuals in both negative and positive ways. Now, more than ever, during and post coronavirus times, it is important that technology is taken advantage of to improve communication and enhance personal, professional, and societal relationships, guaranteeing equal opportunities for access and development for all.

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The Digital Revolution and its Impact on Human Brain and Behavior

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State of the art

The impact of the digital revolution on human brain and behavior: where do we stand?

Martin Korte, PhD

This overview will outline the current results of neuroscience research on the possible effects of digital media use on the human brain, cognition, and behavior. This is of importance due to the significant amount of time that individuals spend using digital media. Despite several positive aspects of digital media, which include the capability to effortlessly communicate with peers, even over a long distance, and their being used as training tools for students and the elderly, detrimental effects on our brains and minds have also been suggested. Neurological consequences have been observed related to internet/gaming addiction, language development, and processing of emotional signals. However, given that much of the neuroscientific research conducted up to now relies solely on self-reported parameters to assess social media usage, it is argued that neuroscientists need to include datasets with higher precision in terms of what is done on screens, for how long, and at what age.

Keywords: addiction; adolescence; amygdala; attention; brain development; cognitive neuroscience; digital media; language development; prefrontal cortex

Introduction

One hundred eleven years ago, E. M. Forster published a short story (The Machine Stops, 1909, *The Oxford and Cambridge Review*) about a futuristic scenario in which a mysterious machine controls everything, from food supply to information technologies. In a situation that evokes internet and digital media events of today, in this dystopia, all communication is remote and face-to-face meetings no longer happen. The machine controls the mindset, as it makes everybody dependent on it. In the short story, when the machine stops working, society collapses.

The story raises many questions, still relevant today, about the impact of digital media and related technology on our brains. This issue of *Dialogues in Clinical Neuroscience* explores in a multifaceted manner how, by what means, and with what possible effects digital media use affects brain function—for the good, the bad, and the ugly sides of human existence.

Overall, digital media use, from online gaming to smartphone/tablet or internet use, has revolutionized societies worldwide. In the UK alone, according to data collected by a regulatory agency for communication (Ofcom), 95% of people aged 16 to 24 years old own a smartphone and check it on average every 12 minutes. Estimates suggest that 20% of all adults are online more than 40 hours per week. There is no doubt that digital media, most of all the internet, are becoming important aspects of our modern life.

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Nearly 4.57 billion people worldwide have access to the internet, according to data published December 31, 2019 on the webpage http://www.internetworldstats.com/stats.htm. The speed of change is astonishing, with an exponential increase in the last decade. How and at what possible costs and/or benefits can our brain and mind adapt?

Indeed, concerns about the effects of digital media use on brain function and structure, as well as physical and mental health, education, social interaction, and politics, are increasing. In 2019, the World Health Organization (WHO) published strict guidelines about children’s screen time. And—announced a law (Assembly Bill 272) that permits schools to restrict smartphone usage. These actions were taken after results were published implicating intensive digital media use in reducing working memory capacity, in psychological problems, from depression to anxiety and sleep disorders; and in influencing the level of text comprehension while reading on screens. The latter is a rather surprising example showing that reading complex stories or interconnected facts in a printed book leads to better recall of the story, of details, and of the connection between facts than reading the same text on screen. The reason for the astonishing results, considering that the words on a light emitting diode (LED) screen or in a printed book are the same, seems to be related to how we use associations of facts with spatial and other sensory cues: the location on a page in a book we read something in addition, for instance, to the fact that each book smells differently seems to boost recall. In addition, the language scientist Naomi Baron, cited in an article by Makin, argues that reading habits are different in such a way that digital environments lead to superficial engagement in text analysis. This possibly depends on the fact that most digital media users glance at and multitask from one item to the next—a habit that might reduce attention span and contribute to the fact that diagnosis of attention-deficit hyperactivity disorder (ADHD) is higher than it was 10 years ago. Is this just a correlation or does it indicate that multitasking with digital media contributes to, or even causes, the higher incidence of ADHD? Two arguments support the hypothesis that intensive digital media use is related to impairments in working memory: simply seeing a smartphone (not even using it) lowers working memory capacity and leads to decreased performance in cognitive tasks, due to the fact that part of the working memory resources are busy ignoring the phone. In addition, the more that people use their smartphones in a multitasking modus (switching quickly between different engagements of the mind), the easier they respond to distraction and indeed perform more poorly in task-switching exams than users who rarely try to multitask. The results have been disputed (see ref 10), and this discrepancy in results might be related to the fact that digital media per se are neither good nor bad for our minds; it is rather how we use digital media. What we use smartphones or any other digital media for and how often are the important parameters to analyze, a point often ignored in this discussion.

Brain plasticity related to the use of digital media

The most straightforward and simple approach to elucidating whether digital media use has a profound effect on the human brain is to explore whether the use of fingertips on touchscreens changes cortical activity in the motor or the somatosensory cortex. Gindrat et al used this approach. It was already known that cortical space assigned to the tactile receptors on fingertips is influenced by how often the hand is used. For example, string instrument players have more cortical neurons of the somatosensory cortex allotted to the fingers they use in playing the instrument. This so-called “cortical plasticity of sensory representation” is not limited to musicians; for example, it also occurs with often-repeated grasp movements. As repeated finger movements occur with use of touchscreen smartphones, Gindrat et al used electroencephalography (EEG) to measure cortical potentials resulting from touching tips of the thumb, middle, or index fingers of touchscreen phone users and control subjects who used only non-touch-sensitive mobile phones. Indeed, the results were remarkable, as only touchscreen
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users showed an increase in the cortical potentials from the thumb and also for the index fingertips. These responses were statistically highly significantly correlated to the intensity of use. For the thumb, the size of cortical representation was correlated even with the day-to-day fluctuations in touchscreen use. These results clearly demonstrate that repetitive use of touchscreens can reshape somatosensory processing in fingertips, and they also indicate that such representation in the thumb can change within a short time frame (days), depending on use.

Taken together, this shows that intensive touchscreen use can reorganize the somatosensory cortex. Therefore, one can conclude that cortical processing is continuously shaped via digital media use. What was not investigated but should be explored in the future is whether such expansion of cortical representation in the fingertips and thumb occurred at the expense of other motor coordination skills. This response is of tremendous importance considering that motor skills are inversely correlated with screen time, due to either competition between cortical space and motor programs or because of an overall lack of exercise (eg, see ref 17).

Influences on the developing brain

Effect on motor skills is one aspect to consider with digital media use, other aspects are effects on language, cognition, and perception of visual objects in the developing brain. In this respect, it is remarkable that Gomez et al18 showed that details of the development of the visual system can be affected by the content of digital media. To explore this, functional magnetic resonance imaging (fMRI) was used to scan brain from adult subjects who had played the game Pokémon intensively when they were children. It was already known that object and face recognition is achieved in higher visual areas of the ventral visual stream, mainly in the ventral temporal lobe.19 Typical Pokémon figures are a mixture of animal-like humanized characters and are a unique type of object otherwise not visible in human environments. Only adults with intensive Pokémon experience during childhood showed distinct distributed cortical responsiveness to Pokémon figures in the ventral temporal lobe near face-recognition areas. These data—as a proof of principle—indicate that digital media use can lead to a unique functional and long-lasting representation of digital figures and objects even decades later. Surprisingly, all Pokémon players showed the same functional topography in the ventral visual stream for Pokémon figures. Also, here it is not clear whether these data simply show the tremendous plasticity of the brain to add new representations for novel classes of objects to the higher visual areas or whether object representation from intensive digital media use might have negative consequences for face recognition and processing as a consequence of competition for cortical space. In this respect, it is noteworthy that in empathy studies in young adults, a correlation between time spent with digital media and a lower cognitive empathy with other humans has been reported.20,21 Whether due to lack of insight into what other people might think (theory of mind) or to problems with facial recognition or lack of exposure to peers (due to excessive online time) is not currently clear. It should be emphasized that some studies reported no correlation between online time and empathy (for reviews, see refs 22 and 23).

Another area of interest is whether the development of processes related to language (semantics and grammar) is by any means affected by intensive digital media use. It is in this respect worrisome that early extensive screen use in preschoolers can have dramatic influences on language networks, as shown by sophisticated diffusion tensor MRI22,23 (Figure 1). This method provides estimates of white-matter integrity in the brain. In addition, cognitive tasks were tested in preschool children. This was measured in a standardized way by using a 15-item screening tool for observers (ScreenQ), which reflects the screen-based media recommendations of the American Academy of Pediatrics (AAP). ScreenQ scores were then statistically correlated with the diffusion tensor MRI measurement and with cognitive test scores, controlling for age, gender, and household income. Overall, a clear correlation was observed between intensive early childhood digital amedia use and poorer microstructural integrity of white-matter tracts, especially between the Broca and Wernicke areas in the brain (Figure 1). Language comprehension and capacity are highly correlated with the development of these fiber tracts, as reviewed in Grosset al24 and Skeide and Friederici.25 In addition, lower executive functions and lower literacy abilities were observed, even when age and the average household income were matched. Also, digital media use correlated with significantly lower scores in behavioral measures for executive functions. The authors conclude25: “Given that screen-based media use is ubiquitous and increasing in children in home, childcare, and school settings, these findings suggest the need for
further study to identify the implications for the developing brain, particularly during stages of dynamic brain growth in early childhood.” This study indicates that reading skills might be compromised if fiber tracts between the language areas are not developed to their full extent. Considering that reading ability in children is an excellent predictor of school success, it would also be beneficial to study if ScreenQ scores correlate to school success or to how traditional reading in books compares with reading on screens, in e-books, and on web pages.

Besides the development of language areas, reading habits might change with the use of electronic media. This change might have implications for new readers and for individuals with reading disabilities. Indeed, this has been explored recently. Here, fMRI was used when children listened to three similar stories in audio, illustrated, or animated format, followed by a test of factual recall. Within- and between-network functional connectivity was compared across formats involving the following: visual perception, visual imagery, language, default mode network.
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For illustration relative to audio, functional connectivity was decreased within the language network and increased between visual, DMN, and cerebellar networks, suggesting decreased strain on the language network afforded by pictures and visual imagery. Between-network connectivity was decreased for all networks for animation relative to the other formats, particularly illustration, suggesting a bias toward visual perception at the expense of network integration. These findings suggest substantial differences in functional brain network connectivity for animated and more traditional story formats in preschool-age children, reinforcing the appeal of illustrated storybooks at this age to provide efficient scaffolding for language. In addition, deep reading can be influenced by digital media. This shift in reading pattern may threaten the development of deep reading skills in young adults.

A particularly important time for brain development is adolescence, a period when brain areas involved in emotional and social aspects are undergoing intensive

**Figure 2.** Magnetic resonance imaging of the human brain and analysis showing correlation between gray-matter volume (GMV) and social-networking site (SNS) addiction score. Depicted is the visualization of the voxel-wise-based morphometry (VBM) exemplified in three different views: (A) rendered brain; (B) coronal view; and (C) sagittal view. The SNS addiction score was negatively correlated with GMV in bilateral amygdala (shown as blue areas) and positively correlated with GMV in the anterior/mid cingulate cortex (ACC/MCC, shown as yellow area). Imaging is displayed in radiological view (right is on the viewer’s left). (D-F) Scatter plots show the pattern of correlation between GMV and SNS addiction score in (D) ACC/MCC, (E) left amygdala, and (F) right amygdala. Adapted from ref 57: He Q, Turel O, Bechara A. Brain anatomy alterations associated with Social Networking Site (SNS) addiction. *Sci Rep.* 2017;7:45064. doi:10.1038/srep45064. Copyright© 2017, The Authors.
changes. Social media might have a profound effect on the adolescent brain due to the fact they allow adolescents to interact with many peers at once without meeting them directly. And indeed, published data indicate a different mode of processing emotions in adolescents, which is highly correlated to the intensity of social media use. This has been shown in the gray matter volume of the amygdala, which processes emotions (Figure 2). This suggests an important interplay between actual social experiences in online social networks and brain development. Emotion precedence, peer conformity, or acceptance sensitivity might make teenagers in particular vulnerable to fake or shocking news, as well as unlikely self-expectations, or vulnerable as regards regulation of emotions due to unfavorable use of digital media. What is missing here are longitudinal studies to elucidate whether the adolescent brain is differently shaped by social network size online instead of direct personal interaction.

As a side note, the evidence that violent games do have a profound effect on human behavior is better defined. A meta-analysis of current papers shows that exposure to violent video games is a highly significant risk factor for increased aggressive behavior and for a decrease in empathy and lower levels of prosocial behavior.

**Synaptic plasticity**

Principally, the study described above supports the notion of high brain plasticity induced by intensive use of digital media. In detail, the effects observed are amazing, but overall, it has been previously shown that the brain changes its functional and structural connectivity with usage, in other words, due to learning, habits, and experience. To judge this effect on the quality of human cognition and health, the question is more whether our brains—by using digital media extensively—are working in a certain cognitive mode, perhaps at the expense of others that are important. The effects of the brain’s potential to adjust its functional and structural connectivity has been demonstrated in many neuroimaging studies with humans; for a review, see ref 38. Other studies, including one by Maguire in London taxi drivers, and studies in pianists (as mentioned above) and jugglers show that intensive usage can stimulate the growth of new synaptic connections (“use it”) while at the same time eliminating neuronal synaptic connections that are used less often (“lose it”).

On the cellular level, this phenomenon has been named synaptic plasticity, reviewed by Korte and Schmitz. It is by now widely accepted that neurons in human cortex and hippocampus, as well as in subcortical areas, are highly plastic, meaning that changes in neuronal activity patterns, for example, generated by intensive training, change synaptic function as well as synaptic structure. Activity-dependent synaptic plasticity alters the efficacy of synaptic transmission (functional plasticity) and modifies the structure and number of synaptic connections (structural plasticity). Synaptic plasticity builds the foundation for adjusting the postnatal brain in response to experience and is the cellular implementation for learning and memory processes, as suggested in 1949 from Donald O. Hebb. He proposed that changes in neuronal activity due to usage, training, habit, or learning are stored in assemblies of neurons and not in single nerve cells. Plasticity by this means happens at the network level by altering the synapses between neurons and is therefore called activity-dependent synaptic plasticity. Hebb’s postulate also includes an important rule, predicting that synaptic strength changes when the pre- and postsynaptic neurons show coincident activity (associativity), and this changes the input/output characteristic of neuronal assemblies. Only if these are activated together again can they be remembered. Important is that the synaptic response to a certain brain activity of a given intensity is enhanced; for further details see Magee and Grienberger. This implies that all human activity performed on a regular basis—including use of digital media, social networks, or simply the internet—will have an imprint on the brain, whether for the good, the bad, or the ugly side of human cognitive function depends on the activity itself, or whether it occurs at the expense of other activities. In this respect, linking multitasking mode with cellular synaptic plasticity, Sajikumar et al showed that activation of three inputs impinging on the same neuronal population within a narrow time window (as is the case of humans trying to multitask) leads to the arbitrary strengthening of inputs, and not necessarily the strongest. This means the storage of relevant facts may be compromised if the input to a neuronal network in a particular brain area exceeds its limit of processing power.

**Digital media impact on the aging brain**

The effects and possible negative or positive aspects of digital media use, culture, and interaction might not
only depend on total consumption time and the cognitive domain involved; it might also depend on age. Thus, the negative effects on preschoolers, as reported by Hutton et al., might be quite different from those seen with usage in adults (like addiction) or to the effects observed in the elderly. Therefore, training of the aged brain with digital media might have different consequences than screen time for preschoolers or permanent distraction in adults.

Aging is not only genetically determined, but also dependent on lifestyle and on how the brain is used and trained; for example, see ref 47. One successful attempt involving digital media resulted in an increased attention span in elderly subjects through training response inhibition via computer games. Here, the training was done on a tablet for just 2 months, and significant cognitive effects on lateral inhibition were observed in comparison with a control group. These results correlated with growth processes, seen as greater cortical thickness in the right inferior frontal gyrus (rIFG) triangularis, a brain area associated with lateral inhibition. These effects, probably mediated via processes of structural plasticity depend on time spent performing the training task: the results became better in linear correlation with training time. Overall, it can be summarized that game-based digital training programs might foster cognition in the elderly and is in line with other studies showing that attention training is mediated via increasing the activity in the frontal lobe. Other studies have supported these results by showing that computer training is a possible means to train the brain in older people (>65 years of age), and brain training programs can assist in promoting healthy cognitive aging (see also ref 53). It will be exciting to probe whether digital media in the future can be used in the elderly to preserve or even increase cognitive capacities, such as attention, that suffer after intensive digital media/multi-tasking use at younger ages.

**Mechanism of addiction and digital media use**

In addition to classical substance-use disorders, behavioral addictions are also classified as addictive behavior. The WHO now includes internet-use disorder (IUD) or internet gaming disorder/internet addiction (IGD) in the *International Classification of Diseases 11th Revision (ICD-11)*, which might in the future also include “smartphone-use disorder” as a behavioral addiction (https://icd.who.int/browse11/l-m/en). Addiction is characterized as a chronic relapsing disorder, depicted by compulsion to seek and use either a substance or a behavior, like gambling. In addition, it includes loss of control in limiting certain behaviors or drug intake, and mostly is associated with the emergence of negative emotions (eg, anxiety, irritability, or dysphoria,) in situations where the drug or behavior is not attainable. Neurologically, addiction is characterized by overall network changes in frontostriatal and frontocingulate circuits. These are also the hallmarks for IGD/IUD addiction. Adolescents in particular might be at risk. For a systematic and more detailed meta-analysis of functional and structural brain changes related to IGD, see the following reviews by Yao et al and D’Hondt et al.

It is also noteworthy that some studies found a correlation between brain anatomy alterations and social networking site (SNS) addiction. It specifically shows that intensive interactions with social media can be correlated to gray-matter alteration of brain areas involved in addictive behavior. Also, other studies reported that intense use of social media can lead to a profound effect on neuronal structures in the human brain, as reviewed in ref 32. Overall, the implications of these data are that neuroscience and psychology research should turn more attention toward the understanding and prevention of online addiction disorders or other maladaptive behaviors related to gaming and social network use.

**Neuroenhancement with electronic devices**

So far, we have discussed digital media, but electronic devices in general can also be used to directly stimulate the human brain. The difficulty here is that the human brain is not a simple Turing machine, and the algorithm it uses is less clear. For this reason, it is unlikely that our brains can be reprogrammed by digital technologies and that simple stimulation of certain brain areas will increase cognitive abilities. However, deep-brain stimulation as a treatment option for Parkinson disease, depression, or addiction is a different story. Additionally, research on so-called brain/machine interfaces (BMIs) has shown that with regard to motor functions and the assimilation of artificial tools, eg, robotic/avatar extremities, incorporation in the somatosensory representation of the brain is possible. This works partly because neurons learn to represent artificial devices via processes of activity-dependent synaptic plasticity. This illustrates that, indeed, our sense of self can be altered
by electronic technologies to incorporate external devices. Nicolelis and colleagues have recently demonstrated that such an extension of the sense of body in paralyzed patients trained to use BMI devices could allow them to steer the movements of artificial avatar bodies, leading to a clinically relevant recovery.64

This does not mean that the human brain can mimic the binary logic or even the algorithm of digital devices, but it highlights how digital machines and digital media could have a huge impact on our mental skills and behavior (discussed in depth by Carr65). This impact is also highlighted by the effect of online cloud storage and search engines on human memory performance. A paradigmatic example is a study in which digital natives were made to believe that facts they had been asked to memorize would be stored in online cloud storage.66 Under this assumption, they performed more poorly than subjects that expected to have to rely only on their own brain memory function (mainly in the temporal lobe), as fMRI analysis illuminated.66 These results suggest that subcontracting some simple mental searches to internet cloud storage and relying on search engines instead of memory systems in our own brain reduces our ability to memorize and recall facts in a reliable manner.

Human well-being and multitasking

Addiction and neuroenhancement are particular effects of digital media and electronic devices. More common are the effects of multitasking on attention span, concentration, and the capacity of working memory.11 Processing multiple and continuous incoming streams of information is certainly a challenge for our brains. A series of experiments addressed whether there are systematic differences in information processing styles between chronically heavy and light media multitaskers (MMTs).5,67 The results indicate that heavy MMTs are more susceptible to interference from what are considered irrelevant external stimuli or representations in their memory systems. This led to the surprising result that heavy MMTs performed worse on a task-switching ability test, probably due to reduced ability to filter out interference from irrelevant stimuli.5 This demonstrates that multitasking, a rapidly growing behavioral trend, is associated with a distinct approach to fundamental information processing. Uncapher et al6 summarize the consequences of intense multimedia use as follows: “American youth spend more time with media than any other waking activity; an average of 7.5 hours per day, every day. On average, 29% of that time is spent juggling multiple media streams simultaneously (ie, media multitasking). Given that a large number of MMTs are children and young adults whose brains are still developing, there is great urgency to understand the neurocognitive profiles of MMTs.” On the other hand, it will obviously be important to understand what information processing is necessary for effective learning within the environment of the 21st century. A growing body of evidence demonstrates that heavy digital MMTs show poorer memory function, increased impulsivity, less empathy, and a higher amount of anxiety.5 On the neurological side, they show a reduced volume in the anterior cingulate cortex. In addition, current data indicate that switching quickly between different tasks (multitasking) during digital media use can negatively affect academic outcomes.6 However, one needs to be careful in the interpretation of these results because, as the direction of causality is not clear, media multitasking behavior might also appear more pronounced in people with reduced prefrontal activity and shorter attention span to start with. Here, longitudinal studies are needed. The overall impact of online social media on our natural social skills (from empathy to theory of other people’s minds) is another realm in which we may experience how and to what extent digital media affects our thinking and sensory processing of social signals. Of many studies, one by Turkle5 should be highlighted here. Turkle used interviews with teenagers or adults who were heavy users of social media and other kinds of virtual environments. One of the outcomes of this study was that extreme use of social media and virtual reality environments can lead to an increase in risk of anxiety, fewer real social interactions, lack of social skills and human empathy, and difficulties in handling solitude. In addition, the people interviewed reported symptoms related to addiction to internet use and digital social media. This mental routine of being “always connected” to hundreds or even thousands of people might indeed be overburdening our brain areas related to social interaction by dramatically expanding the number of people with whom we can closely communicate. The evolutionary constraint might be a group size limit of approximately 150 individuals.68 This may be the reason for our increase in cortical volume, eg, chimpanzees interact regularly with 50 individuals, but it may also be the limit of what our brains can achieve. In contrast to this evolutionary constraint, we are more or less in continuous contact with a group of
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people that by far exceeds our neurobiological limit due to social media. What are the consequences of this cortical overtaxing? Anxiety and deficits in attention, cognition, and even memory? Or can we adapt? So far, we have more questions than answers.

Conclusion

The brain is affected by the way we use it. It is hardly a stretch to expect that intensive digital media use will change human brains due to processes of neuronal plasticity. But it is less clear how these new technologies will change human cognition (language skills, IQ, capacity of working memory) and emotional processing in a social context. One limitation is that many studies thus far did not take into account what humans are doing when they are online, what they are seeing, and what type of cognitive interaction is required during screen time. What is clear is that digital media do have an impact on human psychological well-being and cognitive performance, and this depends on total screen time and what people are actually doing in the digital environment. Over the past decade, more than 250 studies have been published trying to elucidate the impact of digital media use; most of these surveys used self-reporting questionnaires that for the most part did not take into account the vastly different activities people experienced online. However, the pattern of use and the total time spent online will have different effects on a person’s health and behavior. Researchers need a more detailed multidimensional map of digital media use. In other words, what is desirable is a more precise measure of what people do when they are online or looking at a digital screen. Overall, the current situation cannot distinguish in most cases between causal effects and pure correlation. Important studies have been started, and the Adolescent Brain Cognitive Development Study (ABCD study) should be mentioned. It is orchestrated by the National Institutes of Health (NIH) and aims to explore the effect of environmental, social, genetic, and other biological factors affecting brain and cognitive development. The ABCD study will recruit 10,000 healthy children, ages 9 to 10 across the United States, and follow them into early adulthood; for details, see the website https://abcdstudy.org/. The study will include advanced brain imaging to visualize brain development. It will elucidate how nature and nurture interact and how this relates to developmental outcomes such as physical or mental health, and cognitive capabilities, as well as educational success. The size and scope of the study will allow scientists to identify individual developmental trajectories (eg, brain, cognitive, emotional, and academic) and the factors that can affect them, such as the effect digital media use will have on the developing brain.

What remains to be determined is whether the increasing frequency of all users moving toward being knowledge distributors themselves might become a great threat to the acquisition of solid knowledge and the need that each has to develop their own thoughts and to be creative. Or will these new technologies build the perfect bridge to ever more sophisticated forms of cognition and imagination, enabling us to explore new knowledge frontiers that we cannot at the moment even imagine? Will we develop completely different brain circuit arrangements, like we did when humans started to learn to read? Taken together, even if much research is still needed to judge and evaluate possible effects of digital media on human well-being, neuroscience can be of tremendous help to distinguish causal effects from mere correlations.

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Neurobiological mechanisms underlying internet gaming disorder

Aviv Weinstein, BSc, PhD; Michel Lejoyeux, MD, PhD

This review summarizes studies on the neurobiological correlates of internet gaming disorder (IGD), presently the most direct approach to analyzing the impact of digital technology and the internet on brain mechanisms. Brain imaging studies have shown that IGD shares, to a large extent, neurobiological alterations that are typical for other addictions, such as: (i) activation in brain regions associated with reward, as evident from cue exposure and craving studies and neurotransmitter systems studies that indicate an involvement of dopamine-mediated reward mechanisms; (ii) reduced activity in impulse control areas and impaired decision making; and (iii) reduced functional connectivity in brain networks that are involved in cognitive control, executive function, motivation, and reward. Moreover, there are structural changes, mainly reduction in gray-matter volume and white-matter density. Comorbidity studies indicate that executive control networks in attention deficit-hyperactivity disorder (ADHD) may increase the susceptibility to develop IGD. Most importantly, this review also outlines findings that show the effects of excessive use of screens, here referring to the playing of computer games, which activate many brain regions associated with cognitive, motor, and sensory function and not directly involved in other forms of addiction. This review describes and summarizes comprehensively the neurobiological correlates of addictive internet use in adolescents and young adults.

Keywords: brain imaging; control inhibition; cue reactivity; decision making; fMRI; internet gaming disorder; reward

Introduction

Excessive use of certain electronic media, including TV, computer screens, and smartphones, is raising serious concerns among health and educational authorities because of the deleterious effects of such use in children and adolescents. It has recently been shown that, in 5-year-old preschool children, there is an association between increased screen-based media use and reduced microstructural integrity of brain white-matter tracts that are associated with language and literacy skills, tracts that are important in the early years of brain development.1 Furthermore, assessment of 4277 adolescents in the Adolescent Brain Cognitive Development study (ABCD) via functional magnetic resonance imaging (fMRI) has shown a negative correlation between screen-media activity and cortical thickness.2 As cortical thickness naturally declines with age, these findings imply that excessive use of screen media prematurely ages the brain. The study also showed that screen-media use was associated with crystallized and fluid intelligence and that there was a positive association between screen-media use and externalizing but not internalizing psychopathology. The pervasive use of media screens has also been examined in young adults, and heavy media multitaskers are more susceptible to interference from irrelevant environmental stimuli and from irrelevant representations in memory.

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This has been supported by evidence that heavy media multitaskers perform worse on testing of task-switching ability, probably due to impaired ability to ignore irrelevant stimuli. The findings thus far, spanning from early childhood to adolescence, on rapidly growing societal phenomena emphasize the need to assess the effects of media screens on cognitive function and the brain in children, adolescents, and young adults. Specifically, there is extensive research on the excessive use of the internet for gaming and its effects on the brain in young adults and in particular in adolescents. The study of the neurobiological correlates of internet gaming disorder (IGD) appears particularly effective to demonstrate the impact of digital technology and the Internet on brain mechanisms. Furthermore, this evidence has raised major concerns in mental health professionals, and it has led to a major debate as to whether IGD should be classified as a clinical disorder. Brain imaging studies in IGD have been reviewed previously. This review will describe brain imaging studies in IGD, particularly in adolescents from 2014 until December 2019. Keywords were entered into PubMed search using “internet gaming disorder” as a search word. “English language” was used as a search limiter, and publication date was limited from 2014 to December 2019. Studies on treatment and sex differences were excluded due to limitation in the number of studies for this scope. The search yielded 61 studies of IGD and brain imaging.

**Brain imaging studies of the resting state in internet gaming disorder**

This section will describe the effects of IGD on the resting state in the brain, elucidated through studies using a functional neuroimaging technique that measures interactions between brain areas when a participant is not executing a specific action. Changes in resting-state brain activity are evaluated through cerebral blood flow (CBF) changes measured by a blood-oxygen-level–dependent (BOLD) signal in fMRI. Early studies reviewed previously showed that individuals with excessive internet game use had resting-state changes in areas associated with reward and impulse control, memory and learning, the urge to use drugs, inhibition and executive function, sensory-motor coordination, and visual and auditory mechanisms. Enhanced regional homogeneity (ReHo) in the posterior cingulate cortex and lower ReHo in the superior temporal gyrus were shown in IGD participants compared with control participants and participants diagnosed with alcohol-use disorder. ReHo is a voxel-based measure of brain activity that evaluates the similarity or synchronization between the time series of a given voxel and its nearest neighbors. ReHo can provide information about the local/regional activity of areas throughout the brain. Furthermore, amplitude of low-frequency fluctuation (ALFF) values in the superior frontal gyrus (SFG) were lower in IGD participants, and they correlated negatively with measures of impulsivity. ALFF is a measure of the amplitude of low-frequency oscillations that reflect the intensity of regional spontaneous brain activity.

In summary, these studies provide evidence for enhanced cognitive function and decreased activity in sensory-motor coordination in the resting state. Some of these changes are associated with addiction, but others may be associated with sensory, cognitive, and motor effects on the brain. Table I summarizes resting-state and structural studies of IGD.

**Imaging studies on the brain’s gray-matter volume and white-matter density**

This section will review studies on the gray matter of the brain, which is composed of neurons that are associated with emotions, perception, memory, and motor control, and the brain’s white matter, which consists mostly of glial cells and myelinated axons that transmit signals from the cerebellum to other brain regions. An early study by Kuhn et al reported that frequent–video game-playing participants performing the monetary incentive delay task had greater left striatal gray-matter volume and an enhanced activation in the left striatum when exposed to loss. These findings were negatively associated with deliberation time on another task, indicating impaired reward processing.
### Table I (continued overleaf). Resting-state and structural studies of internet gaming disorder.

*Studies arranged chronologically by publication year. †Regional Homogeneity (ReHo) is a voxel-based measure of brain activity that evaluates the similarity or synchronization between the time series of a given voxel and its nearest neighbors. This measure is based on the hypothesis that intrinsic brain activity is manifested by clusters of voxels rather than single voxels. ReHo can provide information about the local/regional activity of regions throughout the brain. ACC, anterior cingulate cortex (ACC); DLPFC, dorsolateral prefrontal cortex; IAT, internet addiction test; MRI, magnetic resonance imaging; OFC, orbitofrontal cortex; PCC, posterior cingulate cortex; RGU, recreational internet game use.

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<th>CITATION*</th>
<th>METHOD</th>
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<tr>
<td>Sun et al,11 2014</td>
<td>Gray-matter diffusion assessed via diffusion kurtosis imaging</td>
<td>18 IGD 21 control participants</td>
<td>Lower gray-matter diffusion in the right anterolateral cerebellum, right inferior and superior temporal gyri, right supplementary motor area, middle occipital gyrus, right precuneus, postcentral gyrus, right inferior frontal gyrus, left lateral lingual gyrus, left paracentral lobule, left ACC, median cingulate cortex, bilateral fusiform gyrus, insula, PCC, and thalamus. Higher gray-matter volume in the right inferior and middle temporal gyri, and right parahippocampal gyrus, and lower volume in the left precentral gyrus.</td>
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<td>Wang et al,12 2015</td>
<td>Gray-matter volume measured via MRI</td>
<td>28 IGD 28 control participants</td>
<td>Smaller gray-matter volume of the bilateral ACC, precuneus, supplementary motor area, superior parietal lobule, left DLPFC, left insula, and bilateral cerebellum in IGD participants than in healthy control participants. Gray-matter volume of the ACC negatively correlated with the incongruent response errors on the Stroop test.</td>
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<tr>
<td>Kim et al,9 2015</td>
<td>Regional homogeneity (ReHo)† measured via MRI</td>
<td>16 IGD alcohol-use disorder 15 control participants</td>
<td>IGD and alcohol-use disorder participants had increased ReHo in the PCC. IGD participants showed decreased ReHo in the right superior temporal gyrus compared with alcohol-use disorder and control participants. Patients with alcohol-use disorder showed decreased ReHo in the ACC.</td>
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<tr>
<td>Lin et al,13 2015</td>
<td>Gray-matter density and white-matter density changes assessed by voxel-based morphometric analysis in MRI.</td>
<td>35 IGD 36 control participants</td>
<td>Higher fractional anisotropy in the thalamus and left PCC. Higher fractional anisotropy in the thalamus was associated with greater severity of internet addiction.</td>
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<td>Takeuchi et al,14 2016</td>
<td>Mean diffusivity assessed via diffusion tensor imaging</td>
<td>114 boys 126 girls</td>
<td>The amount of videogame play positively correlated with mean diffusivity in the left middle, inferior, and orbitofrontal cortex (OFC); left pallidum; left putamen; left hippocampus; left caudate; right putamen; right insula; and thalamus in both cross-sectional and longitudinal analyses. Higher mean diffusivity in the areas of the left thalamus, left hippocampus, left putamen, left insula, and left Heschl gyrus was associated with lower intelligence.</td>
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<tr>
<td>Yuan et al,15 2016</td>
<td>Assessment of white-matter integrity and connectivity</td>
<td>28 IGD adolescents 25 control participants</td>
<td>Reduced fractional anisotropy in the ACC/right DLPFC pathways in IGD.</td>
</tr>
<tr>
<td>Zhai et al,16 2017</td>
<td>White-matter integrity measured via diffusion tensor imaging</td>
<td>16 right-handed adolescents with IGD 16 control participants</td>
<td>Reduced nodal efficiency in frontal cortex, ACC, and pallidium in IGD. Global efficiency of the white-matter network correlated with the IAT scores in IGD.</td>
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<tr>
<td>Jeong et al,17 2016</td>
<td>Assessment of white-matter integrity and connectivity</td>
<td>181 male patients including: 58 IGD subjects without psychiatric comorbidity 26 male control participants</td>
<td>Increased fractional anisotropy values within forceps minor; right anterior thalamic radiation; right corticospinal tract; right inferior longitudinal fasciculus; right cingulum to hippocampus; and right inferior fronto-occipital fasciculus (IFOF) decreases in radial diffusivity value within forceps minor, right anterior thalamic radiation and IFOF relative to control subjects.</td>
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<tr>
<td>Sun et al, 2019</td>
<td>Resting-state cerebral activity alterations assessed via amplitude of low-frequency fluctuation (ALFF) and functional connectivity</td>
<td>30 male IGD, 23 female IGD, 30 male and 22 female age-matched healthy control participants</td>
<td>Greater ReHo* in the brain stem, inferior parietal lobule, cerebellum, and middle frontal gyrus. Lower ReHo in occipital and parietal areas.</td>
</tr>
<tr>
<td>Seok et al, 2018</td>
<td>Assessment of resting-state gray-matter volume and functional connectivity</td>
<td>20 IGD, 20 age- and sex-matched healthy control participants</td>
<td>IGD severity was positively correlated with gray-matter volume in the left caudate and it was negatively associated with functional connectivity between the left caudate and the right middle frontal gyrus.</td>
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<tr>
<td>Pan et al, 2018</td>
<td>Assessment of resting-state gray-matter volume</td>
<td>67 male adolescents</td>
<td>IAT score was negatively correlated with gray-matter volumes of the bilateral postcentral gyri, the bilateral precentral gyri, the right precuneus, the left posterior midcingulate cortex, the left inferior parietal lobe, and the right middle frontal gyrus.</td>
</tr>
<tr>
<td>Lee et al, 2018</td>
<td>Assessment of resting-state gray-matter volume</td>
<td>45 male adults with IGD, 35 age-matched male control participants</td>
<td>IGD subjects had thinner cortices in the right rostral ACC, right lateral OFC, and left pars orbitalis than controls. Smaller gray-matter volume in the right caudal ACC and left pars orbitalis in IGD subjects. Thinner cortex of the right lateral OFC in IGD subjects correlated with higher cognitive impulsivity. Whole-brain analysis in IGD subjects revealed thinner cortices in the right supplementary motor area, left frontal eye field, superior parietal lobule, and posterior cingulate cortex.</td>
</tr>
<tr>
<td>Dong et al, 2018</td>
<td>Assessment of white-matter integrity</td>
<td>42 IGD, 44 RGU participants</td>
<td>Increased fractional anisotropy in the bilateral anterior thalamic radiation, anterior limb of the internal capsule, bilateral corticospinal tract, bilateral inferior fronto-occipital fasciculus, corpus callosum, and bilateral inferior longitudinal fasciculus. Internet-addiction severity was positively correlated with fractional anisotropy values.</td>
</tr>
<tr>
<td>Wang et al, 2018</td>
<td>Assessment of cortical thickness and volume</td>
<td>38 IGD, 66 RGU participants</td>
<td>IGD showed decreased cortical thickness in the left lateral OFC, inferior parietal lobule, bilateral cuneus, precentral gyrus, and right middle temporal gyrus. Reduced cortical volume in the left superior temporal gyrus and right supramarginal gyrus in IGD. Whole-brain correlational analysis indicated different correlations between the two groups.</td>
</tr>
<tr>
<td>Wang et al, 2018</td>
<td>Assessment of cortical thickness and volume</td>
<td>48 IGD male youths, 32 age- and education-matched control participants</td>
<td>IGD showed increased cortical thickness in the bilateral insulae and the right inferior temporal gyrus. Decreased cortical thickness in bilateral superior temporal sulci, the right inferior parietal cortex, the right precuneus, the right precentral gyrus, and the left middle temporal gyrus. A positive correlation between the left insular cortical thickness and symptom severity.</td>
</tr>
</tbody>
</table>

*Studies arranged chronologically by publication year. †Regional Homogeneity (ReHo) is a voxel-based measure of brain activity that evaluates the similarity or synchronization between the time series of a given voxel and its nearest neighbors. This measure is based on the hypothesis that intrinsic brain activity is manifested by clusters of voxels rather than single voxels. ReHo can provide information about the local/regional activity of regions throughout the brain. ACC, anterior cingulate cortex (ACC); DLPFC, dorsolateral prefrontal cortex; IAT, internet addiction test; MRI, magnetic resonance imaging; OFC, orbitofrontal cortex; PCC, posterior cingulate cortex; RGU, recreational internet game use. Parts of Tables I and II reproduced with permission from ref 6: Weinstein A, Livny A, Weizman A. New developments in brain research of internet and gaming disorder. Neurosci Biobehav Rev. 2017;75:314-330. Copyright © Elsevier 2017.
IGD severity was associated with gray-matter volume in the left caudate and was negatively associated with functional connectivity between the left caudate and the right middle frontal gyrus, which mediate reward and cognitive control.\textsuperscript{18}

In adolescents, IGD was associated with changes in gray-matter volumes in brain regions involved in sensory-motor processes and cognitive control\textsuperscript{19} evaluating reward, error processing, and adjusting behavior,\textsuperscript{20} impulse control, attention, emotional regulation, and motor function.\textsuperscript{11} Reduced gray-matter volume was reported in the prefrontal cortex and the amygdala, and the volume of these regions was associated with measures on the Barratt Impulsiveness Scale.\textsuperscript{13} An inverse relationship was found between low gray-matter volume of the anterior cingulate cortex (ACC) and incongruent response errors on the Stroop task.\textsuperscript{12}

Early structural studies reviewed previously\textsuperscript{6} have shown evidence for reduced gray-matter density in brain regions associated with motor, attention, and cognitive control and reduced white-matter volume in brain regions associated with memory, and sensory and motor neurotransmission in IGD. Lower gray-matter volume was found in several brain regions. Reduced fractional anisotropy was shown in other white-matter regions. Further reports have indicated reduced gray-matter volume in brain regions associated with motor and cognitive control and reduced white-matter volume in brain regions associated with cognitive control and planning. Higher white-matter density in the thalamus and left posterior cingulate cortex was associated with greater severity of IGD.\textsuperscript{12}

There is also evidence for reduced white-matter volume in brain regions that are associated with inhibition, decision making, and emotional regulation, and reduced fractional anisotropy in the ACC and the dorsolateral prefrontal cortex (DLPFC) was shown in IGD and associated with performance on the Stroop task.\textsuperscript{15} Video game playing correlated with delayed development of several brain regions such as hippocampus, orbitofrontal cortex (OFC), pallidum, caudate/putamen insula, and the thalamus.\textsuperscript{14} Low intelligence was associated with high diffusion measures in brain regions including the hippocampus, thalamus, putamen, and the insula.\textsuperscript{13} Reduced white-matter in the frontal cortex, ACC, and the pallidum was reported in IGD.\textsuperscript{16} There is further evidence for increased white-matter density and decreased diffusion in fiber tracts in the frontal cortex.\textsuperscript{17} Finally, they showed increased fractional anisotropy in tracts linking reward circuitry and sensory and motor control systems, and these were associated with internet addiction severity.\textsuperscript{21}

To sum up, the studies reviewed have shown evidence for long-term changes in gray-matter volume and white-matter density in brain regions associated with memory, attention, impulse control, emotional regulation, and motor function in IGD. Some of the reported effects of IGD are associated with characteristics of addiction, such as reward and impulsivity, whereas others may result from changes to attention, emotional regulation, and motor functions in the brain.

Figure 1 shows brain regions with reduced gray-matter volume in frequent IGD players.

\textbf{Figure 1.} Regions that showed reduced gray-matter volume in internet gaming disorder (IGD) participants in more than two studies. SMA, supplementary motor area. Figure reproduced from ref 6: Weinstein A, Livny A, Weizman A. New developments in brain research of internet and gaming disorder. Neurosci Biobehav Rev. 2017;75:314-330. Copyright © Elsevier 2017
**Cortical thickness**

Early studies (see ref 6 for review) showed contradictory evidence pertaining to cortical thickness in IGD: some reported enhanced cortical thickness in frontal and temporal areas in adolescents with IGD who performed the Stroop task; some reported decreased cortical thickness. Cortical thickness of the OFC correlated with low performance on the Stroop task. Reduced cortical thickness in the lateral OFC was shown in male adolescents with IGD. Decreased cortical thickness in brain regions that are involved in cognitive control, decision making, and reward/loss processing (OFC, inferior parietal lobe, cuneus, precentral gyrus, and right middle temporal gyrus) was reported in IGD compared with recreational internet game use. Finally, adolescents with IGD showed decreased cortical thickness in distributed cerebral areas and had a positive correlation between the left insular cortical thickness and symptom severity.

In summary, the studies reviewed so far showed changes in cortical thickness in regions associated with addiction processes such as reward, but also with regions associated with executive function and decision making. The conflicting results of enhanced and reduced cortical thickness indicate that the findings are not robust and that changes in cortical thickness merit further study.

**Neuroimaging studies of functional connectivity in internet gaming disorder**

The aim of this section is to review studies on functional connectivity, which measures the level of coactivation of resting-state fMRI time-series between brain regions. Early studies in IGD (see review in ref 6) showed increased functional connectivity between brain regions that are associated with signal processing, cognitive regulation, and auditory-verbal memory, and decreased functional connectivity with brain regions that are associated with evaluation and expectancy of reward in smokers with IGD. Reduced functional connectivity was shown in brain regions associated with executive function and increased functional connectivity in brain regions associated with sensory-motor processing. Reduced functional connectivity correlated with executive control. Increased volume of the caudate and nucleus accumbens (NA) and reduced functional connectivity in brain areas that are associated with reward were reported in young adults with IGD.

Early studies in adolescents with IGD (see review in ref 6) showed reduced functional connectivity in cortical-subcortical circuits related to drug addiction. Recent studies have also shown an impaired functional connectivity in brain regions associated with memory and learning, executive function, sensory and motor processing, and in areas associated with reward (prefrontal cortex and striatal circuits).

Individuals with IGD had greater functional connectivity between the precuneus and brain regions associated with attention, salience, self-monitoring, and craving. However, the nucleus accumbens and the medial OFC in subjects with this disorder were shown to have lower resting-state functional connectivity with the ventral tegmental area. Treatment for this disorder with equine-assisted activities and therapies (EAAT) has improved anxiety and avoidance attachment scores and has increased functional connectivity in affective networks, including the amygdala and the frontal orbital gyrus. Subjects with this disorder were shown to have functional connectivity of the DLPFC with large-scale brain networks, and adolescents with IGD had increased functional connectivity in brain regions involved in working memory, spatial orientation, and attention processing.

Lower functional connectivity in IGD has been shown to affect executive control function and to have an inverse relationship with the Stroop effect. Impulsivity has also been inversely associated with functional connectivity in brain regions such as the amygdala, DLPFC, and the OFC and has been associated with changes in the frontal-limbic networks. Participants with IGD also showed increased volumes of the ventral striatum (nucleus accumbens) and dorsal striatum (caudate).

To sum up, the studies so far have shown decreased functional connectivity in IGD in brain networks that are involved in cognitive control, executive function, motivation, and reward. Some of the changes in functional connectivity associated with motivation, craving, and reward are associated with addiction, whereas others may result from changes in executive function and sensory-motor processing that are not related to addiction per se.

**Table II** summarizes studies on functional connectivity in IGD.
<table>
<thead>
<tr>
<th>CITATION*</th>
<th>METHOD</th>
<th>PARTICIPANTS</th>
<th>MAIN FINDINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wee et al, 2014</td>
<td>Functional connectivity in fMRI</td>
<td>17 IGD adolescents 16 control participants</td>
<td>Disruption of functional connectivity in the frontal, occipital, and parietal lobes. Functional connectivity with the frontal, occipital, and parietal lobes correlated with IGD severity.</td>
</tr>
<tr>
<td>Chen et al, 2014</td>
<td>Functional connectivity in fMRI</td>
<td>29 IGD smokers 22 IGD nonsmokers 30 control participants</td>
<td>Decreased resting-state functional connectivity with posterior cingulate cortex in the right gyrus rectus. Increased resting-state functional connectivity in the left middle frontal gyrus in smokers with IGD compared with nonsmokers with IGD.</td>
</tr>
<tr>
<td>Dong et al, 2015</td>
<td>Functional connectivity in fMRI</td>
<td>35 IGD 36 control participants</td>
<td>Lower functional connectivity in executive-control network. Functional-connectivity measures in executive-control networks were negatively correlated with Stroop effect and positively correlated with brain activations in executive-control regions across groups.</td>
</tr>
<tr>
<td>Ko et al, 2015</td>
<td>Gray-matter density and functional connectivity in fMRI</td>
<td>30 male IGD 30 control participants</td>
<td>Lower gray-matter density in the bilateral amygdala and higher impulsivity. Lower functional connectivity with the left amygdala over the left DLPFC and with the right amygdala over the left DLPFC and OFC. Higher functional connectivity with the bilateral amygdala over the contralateral insula. Functional connectivity between the left amygdala and DLPFC negatively correlated with impulsivity. Functional connectivity of the right amygdala to the left DLPFC and OFC also negatively correlated with impulsivity.</td>
</tr>
<tr>
<td>Hong et al, 2015</td>
<td>Functional connectivity in fMRI in subdivisions of striatum</td>
<td>12 male IGD adolescents 11 male control participants</td>
<td>Reduced dorsal putamen functional connectivity with the posterior insula-parietal operculum. Time spent playing online games predicted significantly greater functional connectivity between the dorsal putamen and bilateral primary somatosensory cortices. Lower functional connectivity between the dorsal putamen and bilateral sensorimotor cortices in healthy control participants.</td>
</tr>
<tr>
<td>Wang et al, 2015</td>
<td>Functional connectivity and voxel-mirrored homotopic connectivity (VMHC) method</td>
<td>17 IGD 24 healthy control participants</td>
<td>Decreased VMHC between the left and right superior frontal gyrus (orbital part), inferior frontal gyrus (orbital part), middle frontal gyrus, and superior frontal gyrus.</td>
</tr>
<tr>
<td>Zhang et al, 2016</td>
<td>Functional connectivity of the insula in fMRI</td>
<td>74 IGD young adults 41 control participants</td>
<td>Enhanced functional connectivity between the anterior insula and a network of regions including ACC, putamen, angular gyrus, and precuneus. Stronger functional connectivity between the posterior insula and post-central gyrus, precentral gyrus, supplementary motor area, superior temporal gyrus. IGD severity was positively associated with connectivity between the anterior insula and angular gyrus, and superior temporal gyrus, and with connectivity between the posterior insula and superior temporal gyrus. Duration of internet gaming was positively associated with connectivity between the anterior insula and ACC.</td>
</tr>
<tr>
<td>Cai et al, 2016</td>
<td>Functional connectivity in fMRI in striatal nuclei (caudate, putamen, and nucleus accumbens) volumes</td>
<td>27 IGD adolescents 30 control participants</td>
<td>Increased volumes of dorsal striatum (caudate) and ventral striatum (nucleus accumbens) and more errors on the Stroop task. Caudate volume correlated with Stroop task performance, and nucleus accumbens volume was associated with the internet addiction test score in the IGD group.</td>
</tr>
</tbody>
</table>

*Studies arranged chronologically by year. ACC, anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; fMRI, functional magnetic resonance imaging; IGD, Internet gaming disorder; OFC, orbitofrontal cortex; VMHC, voxel-mirrored homotopic connectivity; VTA/SN, ventral tegmental area/substantia nigra
### Table II (continued). Studies of functional connectivity in fMRI.


<table>
<thead>
<tr>
<th>CITATION*</th>
<th>METHOD</th>
<th>PARTICIPANTS</th>
<th>MAIN FINDINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Du et al,16 2017</td>
<td>Resting-state functional connectivity density in fMRI</td>
<td>27 male IGD adolescents 35 healthy control participants</td>
<td>IGD adolescents exhibited higher global/long-range resting-state functional connectivity in the bilateral dorsal lateral prefrontal cortex (DLPFC) and the right inferior temporal cortex/fusiform than healthy control participants.</td>
</tr>
<tr>
<td>Jin et al,29 2016</td>
<td>Functional connectivity</td>
<td>25 IGD adolescents 21 age- and gender-matched control participants</td>
<td>Decreased functional connectivity between the insula, and temporal and occipital cortices and dorsal striatum, pallidum, and thalamus in IGD. Some of those changes were associated with the severity of IGD.</td>
</tr>
<tr>
<td>Wang et al,25 2016</td>
<td>Functional connectivity</td>
<td>37 IGD 35 matched control participants</td>
<td>Reduced connectivity in the prefrontal cortex, left posterior cingulate cortex, right amygdala, and bilateral lingual gyrus, and increased functional connectivity in sensory-motor-related brain networks in IGD.</td>
</tr>
<tr>
<td>Park et al,36 2017</td>
<td>Functional connectivity in fMRI</td>
<td>19 IGD adolescents 20 age-matched control participants</td>
<td>Higher impulsiveness, higher global efficiency, and lower local efficiency pathological states. Topological alterations were specifically attributable to inter-regional connections incident on the frontal region, and the degree of impulsiveness was associated with the topological alterations over the frontal-limbic connections.</td>
</tr>
<tr>
<td>Yuan et al,35 2016</td>
<td>Functional connectivity in fMRI</td>
<td>28 IGD adolescents 25 control participants</td>
<td>Reduced fractional anisotropy in salience network, right central executive network tracts, and between-network (the ACC-right DLPFC tracts) Correlation between the effective and structural connection from salience network to central executive network and the number of errors during incongruent condition in Stroop task in both IGD and control participants.</td>
</tr>
<tr>
<td>Kang et al,32 2018</td>
<td>Resting-state functional connectivity</td>
<td>15 IGD adolescents with insecure attachment 15 healthy control adolescents with secure attachment</td>
<td>Functional connectivity from the left amygdala to the left parahippocampal gyrus, left medial frontal gyrus, and left inferior frontal gyrus, and from the right amygdala to the left caudate, right claustrum, and left inferior frontal gyrus increased. In IGD adolescents, functional connectivity from the left amygdala to the left frontal orbital gyrus, and from the right amygdala to the right corpus callosum also increased.</td>
</tr>
<tr>
<td>Han et al,33 2018</td>
<td>Resting-state functional connectivity</td>
<td>30 IGD 30 control participants</td>
<td>IGD showed lower static functional connectivity between the right DLPFC and the left Rolandic operculum and higher static functional connectivity between the right DLPFC and the left pars triangularis. IGD had decreased dynamic functional connectivity between the right DLPFC and the left insula, right putamen and left precentral gyrus, and increased dynamic functional connectivity in the left precuneus. The dynamic functional connectivity between the right DLPFC and the left insula was negatively correlated with the severity of IGD.</td>
</tr>
<tr>
<td>Wang et al,31 2019</td>
<td>Resting-state functional connectivity and diffusion tensor imaging–based structural connectivity of VTA/SN circuits</td>
<td>33 male IGD 28 male control participants</td>
<td>The nucleus accumbens and medial OFC showed lower resting-state functional connectivity with VTA in IGD participants. Resting-state functional connectivity strength of VTA–right nucleus accumbens and VTA-left medial OFC correlated negatively with internet addiction test score in IGD participants. IGD participants showed lower structural connectivity in bilateral VTA-nucleus accumbens tracts, but the connectivity did not correlate with internet addiction test score.</td>
</tr>
</tbody>
</table>
Studies of brain activation

The aim of this section is to evaluate brain activation studies that measure and interpret the change between a baseline condition and a stimulation condition. Early studies (see review in ref 6) in IGD participants who were presented with gaming and neutral images during fMRI showed activation of brain regions associated with reward, response inhibition, and cognitive control, and the activation of these areas was associated with craving in response to the gaming images. Participants with IGD who played videogames for 6 weeks responded to videogame cues by showing increased reactivity in the OFC and ACC. Such cues activated regions associated with working memory, attention, and executive function in IGD. A positive relationship was noticed between the activation and cue-induced self-reported urges for gaming. Similar mechanisms of cue-induced reactivity of the frontal-limbic network were shown for gaming and smoking cues. Finally, exposure to figures from the World of Warcraft game activated the left caudate nucleus, parahippocampal gyrus, right hippocampus, right cuneus, right inferior parietal lobule, cerebellum, bilateral temporal cortex, and DLPFC, and activity in brain regions associated with motivation, emotion, and cognitive function was positively associated with craving. Recent studies have shown that watching video games activates brain regions associated with attention, executive function, and visuospatial orientation in individuals with IGD. They have also reported changes in attention to game images and in medial prefrontal cortex (MPFC) and ACC activation. Four functional connectivity networks related to the response to game cues showed altered engagement/disengagement in IGD. Finally, greater cue-induced activations within both the ventral and dorsal striatum were shown in IGD subjects. Activity within the left ventral striatum correlated negatively with cue-induced craving in IGD, and activations within the dorsal striatum had positive associations with duration of IGD play. These results suggest that a transition from ventral to dorsal striatal processing may occur in individuals with IGD.

Players of massively multiplayer online role-play games (MMORPGs) have shown lower activity in areas associated with visuospatial attention and body self-awareness while reflecting on their own body image. Furthermore, increased identification with one’s avatar has been associated with high left angular gyrus activation in pathological internet gamers. Evaluation of ideal self and actual self in young adults with IGD have been reported to be more negative than in healthy control participants, and fMRI-measured brain activity in the inferior parietal lobule found to be decreased, indicating dysfunctional emotional regulation. While thinking about their game characters, adolescents with IGD showed activation within MPFC and ACC, indicating attachment to game figures that are equated with humans. Adolescents with IGD have also shown changes in emotional regulation, indicated by blunted neural responses within the striatum, insula, lateral prefrontal cortex, and ACC in response to negative affective cues and emotion regulation. Finally, impairment in executive function and related visual networks, as indicated by performance on the Stroop task in fMRI, has been reported. Adults with IGD showed impaired functional connectivity of the right executive control network, increased cognitive control processing, and diminished response inhibition.

An early study (review in ref 6) by Dong et al, found that IGD subjects performing the Stroop task showed impaired response inhibition during exposure to gaming-cue distraction, revealed by higher activity in the posterior cingulate cortex and ACC. Participants with IGD showed stronger impulsivity and reduced activation of the supplementary motor areas while performing the Go/No-Go task. Adolescents with IGD showed activation in brain regions associated with attention and cognitive control during No-Go trials. During performance on the Go-Stop task, they showed reduced activation of the frontal-basal ganglia network and reduced inhibition of undesired movements, indicating that changes in the prefrontal cortex may be associated with impulsivity and impaired cognitive control. IGD participants processing social anxiety words showed decreased temporal gyrus activation.

In summary, activation studies show evidence that individuals with IGD have impaired inhibition, a finding supported by meta-analysis. There is further evidence that videogame cues activate craving, as well as working memory, attention, and executive function. Some of these cognitive, sensorimotor, and emotional processes may not be associated with addiction per se but with changes to the brain as a result of prolonged exposure to screens.
The following section will describe studies of decision making and delay discounting in IGD. While performing a guessing task, IGD participants experienced monetary gain and loss. An early study by Dong et al (see review in ref 6) showed that with consecutive wins on a repeated wins-and-losses task in fMRI, IGD participants had higher brain response in the ACC, insula, and inferior frontal cortex and lower brain response in the caudate and posterior cingulate cortex. After consecutive losses, they showed activation of the inferior frontal gyrus and deactivation of the posterior cingulate cortex. IGD participants preferred probable options to safe ones on a probability-discounting task, and they were faster than control subjects, indicating impulsive decision making. IGD participants also showed lower response in the inferior frontal gyrus and the precentral gyrus in response to options with varying probability. Compared with recreational internet game users, IGD participants preferred risky options to the fixed ones and spent less time in making risky decisions. This was indicated by stronger functional connectivity than seen in recreational internet game users in reward circuits and the executive control network and lower functional connectivity in the anterior salience network (ASN).

The behavioral performance and fMRI measures suggest that altered risk assessment might explain why individuals with IGD persist in playing online games in spite of detrimental consequences. IGD participants, while choosing probabilistic options, showed decreased activation in the inferior frontal gyrus and the precentral gyrus. They also preferred risk-disadvantageous choices and made quick, risky decisions without utilizing brain regions associated with impulse control. Similarly, decreased reward sensitivity and enhanced sensitivity to error monitoring regardless of satisfaction was indicated in adolescents who performed the probability-discounting task. There is also evidence that negative outcomes have influenced the covariance between the level of risk and the activation of brain regions associated with estimation of value, anticipation of reward, and learning, delineating the underlying neural mechanisms of risky decision making. IGD participants performing a decision-making task have shown lower changes in the DLPFC and inferior parietal lobule in response to risk exposure for potential losses and higher activity in response to reward in the OFC, ventromedial prefrontal cortex (vmPFC), and ventral striatum for potential gains during outcome processing. Participants with IGD and nicotine smokers who performed the delay-discounting task showed lower response accuracy in the DLPFC and vmPFC, and decoding accuracy in the

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**Figure 2.** Regions that showed activation in response to internet and videogame cues in internet gaming disorder (IGD) participants in more than two studies. DLPFC, dorsolateral prefrontal cortex. Reproduced from ref 6: Weinstein A, Livny A, Weizman A. New developments in brain research of internet and gaming disorder. *Neurosci Biobehav Rev*. 2017;75:314-330. Copyright © Elsevier 2017
Brain imaging studies on dopamine and serotonin

Dopamine and serotonin (5-HT) have an important role in drug and alcohol dependence, in particular in reward and withdrawal mechanisms. This section will review brain imaging studies on dopamine and 5-HT in IGD. Early studies in IGD (review in ref 6) that included a small number of participants showed low levels of dopamine D2 receptor availability and dopamine transporter (DAT) availability in the striatum. A following study with a larger number of participants (12 with IGD and 14 control participants) measured dopamine D2 receptor and 5-HT2A receptor occupancy together with 18F-fluorodeoxyglucose (18F-FDG) to assess regional brain glucose metabolism via positron emission tomography.61 Results showed decreased glucose metabolism in the prefrontal, temporal, and limbic regions together with low dopamine D2 receptor availability in the striatum, which correlated with years of gaming. Reduced glucose metabolism in the OFC correlated with dopamine D2 receptor occupancy in the striatum.62 In summary, these results suggest that low levels of dopamine-D2 and 5-HT2A-receptor occupancy together with dysregulation of the OFC could be an underlying mechanism of compulsive behavior and loss of control in IGD.63

Discussion

Similar to drug-abuse research, neuroimaging studies of reward have shown lower dopamine-transporter density and reduced occupancy of dopamine D2 receptors in the striatum, an area that mediates dopamine reward in IGD. This evidence is further supported by brain-activation studies showing that video game-playing stimuli activate the brain similarly to activation by drug cues. These studies show how cue exposure can affect the brain’s reward, processing of sensory information, and self-reflection. There is also evidence for long-term changes as a result of play, indicated by an association between activity in the striatum and duration of IGD. Regular use of the internet for gaming was also associated with impulsivity and impaired cognitive control and impaired function of the prefrontal cortex in adults and adolescents. There is further evidence for lower connectivity in brain regions that are involved in cognitive control, executive function, and processing of motivation and reward that are also involved in substance-use disorders. This evidence provides strong support for the inclusion of IGD as a behavioral addiction alongside other behavioral addictions such as gambling disorder.

Studies of comorbidity of IGD with attention deficit-hyperactivity disorder (ADHD) and depression have provided new insights into the brain mechanisms that underlie these disorders. Executive control mechanisms in ADHD may increase susceptibility to develop IGD.64 Adolescents with ADHD may play cyber games to increase their capacity to focus their attention.65 IGD participants with ADHD had larger gray-matter volume in the right precuneus and smaller gray-matter volume in the right inferior frontal gyrus than IGD participants without ADHD and control participants.66 Patients with ADHD and IGD who were treated with cognitive behavioral therapy and medication showed improved functional connectivity between the cortex and subcortex in all ADHD and IGD patients, with good prognoses after 1-year treatment.67 IGD patients with a major depressive episode had an impaired ability to inhibit activity in the hippocampus while performing the Wisconsin Card-Sorting Test.68 Furthermore, they showed diminished functional connectivity with...
the prefrontal cortex. Treatment of IGD was associated with decreased connectivity between the amygdala and the middle frontal and precentral gyrus. Impaired functional connectivity between executive control and emotional mechanisms, a characteristic of depression, can be ameliorated in IGD. IGD participants also showed greater functional connectivity of brain areas involved in executive control that are associated with comorbid ADHD and depressive disorder.

**Conclusions**

Studies thus far have shown reward deficiency, reduced impulse control mechanisms, impaired decision making, and impulsivity in IGD. Studies on comorbidity of IGD and ADHD indicate that executive control networks in ADHD may increase the susceptibility to develop IGD. Similarly to depression, IGD can be ameliorated by treating dysfunctional connectivity between emotion and executive control mechanisms. Finally, the neurobiological mechanisms of IGD and excessive use of digital media require further examination, in particular in young children and adolescents since it expands to domains such as media, social communication, and multitasking, with deleterious effects on reading and executive function.

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Original article
Neurobiological mechanisms underlying internet gaming disorder - Weinstein, Lejoyeux

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Original article

Neurobiological mechanisms underlying internet gaming disorder - Weinstein, Lejoyeux


Adolescent brain and the natural allure of digital media

Jay N. Giedd, MD

The growing amount of screen time among adolescents has raised concerns about the effects it may have on their physical and psychological health. Although the literature is divided on whether the effects are mostly positive, neutral, or mostly negative, it is likely that the impacts will be highly individualized with a mixture of good and bad consequences for each person. Understanding behavioral and neurobiological phenomena of adolescence may help to guide research and interventions to optimize the benefits and minimize the risks. Particular aspects of adolescent development relevant to the issue include: (i) hunger for human connectedness; (ii) appetite for adventure; and (iii) desire for data.

Introduction

Digital technologies such as computers, tablets, smartphones, and gaming consoles are having a dramatic impact on the way adolescents learn, play, and interact with each other.1 Time spent with such devices continues to rise around the world. In the United States, teen screen time averages over 7 hours a day, and this is excluding time used for homework.2 This has naturally led to growing concerns about the impact of increasing screen time on the health and well-being of youth.3

Although there is little disagreement on the growing amount of screen time, there is much disagreement regarding the implications.4 Some studies report correlations of screen time with depression, anxiety, sleep disturbance, and poor school performance.5-7 Additional studies report changes in brain anatomy and physiology related to digital media.8,9

However, other studies point out that the variance of negative outcomes attributed to screen time is less than 1% (less than whether or not the student wears glasses) and that it is spurious to scapegoat screen time for increases in social ills that have complex and nuanced origins and influences.10,11 They also note that rigorous data and sophisticated methods of analysis are essential to address the arrow of causality of technology use and negative outcomes (eg, people feeling depressed may seek out more social media use).12 One of the clear implications is that not only the quantity of screen time but also the type and quality of screen time needs to be considered with attention to interactions with age, whether male/female, culture, socioeconomic status, and other variables.

As data continues to be gathered about the specific positive and negative effects of interactions with specific digital technologies for specific individuals in specific contexts, there remains a common refrain that despite some possible benefits there is something about the whole phenomenon that is just plainly and simply not “natural.” The argument is that we did not evolve to be staring at a screen for most of our waking hours. We evolved to be interacting with
each other face to face, using our senses of smell and touch and taste, not just sight and sound. The argument leads to the assertion that it cannot be healthy to stray so far from the activities for which nature has shaped our brains and our bodies. Articles in general readership magazines with titles such as “Have smartphones destroyed a generation?,” catchy acronyms such as FOMO (fear of missing out), and colorful descriptions such as smartphones being “weapons of mass distraction” capture the public’s attention. Negative implications are eagerly embraced by a generation not as facile with the technologies as their children.

In assessing the data, we should be careful to avoid the historically common pitfall of viewing change as inherently dangerous. For example, the following quote—:

…This discovery will create forgetfulness in the learners’ souls, because they will not use their memories; they will trust to the external and not remember of themselves. It is an aid not to memory, but to reminiscence, and will give youth not truth, but only the semblance of truth; they will be hearers of many things and will have learned nothing; they will appear to be omniscient and will generally know nothing; they will be tiresome company, having the show of wisdom without the reality.

is attributed to Socrates (~370 BC), and the dangerous “discovery” he was referring to was reading. Similar generational pronouncements of impending doom, sounding strikingly similar to today’s headlines about smartphones and social media, were heralded with the introductions of radio, television, pulp novels, comic books, music, and fashion preferences of youth throughout the ages. Use of digital technologies joins a long list of human activities that have been initially deemed as unnatural, immoral, and dangerous. From the perspective of an evolutionary time scale, reading—which is only approximately 5000 years old—has been around only slightly longer than smartphones, and neither existed for the vast majority of humanity.

With no intention to dismiss or undermine the many legitimate concerns of negative effects of digital media and other technologies, I challenge the notion that the appeal is not “natural” (ie, in accordance with our nature/biology). The desire for digital media is in fact exquisitely aligned with the biology of the teen brain and our evolutionary heritage.

Three features of adolescence that are particularly relevant to the issue are: (i) hunger for human connectedness; (ii) appetite for adventure; and (iii) desire for data.

**Hunger for human connectedness**

Behavior is driven by desire. The neuroanatomical substrate of desire involves complex interacting circuitry incorporating dozens of brain components including areas of the cortex, basal ganglia, thalamus, cerebellum, ventral striatum, amygdala, and hippocampus. The brain reward system undergoes dramatic changes during adolescence with an ignition of passions driven by hormonally mediated changes in anatomy, neurotransmitter type and distribution, and connections among brain regions.

A remarkable feature of brain reward circuitry is its commonality across a vast range of stimuli. For example, all addictions (eg, behaviors repeated compulsively despite adverse consequences) increase dopamine in a small part of the brain called the nucleus accumbens. The staggering array of conditions that engage our brain reward system are united by the common theme of fulfilling our evolutionary imperatives of survival and reproduction. Obvious triggers include the desire for food, sex, sleep, homeostasis for heat and cold, and safety. However, we are a species that also relies heavily upon social connections for survival. Early in life we rely on members of our group to regulate our basic physiology (ie, allostasis). During the teen years, social connections become vitally salient for our very existence.

The high reward valuation of successfully connecting with others is reflected in numerous functional magnetic resonance imaging (fMRI) studies of the adolescent brain showing large changes from baseline, both for the sorrow of social exclusion and the joy of social acceptance. Brain effects of social exclusion are commonly assessed using a variation of the Cyberball paradigm. In a virtual environ-
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Appetite for adventure

It may seem that we should have evolved to seek nothing more than peace and quiet, comfort, and safety. However, because it is not the mundane and predictable that pose the greatest risks to our survival, our brain reward systems reinforce our efforts to seek out and engage in adventure. Even other primates engage in play that seeks to master the threats that may harm them. It is part of the phenomenon of why the teen years are the peak market for scary carnival rides and frightening movies. That adolescent increases in sensation seeking and risk taking occur not only in humans but in all social mammals is a testament to how deeply rooted in our biology this drive is. In teens, the desire to overcome boredom rivals that of the desire for social acceptance.

The internet, social media, and game technologies provide fantastic outlets for adventures. They offer an arena to explore, express, experiment upon, and refine the puberty-related surges in drives of sex and aggression. It is interesting to note that despite extreme amounts of sex and violence in some games, limited only by human imagination, real-world behaviors in these domains do not seem to be taking a turn for the worse. In fact, teen pregnancies, sexually transmitted diseases, and the number of serious violent crimes committed by youth aged between 12 and 17 years are at historical lows in the United States. Perhaps it is that youth are in their basement playing games and not on the street mugging strangers. However, it may also be the case that adolescents are working through some of the powerful dynamics of emerging sex, aggression, sensation seeking, and risk taking in ways that may be extreme in the virtual world but are not harmful to others in the real world and overall safer than in times of past.

As the winners of an intensely competitive multibillion-dollar industry engaging some of the brightest and creative minds, today’s games are masterful at engaging the brain reward system. The obvious notion is that by continuous improvement of variable reinforcement practices, bolstered by decades of data from Las Vegas, the game developers have optimized the games to be easy enough to win sufficiently often to not give up playing, but difficult enough to maximize the sense of achievement. This is undoubtedly part of the story, but an extensive body of literature involving thousands of subjects has convincingly established that conventional reward reinforcement theory is insufficient to account for the persistence of gaming behavior. One of many aspects of this is a concept termed “gamer identity strength,” the degree to which people define gaming as part of their social identity. It is an essential variable to augment traditional reinforcement theory in predicting and understanding gaming behavior. As alluded to in the preceding section, the desire to belong to a group, to have an identity in common with others, is a fervently compelling drive in adolescence. Being a “gamer” is an increasingly common group by which people share and shape their identity.

Pursuing adventure, developing a sense of mastery, and exploring different identities and values in a virtual environment can be as rewarding to the brain as those achievements in the real world. At the level of brain synapses, the distinction between “virtual” and “real” is not as large as some would expect. In both, the brain receives input in the form of patterns of electrical activity that help it create a model of the world. Virtual wins can be every bit as rewarding to the brain, but the downsides of failure in a virtual world are much more forgiving. Failure is much easier to bear if no one is watching, and being able to start over again and again with the stroke of a key is a luxury rarely afforded in the real world. In a virtual world, we are emboldened to take risks. Teens do not have to inhibit their emotions and rein in their passions. They can have the freedom to alter contingencies and rules (i.e., have controllable agency) to suit their preferences, as opposed to their limited control in the real world. Video games are most appealing and have the greatest impact on emotions when they close the gap between how they are and how they wish to be.
Another relevant behavioral aspect of adolescence is the yearning for immediacy. Neuroanatomically, this is related to the ongoing maturation of the frontal lobes, which are involved in “executive function,” including such things as delaying gratification, controlling attention, inhibiting impulses, and considering longer-term consequences of our choices. Frontal-lobe function is far from absent in adolescents, but it is not as good as it is going to get. Sleep deprivation, sometimes related to screen time, further impairs frontal-lobe inhibitory functions. A strength of digital technologies is the ability to provide immediate results, immediate access to information, and immediate novel stimuli. From an evolutionary standpoint, there is a premium valuation placed on immediate, actionable information. It is often not a matter of eventually finding the best or “right” solution but rather the immediate “right now” solution. The ability to delay gratification generally improves with age, but most teens are more likely to choose sooner, smaller rewards over larger, later rewards.

A concern is that the social interactions occurring during modern gaming is quite different than in the past. Popular board games such as Monopoly were often mere mechanisms to foster face-to-face peer interactions useful for honing social skills. Like the stone in the stone soup fable, the game itself was not the important ingredient, it was the ensuing social interactions that mattered. There is a possibility that with so much immediate gratification available, our motivation for delaying gratification will lessen and youth will fail to learn the discipline necessary to achieve worthwhile goals. However, there is also a possibility that social interactions fostered via the new digital media will be healthy and that with greater access to information and knowledge, and a broader peer group with potentially positive attributes to emulate, today’s youth will far surpass the accomplishments of their parents’ generation. 

**Desire for data**

The brain’s fundamental mission is to assess the environment and initiate behaviors to survive. We are hard-wired to attend to the most relevant data that informs the accuracy of the brain’s internal model of the world. One of our most effective strategies has been to learn survival strategies from imitating the behavior of others. For young children, the modeling of behavior is often learned from parents and older siblings. During adolescence, the modeling often switches from parents to peers. Like increased sensation seeking and risk taking, this phenomenon also occurs in all social mammals. For adolescents, the influence of peers is a dominant factor in shaping values, opinions, and decision making. Throughout most of human history, adolescent peer interaction was with those geographically nearby. Now, the potential pool of adolescent peers to emulate is global, which may have positive or negative social effects, but is a profound departure from the past.

These tendencies to seek new and relevant information would not be enough to fully justify the classification of the allure of digital technologies as natural if it were not for the brain’s yearning to embrace change. Prolonged plasticity and environmentally driven specialization are the key additional neurobiological attributes to make the digital appeal so compelling. It may seem out of place to discuss Neanderthals in a manuscript addressing the impact of digital media on youth of today, but a key difference in the rate of brain development between the species may shed light on the strong attraction human youth have to current technologies. Neanderthal brains were approximately 13% larger than human brains, and Neanderthals were able to survive in quite harsh conditions. However, their tool use changed little over 200,000 years. They were well adapted to a certain climate and environment, but when the climate and environment changed, they were not as flexible as humans in adapting. The less-adaptable Neanderthal brain may be related to their faster maturation. Maturation can be thought of as achieved when developmental changes stop or greatly reduce. Rate of maturation can be inferred from studies of fossilized teeth. Like trees, teeth have growth rings. Less space between growth rings indicates stabilization and has been shown to correlate highly with other measures of maturation. Comparisons of human and Neanderthal tooth fossils suggest that Neanderthals matured more rapidly than humans. If you find the tooth of an 11-year-old Neanderthal in a cave, when you find other teeth in the cave, you are likely to find her children, not her parents. Rapid maturation is not inherently maladaptive. However, it could be detrimental in a situation of rapid environmental change where a premium would be placed on ongoing plasticity—the ability of the brain to change in response to environmental demands.

Brain maturation and ongoing plasticity are fundamentally at odds with each other at a cellular and molecular
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Figure 1. Illustration of naturally alluring features of digital media with adolescent neurobiological changes of steadily increasing white matter (greater connectivity), decreasing gray matter (environmentally driven specialization active through at least the mid 20’s), and puberty-related changes in reward circuitry with intensification of drives.\textsuperscript{42-44}

GABA, \(\gamma\)-aminobutyric acid. Compiled by Jacob B. Giedd. Two images reproduced from ref 44: Lenroot RK, Giedd JN. Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging. \textit{Neurosci Biobehav Rev.} 2006;30(6):718-29. Copyright © 2006 Elsevier. Every effort has been made to trace copyright holders and to obtain their permission for the use of copyright material. The publisher apologizes for any errors or omissions in the above and would be grateful if notified of any corrections that should be incorporated in future online editions of this article.
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level. A key component of childhood and adolescent brain maturation is an increase in connectivity among disparate regions of the brain. This greater connectivity is subserved by myelin, a wrapping around neuronal axons that can increase neural transmission speeds by 100x and reduce recovery time between firings by 30x. The color of myelin is what makes brain white matter white, and white matter increases in the brain throughout childhood and adolescence. Myelination enables remarkable enhancements of physical and cognitive skills, but at a cost—myelin releases molecules that impede arborization of new connections and thus decreases plasticity. Our evolutionary heritage has forged a balance between these forces that has resulted in unusually protracted maturation but equally unusually prolonged plasticity.

Across many species of birds and mammals, there is a positive correlation between the time of dependence upon a parent or caregiver and the size and functionality of the brain. For instance, species of crows that have longer periods of parental care have larger brains and more complicated vocalizations and food-gathering strategies than similarly sized crows with shorter dependency. Humans are the most extreme example of protracted maturation in all of nature. It is one of the most distinctive features of our species. With the adaptability afforded by our protracted maturation, humans can survive in nearly every habitat on earth. Survival skills are quite different in cold versus warm climates, and survival skills have changed dramatically across time as well. Ten thousand years ago, a brief time in evolutionary terms, humans spent much of their time securing food and shelter. Now, in relatively short amounts of time and energy expenditure, we can obtain all of the calories we need for survival. We have more time to feed our brain’s yearning for information and novelty during the highly plastic periods of our adolescent development. It is no wonder that access to the internet, where the world’s knowledge is a click away, is steep competition for attending to the often-mundane matters of parents, family, or even friends. As we seek to optimize our decision-making for the best outcomes, we constantly compare choices leading to a neverending search for “bigger and better options.” The internet allows awareness of a far greater number of options, which may contribute to a feeling that we are missing out or not living an adequate life in comparison with others. It also allows ever greater ability to give our brains what they are seeking and to harness the collective wisdom of our species to live healthier, happier lives.

Summary

Our computer-age attraction to the nearly limitless novelty and socially relevant peer data afforded by modern screen-media technologies is deeply rooted in our stone-age brain.

Like fire, or any powerful tool, technologies can be used, misused, or abused. For many, technologies contribute to health, happiness, productivity, and prosperity. Others are mired in the irony that devices that can connect us to each other more effectively than ever before may lead to increased loneliness; that technologies that put the world’s collective knowledge at our fingertips may lead to increased distractibility and lessened critical thinking; and that the same technologies that can lead to earlier detection and innovative treatments of mental illness may also be related to increased rates of anxiety and depression.

There is little utility in broadly labeling the phenomenon of digital media use as “good” or “bad.” The technological genie is out of the bottle, and it seems unlikely that efforts to put it back would succeed even if we deemed it the desired course of action. Rather, our goal should be to maximize the positive aspects of digital media and technologies and minimize the negative. Toward that end, greater understanding of the adolescent brain may guide interventions and inform hypotheses to be generated and tested in future research projects.

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The impact of digital technology use on adolescent well-being

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This review provides an overview of the literature regarding digital technology use and adolescent well-being. Overall, findings imply that the general effects are on the negative end of the spectrum but very small. Effects differ depending on the type of use: whereas procrastination and passive use are related to more negative effects, social and active use are related to more positive effects. Digital technology use has stronger effects on short-term markers of hedonic well-being (eg, negative affect) than long-term measures of eudaimonic well-being (eg, life satisfaction). Although adolescents are more vulnerable, effects are comparable for both adolescents and adults. It appears that both low and excessive use are related to decreased well-being, whereas moderate use is related to increased well-being. The current research still has many limitations: High-quality studies with large-scale samples, objective measures of digital technology use, and experience sampling of well-being are missing.

Keywords: adolescent; digital technology; life satisfaction; media effect; mental health; smartphone; social media; social networking site; review; well-being

With each new technology come concerns about its potential impact on (young) people’s well-being.1 In recent years, both scholars and the public have voiced concerns about the rise of digital technology, with a focus on smartphones and social media.2 To ascertain whether or not these concerns are justified, this review provides an overview of the literature regarding digital technology use and adolescent well-being.

Digital technology use and well-being are broad and complex concepts. To understand how technology use might affect well-being, we first define and describe both concepts. Furthermore, adolescence is a distinct stage of life. To obtain a better picture of the context in which potential effects unfold, we then examine the psychological development of adolescents. Afterward, we present current empirical findings about the relation between digital technology use and adolescent well-being. Because the empirical evidence is mixed, we then formulate six implications in order to provide some general guidelines, and end with a brief conclusion.

Digital technology use

Digital technology use is an umbrella term that encompasses various devices, services, and types of use. Most adolescent digital technology use nowadays takes place on mobile devices.3,4 Offering the functions and affordances of several other media, smartphones play a pivotal role in adolescent media use and are thus considered a “metamedium.”5 Smartphones and other digital devices can host a vast range of different services. A representative survey of teens in the US showed that the most commonly used digital services are YouTube (85%), closely followed by the social media Instagram (72%), and Snapchat (69%). Notably, there exist...
two different types of social media: social networking sites such as Instagram or TikTok and instant messengers such as WhatsApp or Signal.

All devices and services offer different functionalities and affordances, which result in different types of use. When on social media, adolescents can chat with others, post, like, or share. Such uses are generally considered active. In contrast, adolescents can also engage in passive use, merely lurking and watching the content of others. The binary distinction between active and passive use does not yet address whether behavior is considered as procrastination or goal-directed. For example, chatting with others can be considered procrastination if it means delaying work on a more important task. Observing, but not interacting with others’ content can be considered to be goal-directed if the goal is to stay up to date with the lives of friends. Finally, there is another important distinction between different types of use: whether use is social or nonsocial. Social use captures all kinds of active interpersonal communication, such as chatting and texting, but also liking photos or sharing posts. Nonsocial use includes (specific types of) reading and playing, but also listening to music or watching videos.

When conceptualizing and measuring these different types of digital technology use, there are several challenges. Collapsing all digital behaviors into a single predictor of well-being will inevitably decrease precision, both conceptually and empirically. Conceptually, subsuming all these activities and types of use under one umbrella term fails to acknowledge that they serve different functions and show different effects. Understanding digital technology use as a general behavior neglects the many forms such behavior can take. Therefore, when asking about the impact of digital technology use on adolescent well-being, we need to be aware that digital technology use is not a monolithic concept.

Empirically, a lack of validated measures of technology use adds to this imprecision. Most work relies on self-reports of technology use. Self-reports, however, have been shown to be imprecise and of low validity because they correlate poorly with objective measures of technology use. In the case of smartphones, self-reported duration of use correlated moderately, at best, with objectively logged use. These findings are mirrored when comparing self-reports of general internet use with objectively measured use. Taken together, in addition to losing precision by subsuming all types of technology use under one behavioral category, the measurement of this category contributes to a lack of precision. To gain precision, it is necessary that we look at effects for different types of use, ideally objectively measured.

**Well-being**

Well-being is a subcategory of mental health. Mental health is generally considered to consist of two parts: negative and positive mental health. Negative mental health includes subclinical negative mental health, such as stress or negative affect, and psychopathology, such as depression or schizophrenia. Positive mental health is a synonym for well-being; it comprises hedonic well-being and eudaimonic well-being. Whereas hedonic well-being is affective, focusing on emotions, pleasure, or need satisfaction, eudaimonic well-being is cognitive, addressing meaning, self-esteem, or fulfillment.

Somewhat surprisingly, worldwide mental health problems have not increased in recent decades. Similarly, levels of general life satisfaction remained stable during the last 20 years. Worth noting, the increase in mental health problems that has been reported could merely reflect increased awareness of psychosocial problems. In other words, an increase in diagnoses might not mean an increase in psychopathology.

Which part of mental health is the most likely to be affected by digital technology use? Empirically, eudaimonic well-being, such as life satisfaction, is stable. Although some researchers maintain that 40% of happiness is volatile and therefore malleable, more recent investigations argued that the influences of potentially stabilizing factors such as genes and life circumstances are substantially larger. These results are aligned with the so-called set-point hypothesis, which posits that life satisfaction varies around a fixed level, showing much interpersonal but little intrapersonal variance. The hypothesis has repeatedly found support in empirical studies, which demonstrate the stability of life satisfaction measures. Consequently, digital technology use is not likely to be a strong predictor of eudaimonic well-being. In contrast, hedonic well-being such as positive and negative affect is volatile and subject to substantial fluctuations. Therefore, digital technology use might well be a driver of hedonic well-being: Watching entertaining content...
Adolescents

Adolescence is defined as “the time between puberty and adult independence,” during which adolescents actively develop their personalities. Compared with adults, adolescents are more open-minded, more social-oriented, less agreeable, and less conscientious; more impulsive and less capable of inhibiting behavior; more risk-taking and sensation seeking; and derive larger parts of their well-being and life satisfaction from other peers. During adolescence, general levels of self-esteem and self-esteem drop and are often at their all-time lowest. At the same time, media use increases and reaches a first peak in late adolescence. Analyzing the development of several well-being-related variables across the last two decades, the answers of 46 817 European adolescents and young adults show that, whereas overall internet use has risen strongly, both life satisfaction and health problems remained stable. Hence, although adolescence is a critical life stage with substantial intraper-sonal fluctuations related to well-being, the current generation does not seem to do better or worse than those before.

Does adolescent development make them particularly susceptible to the influence of digital technology? Several scholars argue that combining the naturally occurring trends of low self-esteem, a spike in technology use, and higher suggestibility into a causal narrative can take the form of a foregone conclusion. For one, although adolescents are in a phase of development, there might be more similarities between adolescents and adults than differences. Concerns about the effects of a new technology on an allegedly vulnerable group has historically often taken the form of paternalization. For example, and maybe in contrast to popular opinion, adolescents already possess much media literacy or privacy literacy.

This has two implications. First, asking what technology does to adolescents ascribes an unduly passive role to adolescents, putting them in the place of simply responding to technology stimuli. Recent theoretical developments challenge such a one-directional perspective and advise to rather ask what adolescents do with digital technology, including their type of use. Second, in order to understand the effects of digital technology use on well-being, it might not be necessary to focus on adolescents. It is likely that similar effects can be found for both adolescents and adults. True, in light of the generally decreased life satisfaction and the generally increased suggestibility, results might be more pronounced for adolescents; however, it seems implausible that they are fundamentally different. When assessing how technology might affect adolescents compared with adults, we can think of adolescents as “canaries in the coalmine.”

If digital technology is indeed harmful, it will affect people from all ages, but adolescents are potentially more vulnerable.

Effects

What is the effect of digital technology use on well-being? If we ask US adolescents directly, 31% are of the opinion that the effects are mostly positive, 45% estimate the effects to be neither positive nor negative, and 24% believe that effects are mostly negative. Teens who considered the effects to be positive stated that social media help (i) connect with friends; (ii) obtain information; and (c) find like-minded people. Those who considered the effects to be negative explained that social media increase the risks of (i) bullying; (ii) neglecting face-to-face contacts; (iii) obtaining unrealistic impressions of other people’s lives.

Myriad studies lend empirical support to adolescents’ mixed feelings, reporting a wide range of positive, neutral, or negative relations between specific measures of digital technology use and well-being. Aligned with these mixed results of individual studies, several meta-analyses support the lack of a clear effect. In an analysis of 43 studies on the effects of online technology use on adolescent mental well-being, Best et al found that “[t]he majority of studies reported either mixed or no effect(s) of online social technologies on adolescent wellbeing.” Analyzing eleven studies on the relation between social media use and depressive symptoms, McCrae et al report a small positive relationship. Similarly, Lissak reports positive relations between excessive screen time and insufficient sleep, physiological stress, mind wandering, attention deficit-hyperactivity disorder...
(ADHD)-related behavior, nonadaptive/negative thinking styles, decreased life satisfaction, and potential health risks in adulthood. On the basis of 12 articles, Wu et al. find that “the use of [internet] technology leads to an increased sense of connectedness to friend[s] and school, while at the same time increasing levels of anxiety and loneliness among adolescents.” Relatedly, meta-analyses on the relation between social media use and adolescent academic performance find no or negligible effects.47

It is important to note that the overall quality of the literature these meta-analyses rely upon has been criticized.48 This is problematic because low quality of individual studies biases meta-analyses.49 To achieve higher quality, scholars have called for more large-scale studies using longitudinal designs, objective measures of digital technology use that differentiate types of use, experience sampling measures of well-being (ie, in-the-moment measures of well-being; also known as ambulant assessment or in situ assessment), and a statistical separation of between-person variance and within-person variance.50 In addition, much research cannot be reproduced because the data and the analysis scripts are not shared.51 In what follows, we look at studies that implemented some of these suggestions.

Longitudinal studies generally find a complex pattern of effects. In an 8 year study of 500 adolescents in the US, time spent on social media was positively related to anxiety and depression on the between-person level.52 At the within-person level, these relationships disappeared. The study concludes that those who use social media more often might also be those with lower mental health; however, there does not seem to be a causal link between the two. A study on 1157 Croatians in late adolescence supports these findings. Over a period of 3 years, changes in social media use and life satisfaction were unrelated, speaking to the stability of life satisfaction.53 In a sample of 1749 Australian adolescents, Houghton et al.54 distinguished between screen activities (eg, web browsing or gaming) and found overall low within-person relations between total screen time and depressive symptoms. Out of all activities, only web surfing was a significant within-person predictor of depressive symptoms. However, the authors argue that this effect might not survive corrections for multiple testing. Combining a longitudinal design with experience sampling in a sample of 388 US adolescents, Jensen et al.55 did not find a between-person association between baseline technology use and mental health. Interestingly, they only observed few and small within-person effects. Heffer et al.56 found no relation between screen use and depressive symptoms in 594 Canadian adolescents over 2 years. These results emphasize the growing need for more robust and transparent methods and analysis. In large adolescent samples from the UK and the US, a specification curve analysis, which provides an overview of many different plausible analyses, found small, negligible relations between screen use and well-being, both cross-sectionally and longitudinally.57 Employing a similar analytical approach, Orben, Dienlin, and Przybylski58 found small negative between-person relations between social media use and life satisfaction in a large UK sample of adolescents over 7 years. However, there was no robust within-person effect. Similarly, negligible effect sizes between adolescent screen use and well-being are found in cross-sectional data sets representative of the population in the UK and US.59 In analyzing the potential effects of social media abstinence on well-being, two large-scale studies using adult samples found small positive effects of abstinence on well-being.60 Two studies with smaller and mostly student samples instead found mixed61 or no effects of abstinence on well-being.62

The aforementioned studies often relied on composite measures of screen use, possibly explaining the overall small effects. In contrast, work distinguishing between different types of use shows that active use likely has different effects than passive use. Specifically, active use may contribute to making meaningful social connections, whereas passive use does not.9 For example, meaningful social interactions have been shown to increase social gratification in adults,63,64 whereas passive media use or media use as procrastination has been negatively related to well-being.65 This distinction should also apply to adolescents.66 The first evidence for this proposition already exists. In a large sample of Icelandic adolescents, passive social media use was positively related to anxiety and depressive symptoms; the opposite was the case for active use.65
Furthermore, longitudinal work so far relies on self-reports of media use. Self-reported media use has been shown to be inaccurate compared with objectively measured use. Unfortunately, there is little work employing objective measures to test whether the results of longitudinal studies using self-reports hold up when objective use is examined. The limited existing evidence suggests that effects remain small. In a convenience sample of adults, only phone use at night negatively predicted well-being. Another study that combined objective measures of social smartphone applications with experience sampling in young adults found a weak negative relation between objective use and well-being.

Effects might also not be linear. Whereas both low and high levels of internet use have been shown to be associated with slightly decreased life satisfaction, moderate use has been shown to be related to slightly increased life satisfaction. However, evidence for this position is mixed; other empirical studies did not find this pattern of effects.

Taken together, do the positive or the negative effects prevail? The literature implies that the relationship between technology use and adolescent well-being is more complicated than an overall negative linear effect. In line with meta-analyses on adults, effects of digital technology use in general are mostly neutral to small. In their meta-review of 34 meta-analyses and systematic reviews, Meier and Reinecke summarize that “[f]indings suggest an overall (very) small negative association between using SNS [social networking sites], the most researched CMC [computer mediated communication] application, and mental health.” In conclusion, the current literature is mostly ambivalent, although slightly emphasizing the negative effects of digital technology use.

**Implications**

Although there are several conflicting positions and research findings, some general implications emerge:

1. The general effects of digital technology use on well-being are likely in the negative spectrum, but very small—potentially too small to matter.
2. No screen time is created equal; different uses will lead to different effects.
3. Digital technology use is more likely to affect short-term positive or negative affect than long-term life satisfaction.
4. The dose makes the poison; it appears that both low and excessive use are related to decreased well-being, whereas moderate use is related to increased well-being.
5. Adolescents are likely more vulnerable to effects of digital technology use on well-being, but it is important not to patronize adolescents—effects are comparable and adolescents not powerless.
6. The current empirical research has several limitations: high-quality studies with large-scale samples, objective measures of digital technology use, and experience sampling of well-being are still missing.

**Conclusion**

Despite almost 30 years of research on digital technology, there is still no coherent empirical evidence as to whether digital technology hampers or fosters well-being. Most likely, general effects are small at best and probably in the negative spectrum. As soon as we take other factors into account, this conclusion does not hold up. Active use that aims to establish meaningful social connections can have positive effects. Passive use likely has negative effects. Both might follow a nonlinear trend. However, research showing causal effects of general digital technology use on well-being is scarce. In light of these limitations, several scholars argue that technology use has a mediating role; already existing problems increase maladapted technology use, which then decreases life satisfaction. Extreme digital technology use is more likely to be a symptom of an underlying sociopsychological problem than vice versa. In sum, when assessing the effects of technology use on adolescent well-being, one of the best answers is that it’s complicated.

This lack of evidence is not surprising, because there is no consensus on central definitions, measures, and methods. Specifically, digital technology use is an umbrella term that encompasses many different behaviors. Furthermore, it is theoretically unclear as to why adolescents in particular should be susceptible to the effects of technology and what forms of well-being are candidates for effects. At the same time, little research adopts longitudinal designs, differentiates different types of technology use, or measures technology use objectively. Much work in the field has also been criticized for a lack of transparency and rigor. Last, research (including this review) is strongly biased toward a Western perspective. In other cultures, adolescents use markedly different services (such as WeChat or Renren).
etc). Although we assume most effects to be comparable, problems seem to differ somewhat. For example, online gaming addiction is more prevalent in Asian than Western cultures.29

Adults have always criticized the younger generation, and media (novels, rock music, comic books, or computer games) have often been one of the culprits.1 Media panics are cyclical, and we should refrain from simply blaming the unknown and the novel.1 In view of the public debate, we should rather emphasize that digital technology is not good or bad per se. Digital technology does not “happen” to individuals. Individuals, instead, actively use technology, often with much competence.3 The current evidence suggests that typical digital technology use will not harm a typical adolescent. That is not to say there are no individual cases and scenarios in which effects might be negative and large. Let’s be wary, but not alarmist. ■

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Adolescent development and growing divides in the digital age
Candice L. Odgers, PhD; Michaeline R. Jensen, PhD

Adolescents are constantly connected to their devices, and concerns have been raised that this connectivity is damaging their development more generally, and their mental health in particular. Recent narrative reviews and meta-analyses do not support a strong linkage between the quantity of adolescents’ digital technology engagement and mental health problems. Instead, it appears that offline vulnerabilities tend to mirror and shape online risks in ways that may further amplify mental health inequalities among youth. New approaches for supporting youth mental health, especially for vulnerable youth and those typically excluded from traditional services, are now both possible and required.

Keywords: adolescent mental health; developmental science; digital mental health; digital technology; inequality; social media

Adolescents today are the most digitally connected generation in history. However, fears about potential harm that might arise from this constant connection to devices and social media abound among educators, mental health professionals, and parents. These worries are fueled by media reports that equate the attractiveness of social media to drug addiction, claiming that it is deteriorating young minds and disconnecting children from the “real” world. This narrative around social media and smartphones is alarming, but science and streaming data from young people’s devices paint a different picture.

This article highlights key study results on the linkages between new digital technologies and adolescents’ social relationships and mental health, using, in some cases, information collected directly from adolescents’ mobile phones. These findings are presented alongside a brief synthesis of what we know about the links between smartphone, social-media use, and adolescent mental health to date. Insights from diverse types of studies and populations are integrated to surface areas of concern, as well as opportunities for supporting adolescents’ mental health in the digital age.

A key take-home message stemming from recent reviews related to this topic is that there are significant limitations and foundational flaws in the existing knowledge base. Nonetheless, as detailed below, key insights regarding both the risks and opportunities faced by contemporary youth are emerging, and urgent action is required by researchers, educators, policy-makers, and others invested in supporting healthy development in the digital age. After synthesizing what is known about the links between social media, smartphone usage, and adolescents’ mental health, this article explores future risks and opportunities for research and intervention.

What do we know about the links between adolescents’ mental health and their smartphone and social media usage?

Adolescents in many places around the world now spend more time on their digital devices than they do in traditional classrooms. For example, in the United States, teens spend, on average, nearly 7.5 hours each day with digital enter-
Recent years have seen concerns that this continuous connectivity is harmful to multiple aspects of youth’s psychosocial well-being, with an intense focus on the potential linkage between both screen time and social media usage and increasing rates of depression among adolescent girls.²³ Fears related to links between social-media usage and depression (and related problems) have received widespread public attention and resulted in differing perspectives on whether social media is to blame or, alternatively, could be used to respond to increasing levels of anxiety and depression that have been observed among some populations of youth. There are trustworthy data and disturbing trends pointing to the need to be concerned about increasing internalizing problems among adolescents, particularly young female adolescents.⁵ Emotional problems have been increasing since the 1980s among young people across a number of countries, including China, Greece, Germany, Iceland, New Zealand, Norway, and Sweden.⁶ In the United States, studies likewise reveal rapid increases in adolescent depressive symptoms⁷ and suicidal behavior.⁸⁹ Deaths by suicide have increased across all age ranges, but the data are particularly troubling among adolescent girls, where suicide rates have tripled among 10- to 14-year-old girls from 1999 through 2017.¹⁰

Due to the fact that engagement with digital technologies has also increased rapidly during this period, many have asked whether screen time, and social media more specifically, is to blame for rising rates of mental health problems. For psychologists and those treating adolescents suffering from serious mental health problems, it would actually be helpful if smartphones and social media were found to be responsible for a significant share of this increase. If that were the case, then there would be an identifiable and malleable target for intervention. Mobile phones could be turned off and social media restricted to help youth who are struggling. But, as many who have studied complex mental health problems and diseases know, it is rare to identify this type of silver-bullet treatment or high-value target for intervention. Simply put, the causal story is never that straightforward. Thus, it should not be surprising to learn that although there is still significant research to be completed, claims that social media and smartphone use are driving increases in serious mental health problems such as depression and suicide have not been widely supported (see recent reviews in refs 11-18).

Two large-scale reviews in this area were completed earlier this year, and both converged on similar conclusions regarding the connection between adolescents’ digital technology use and well-being.¹⁶,¹⁷ In the first review,¹⁶ we synthesized over 50 studies examining adolescent mental health and observed associations across studies that were uniformly small, almost always correlational and confounded by third factors, and characterized by a mix of positive, negative, and null associations. Perhaps most troubling was the fact that almost none of the studies reviewed relied on research designs that facilitated causal inference (eg, experimental or quasi-experimental design) or allowed for conclusions regarding directionality. That is, when associations were found, it was equally likely that depressive symptoms or mental health problems were driving digital technology usage and, as a result, there was no opportunity to test these competing hypotheses.

Correlations between digital technology usage and mental health from these studies tended to be small in size, regardless of the direction. For example, social media and screen time measures typically accounted for less than 1% of the variation in the mental health measures (note these estimates were typically cross-sectional and confounded by unmeasured third factors and bias introduced by relying on a sole informant for both the predictor and the outcome). When interpreting these findings, there has been much discussion regarding “how big” an effect size needs to be in order to have clinically significant implications, with many raising the point that even tiny effect sizes can generate large and important effects when scaled to the population level and/or when the outcomes are costly (eg, suicide or depression). This is an excellent point; however, it is difficult to apply this logic to the present data as the vast majority of findings represent cross-sectional correlations versus properly

Offline vulnerabilities tend to mirror online vulnerabilities

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estimated effect sizes. Moreover, in studies where adolescents’ digital technology use and mental health are tracked longitudinally, very few associations between smartphone/social media use and mental health symptoms are found, with one of the most recent longitudinal studies of sixth- to eighth-grade students (n=600) and undergraduate students (n=1100) tracked over 2 years finding no longitudinal associations between social media use and depressive symptoms, and for females only, depressive symptoms at time 1 predicted later social media use, but earlier social media use did not predict later depressive symptoms.

In the second large-scale review that included studies focusing on a wide range of well-being outcomes and methodologies, Orben also concluded that the majority of study designs did not enable researchers to determine whether adolescents’ technology use drove mental health problems, or vice versa. When associations between digital technology use and well-being indicators were found, estimated associations were small in size and measured imprecisely. The lack of methodological rigor across studies, combined with the almost sole reliance on screen time metrics made it difficult, if not impossible in most cases, to speculate as to whether technology use was a cause, effect, or nonfactor in young people’s mental health issues. A strong case was made for raising standards with respect to the design of future research; transparency in registering, analyzing, and reporting findings; and a need for future work to focus on the role of individual differences in estimating potential impacts of digital technologies on young people’s well-being and development.

To summarize, a number of common themes emerged across these recent reviews (and the hundreds of studies that they were based on). First, there is a large mismatch between the data and bold claims that have been made of harm to mental

Box 1. Supporting youth in an increasingly digital, unequal, and uncertain age.

PARENTS AND CAREGIVERS

• Focus less on how much time youth are spending online and more on how youth are spending their time online.
• Join youth in their online spaces when you can and use this time to learn what draws them into and interests them in online spaces.
• If your child is struggling offline with anxiety, difficulties with peers, sleeping, or school, pay closer attention to how and when they are using online spaces and networks because offline risk often predicts online risk. Ask: Are they online searching for support? Seeking out negative content? Avoiding offline interactions and responsibilities? Spending time with peers and in communities that support them?

EDUCATORS AND DESIGNERS

• Design with and for youth. Young people are often left out of the design and creation of online spaces, especially those targeting mental health, yet they are one of the highest-need and most-likely-to-engage populations.
• Take steps to minimize the digital divide—not only with device access but also with respect to the supports, protections, and scaffolding that is provided to all young people, especially to young adolescents who are just entering into social-media platforms and learning how to navigate these spaces.

ADOLESCENTS

• Don’t believe everything you read about your generation! Smartphones and social media are not like addictive drugs. Rather, they are tools you use to navigate your daily life with family, school, and friends and, especially now, are one of the main ways you stay connected with your offline networks and those you care about.
• Pay attention to why you are going online and what you are getting out of these experiences. Positive online interactions allow you to connect, create, and contribute to your online and offline communities.
• Avoid negative online interactions, which—similar to negative offline interactions—may increase stress and negative affect. Work to maximize positive experiences and minimize negative ones, and support your peers in doing the same.
• Know that there are places online that you can go to for support in times of crisis, including Youth Crisis Text Lines, and to develop strategies for managing anxiety, stress, and other problems when they arise (eg, apps like Headspace and those reviewed by Cyberguide).

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health and well-being resulting from social media and smartphone use. That is, findings have been mixed and associations small and typically confounded, with the most rigorous studies detailing very small to null associations. Nonetheless, fears about the negative impacts of smartphones and social-media use on adolescent well-being remain high. Second, there is a clear need to move beyond screen-time metrics and to raise the quality and rigor of research designs in ways that allow for the estimation of causal impacts and, more generally, invest in research that is positioned to address not just whether but how and for whom social media and smartphone use relates to well-being.

Moving from the population of adolescents to an N of 1

One of the key challenges in determining whether time spent online or certain types of social media are related to adolescents’ mental health and behavior is that digital technology has become almost universal; interpretations of comparisons between youth who are “heavy” versus “more infrequent” users of digital technology are threatened by the fact that a young person who spends 1 hour online per day is very different, across a host of dimensions, from his or her peer spending 6 or more hours online each day. Similarly, two young people spending an equivalent amount of time online each day may differ dramatically in the types of experiences they are having and, importantly, with respect to the vulnerabilities and strengths they bring into their digital environments.

To address some of these limitations, our research team has been intensively following adolescents on their mobile devices across multiple days, which enables us to use each adolescent as her or his own control when making comparisons between time spent on screens, the types of activities that young people are engaging in online, and their daily reports of mental health symptoms and related behaviors. Our most recent study began with a population-representative sample of over 2000 youth attending public schools in a large southeastern state of the United States and then tracking close to 400 youth, 11 to 15 years of age, on their smartphones each day over 14 days. We collected reports of mental health symptoms from the adolescents three times a day, and they also reported on their daily technology usage each night, including multiple types of technology use (texts sent; time spent on technology for school work, communication, entertainment, creating content, and total screen time) and a wide range of mental health symptoms (conduct problems, inattention/hyperactivity, depression, and worry).

After monitoring young adolescents daily, we found little evidence to support the claims that time spent online (for specific types of activities listed above that were measured in this study) is associated with increased risk for mental-health problems.19 Because we had both cross-sectional and daily data, we asked two types of questions. First, we asked whether adolescents who generally spent more time on their devices were also more likely to experience mental health problems. Second, we asked whether those days on which adolescents spent more time using digital technology (for various purposes) were also days when they reported more mental health symptoms (here using each adolescent as their own control). In both cases, more digital technology use was not related to worse mental health. Instead, in the few instances when significant associations did emerge, they were small and in the opposite direction than would have been expected (given widespread concerns about potential damaging effects of digital technology use). For instance, those teens who were heavier texters over the study period actually reported less depression than teens who texted less frequently. Looking over longer stretches of time, we found very few robust associations between adolescents’ mobile-phone ownership or the frequency of their social-media use and their mental health over a 2-year period, especially after we accounted for existing mental health problems and offline risks.

In line with these findings, Orben and colleagues analyzed repeated within-person assessments from the UK Household Longitudinal study (10- to-15-year-old adolescents; N=12 672) and tested for associations between digital-technology use and life satisfaction over time.20 Their specification-curve analysis yielded inconsistent estimates across models that varied considerably depending on which factors were entered into the model. The authors concluded that (at the population level) social media use was not strongly or robustly linked to adolescents’ life satisfaction and that, over time, results were likely to be small, bidirectional, and largely dependent on the analytic approach taken (although more consistent associations were observed among adolescent females).

Looking across recent reviews and studies that have intensively monitored young adolescents on their phones, we see
little evidence of a strong or robust connection between time spent online and adolescents’ mental health and well-being. This raises the question of why there has been such a rush to judgment with respect to the negative impacts of smartphones and social media among adolescents. A commonly cited reason for these fears is the fact that each successive generation seems to find fault in how the youth that comprise the next one are spending their time.22 Or perhaps it is simply easier to blame smartphones and social media for problems youth are facing than to address the complex and deeply rooted causes of mental health disorders that psychiatry and psychology worked so long to understand and treat.23 But, it is also possible that the instincts and occasional signals observed by those sounding the alarms about the negative impacts of digital technologies are indeed true but have not yet been reliably detected because we lack the types of research designs, measures, and investments that would allow for more definitive conclusions. Future research is required to fully answer many of these questions. But, in the meantime, we have decades of data and a robust developmental science of what young people need to support healthy development more generally that can be applied to understand adolescent development in the digital age. That is, many of the same factors that we know impede or promote positive relationships and social and emotional development through this transition can be applied to understand and respond to risks and opportunities in the digital age.

What do we know about risks and opportunities for adolescent psychosocial development in the digital age?

One of the most consistent findings across multiple research teams and diverse samples is that offline vulnerabilities tend to mirror online vulnerabilities.24 In other words, much of what young people bring with them to digital interactions reflects broader assets and risks present in their communities, families, and schools, and can help to explain whether they have positive or negative experiences online. Therefore, these factors can help us to understand how adolescents are best supported online, which young people may be most at risk, and how to work with youth to build the capacity for safely navigating online spaces. For example, we and others have found that low-income teens in the United States spend, on average, about 3 hours more each day engaging with screens than their peers from more affluent families,25 and their online activities tend to be less directed at educational content and more reflective of passive media consumption.26 Supports available for navigating online spaces also differ markedly by family resources and income. For example, spanning a set of studies conducted across multiple European countries, a higher percentage (73%) of children growing up in wealthier homes have parents who are engaging in two or more forms of active mediation of internet as compared with 64% of their peers living in low-income households.27 Adolescents from low-income homes in our research are also more likely to report more negative spillovers from social media into their offline lives (eg, physical fights, problems at school) than their peers from more affluent families.28 The overlap between offline and online risks is consistent with a growing body of research on online bullying and harassment, whereby youth who are bullied offline29 and with a previous history of victimization30 are more likely to be bullied online. Likewise, offline risk factors and behaviors, including the absence of strong and supportive offline relationships and patterns of self-disclosure online, are strong predictors of whether youth are solicited online (see review in ref 24). Finally, adolescents already struggling with offline mental health problems tend to seek out more depressive or negative content and tend to spend more time “lurking” versus actively engaging with others in online spaces,31 and those who report elevated psychological distress in their offline lives are also more likely to report distressing aspects in their digital technology usage.32,34

Similar to how risks and opportunities are stratified in the offline world, it is becoming clear that young people are increasingly segregated within their online access, opportunities, and experiences. Traditionally, the “digital divide” has referred to the gap between lower- and higher-income individuals with respect to device ownership and connectivity. This is still a concern for many young people around the world and has been one of the key issues identified, as educational systems, from pre-K to university, have been forced to move classes and educational instruction online due to the COVID-19 crisis. However, we are also seeing the emergence of a new type of digital divide whereby the most vulnerable youth have the most to gain if afforded access to resources and support online, but are the least supported in their entry into online spaces, tailoring digital tools for their needs, and accessing supportive communities and networks. Most data support a “rich-get-richer” pattern
Can digital technologies be leveraged to reach vulnerable youth and provide new opportunities to support and connect young people?

Many young people turn to the internet for information and support related to their mental health. A large US study suggests that the vast majority (87%) of adolescents have gone online to seek information about mental health, while most (64%) have used a mental health app. Social media is also endorsed by young people as a source of mental health advice, especially for adolescents already struggling with moderate to severe depressive symptoms who, in one study, were more likely than their nondepressed peers to report using social media to access emotional support.

Given that the majority of youth in high-income countries are online, that youth are naturally turning to online spaces for information and support, and that the internet has become a primary mode of communication, it seems that online platforms could be effectively mobilized to support youth mental health and respond in times of crisis. Worldwide, rates of access to internet and mobile phones vary considerably (with dramatic differences not just between high- and low-income countries but even among high-income countries). Access to mobile devices capable of connecting youth to these services in high-income countries, although not universal or ideally networked for many youths, has increased markedly over the last decade. A study across seven European countries of youth aged 9 and 16 found that 80% of youth owned either a mobile phone or smartphone, and in the US, practically all adolescents (95%) own at least one mobile device.

The hope is that digital technologies will connect youth (either informally or formally) to networks of support and expertise to understand and manage their mental health needs and, ideally, reach youth who would otherwise never access traditional mental health services. Digital tools offer great potential for reducing disparities in access to treatment and scaling evidence-based interventions. There are already a number of excellent examples of impactful programs, including Youth Crisis Line, and various online community referral and support systems (eg, 7 Cups; https://www.7cups.com). Indeed, there have been a number of efforts to leverage new technologies to support wellness more broadly and extend clinical treatments more specifically. Unfortunately, many of the platforms and services that exist have not been designed with adolescents in mind. Rather, most wellness and mental health apps have been designed for adults or for use with young children.

More generally, adolescents, despite their high mental health needs and rates of connectivity, have been neglected in both ambulatory assessment research and the tailoring of digital platforms and apps in the mental health space. A spotlight is often shone on potential problems with adolescents and digital technologies, but there is much less focus on proposed solutions or innovative uses of technology to address mental health issues among adolescents, with some notable exceptions. Moving forward, it is critical that adolescents are included in plans to extend mental health services and support digitally, especially during the current economic and health crisis, where mental health problems are expected to rise, especially among youth who are often the most vulnerable and who now find themselves physically removed from familiar settings and peer and support networks.

Conclusion

The current year, 2020, has already brought difficult global challenges that will define this generation of young people—almost overnight schools, peer networks, workplaces, and communities have been pushed online. This means that there is currently an urgent need to adopt health practices and create digital spaces for young people that support developmental needs and mitigate risks. Screen time is set to increase even more among adolescents, and consistent with main take-home messages from the review of the literature to date, parents, educators, and clinicians should be concerned less with how much time young people are spending online and more with how they are spending their time online. Previous fears about screen time and mental health are not supported by the science. While most attention has been paid to fears, we have missed opportunities to innovate and support youth in online spaces. Now, more
than ever, there is an urgent need to innovate to support young people through this crisis as physical and social distancing disrupts opportunities and supports traditionally available in the daily lives of young people, while adding increased stress and uncertainty, especially to those already vulnerable. Ideally, necessity will foster innovation and help to remove current barriers to reaching and supporting youth both in and outside of online spaces.

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Media coverage of research on phones and social media over the last decade has prompted widespread concern and one-size-fits-all guidance to limit screen time. Recognizing the limitations of screen time as a metric, researchers are now studying technology use in terms of affordances, individual differences, and longitudinal patterns. The current review examines technology use by parents, caregivers, couples, and clinicians. Individuals in these roles navigate risks, such as privacy violations, with benefits such as improved communication, empathy, and progress toward shared goals. Successful approaches vary by relationship type but have commonalities such as engaging with the technologies used by the other person to open up sensitive conversations, negotiate conflict, and illuminate patterns that would otherwise be hard to detect.

To enhance relationships, some individuals depart from the intended use of technologies, for example, adapting connected devices for emotional communication or drawing on games to cope with social anxiety. One promising way in which individuals adapt technology to improve communication involves sharing technologies that were designed for personal use. This review highlights the importance of context, motivation, and the nuances of use to understand how technologies can be optimally used in personal and clinical relationships.

Advice for screen-time limits and digital minimalism have flooded the popular press over the last decade. Because they act as portals to social media, games, and other technologies, phones are argued to distract individuals from close relationships. Massachusetts Institute of Technology (MIT) professor Sherry Turkle, who for decades has studied complex psychological dynamics with technology, expressed caution as her attention turned to phones. In *Alone Together* and *Reclaiming Conversation*, Turkle points to ways in which texting and other digital communications offer escapes from difficult conversations and threaten empathic abilities.\(^1\)\(^2\) Supporting this concern are findings that people commonly feel ignored as a result of household members’ phone use\(^3\)\(^4\) and that the mere visibility of a phone impairs interpersonal connection.\(^5\) Jean Twenge’s *Atlantic* article, “Have Phones Destroyed a Generation?”,\(^6\) which associates screen time with loneliness and depressive symptoms among teens, shifted the public conversation from concern to alarm.

Research is shifting away from sweeping questions about the psychological effects of screens to more specific inqui-
Connecting during COVID-19 and beyond

When I wrote this article, I was pushing against widely held concerns that screens deteriorated relationships and well-being. I asserted that we could not boil diverse experiences with technology into a single metric of screen time or discuss the effects of technologies as if we passively absorbed them. We shape our experiences with technologies, adapting them as we pursue relational and personal goals.

Since the onset of physical distancing due to COVID-19, the public conversation about technology has changed. "Coronavirus Ended the Screen-Time Debate. Screens Won," cheered a New York Times headline in March. Celebratory news coverage of live-streamed concerts, Minecraft graduations, and Animal Crossing weddings replaced dire warnings to limit screen time. There was hope that we could get through the pandemic by coming together virtually.

But as stay-at-home orders have extended and it becomes clear that we will not be returning to life as we knew it, the ebullience about technology has dimmed. Concerns have risen about security in videoconferencing, irreversible privacy concessions in contact tracing, and socioeconomic disparities in technology access. There is, to say the least, Zoom fatigue. To meaningfully connect, we will need to do more than show up online. Now, more than ever, it's important to use technology intentionally.

Five directions to build on as we connect during and after the pandemic:

1. Being with each other. Staring at coworkers' faces, up close, for hours on end, is **exhausting**. Adults working from home could take a cue from kids. One mom described her 7-year-old’s online playdates as a form of show and tell: All they do is share their toys and newly discovered virtual backgrounds. Looking at something together can be more engaging than looking at each other. Videochat can also be dialed down for a low fidelity co-presence. With the shift to online classes and increased individual work during the pandemic, some university students leave video calls on for hours at a time to help each other stay on task. They don't talk much and rarely look at the video feed, but the lightweight persistent connection holds them accountable to each other.

2. Seeing more of each other. Colleagues who formerly interacted in an office are now virtually in each others' homes and drawing on contextual cues to forge deeper connections. One director's impressions of her hard-working teammates are reinforced: color-coordinated pillows appear behind her fastidious assistant, while a no-nonsense higher up reveals his basement surroundings and even the cardboard box supporting his laptop. Others find colleagues more relatable as they catch glimpses of children, pets, and living spaces. Not everyone wants to reveal themselves or their homes, however, and sensitivity to the cultural and individual factors underlying these boundaries is critical. The revealing of personal space is especially salient in therapy, which traditionally required meeting in person. Trained to listen within the boundaries of a session, some therapists feel invasive and personally uncomfortable peering into patients' domestic lives. One therapist I interviewed felt ambushed when she saw her video therapy client, a man in his thirties, in his kitchen wearing a "onesie." Along with awkward revelations, there are rich cues in patients’ homes that therapists can draw on to deepen their understanding of that person's struggles. Similarly, when a patient comments on something in a therapist's home, it is an opportunity to open the conversation and deepen rapport.

3. Drawing boundaries. As we open up our homes on videoconferencing, work encroaches into home life. We are more exposed. Deliberate impression management tactics and accidental behavioral residue are both on display. Transitional spaces evaporate. There is no true equivalent of a hallway conversation or a morning commute. As spatial divisions blur, boundaries of time become more important. Some business professionals are trying out the "50-min hour" and strictly ending calls at the end of the day.

4. Matching helpers with people in need. The closing of clinical offices and the rise in mental health needs during the pandemic have fueled innovation to disrupt what is often a frustrating and drawn-out process of finding a therapist. Demand for existing teletherapy services such as Talkspace has increased, and several grassroots efforts, including NYC COVID Care Network and Project Parachute, have cropped up to match volunteer therapists with essential workers and frontline medical workers. Berkeley Mutual Aid matches older adults and others in need with a volunteer "buddy" for the duration of the pandemic rather than dispatching a random volunteer to drop off groceries on a given day. I suspect that this relational model to developing matching criteria, which grapples with complex psychological, social, and economic factors along with more pragmatic ones such as location and availability, will be critical as we think about the future of mental health care.

5. Intergenerational participation. The shift to video gatherings has both opened and closed doors to participation. One 50-year-old woman led a Passover Seder for the first time, hosting her extended family and friends over video in a way that would not have been possible in her compact New York City apartment. Not knowing the prayers as well as some family members was no longer a barrier as she could cut and paste from the Haggadahs she found online into a sharable file. But video gatherings are less accessible to many older adults and school-age children. One friend has a strategy for giving everyone a voice. Before video calls with her extended family, she invites her daughters to get online with their grandmother. The girls hold up stuffed animals, puppet-style, and their grandmother pretends to chat with the toys. The grandmother and granddaughters love this warm-up to the main call, where they may not have a chance to engage as much as others. A father takes similar effort to enable his daughter's online piano lesson, sitting beside her the entire time streaming video to the teacher (Figure 1). Without the right devices, internet bandwidth, and human support, vulnerable populations face risks of disconnection.

As we cope with the pandemic over time, we will learn more about what enhances connection in different situations and cultural contexts. We should never insist that someone turn on video or engage in a shared online activity. And setting limits on availability may require trial and error. One person's boundary may be another person's trigger, as the song goes. Matching services designed to increase access to care will not meet everyone's needs and run the risk of commoditizing therapy. Most importantly, inclusivity goes beyond age considerations. Meaningful interventions need to address the socioeconomic disparities that determine access to technology and health care.
ries. Instead of examining screen time, which collapses all technology use into a single metric, researchers are studying differences associated with particular platforms, characteristics of users, and social media elements, such as groups of features that allow for self-representation or messaging. To model the complexity of all the platforms and channels used over the course of a day, with their different affordances, content, and networks, “screenome” analyses examine images of individuals’ screens, captured at frequent intervals throughout the day.

But as we all know from personal experience, the effects of technology depend not only on what apps we use or for how long, but also on our motivations. Learning to use Snapchat to communicate with one’s teenage niece involves far more effort, with the potential of far more reward, than browsing the app as a pastime. It doesn’t make sense to study technologies as if they were pills or injections. We shape the experiences we have with technologies and the results of those experiences.

In the sections below, I discuss how technology can be shaped in positive ways by parents, caregivers, romantic partners, and clinicians. I add examples from my interviews of individuals pushing technologies beyond their intended use to enhance relationships. These individuals use phones, apps, social media, and smart devices such as lights in creative ways to start difficult conversations, empathize, and express emotions. The value comes not in the particular technologies they use, which could just as easily create distance as closeness, but in the care with which they are applied. Through these examples and the surrounding research, we see the importance of using technology with intention, creativity, and sensitivity.

The COVID-19 pandemic has increased the urgency of using technology in ways that strengthen our relationships. Much of the world has been working, learning, and socializing online for months, and many important activities will remain virtual for the foreseeable future. This period of physical distancing has shed light on what we need from technology and each other. In the synopsis that opens this article (see Box 1 “Connecting during COVID-19 and beyond”), I describe promising directions for using technology to meaningfully connect during the pandemic and beyond.

**Parenting**

Concerns about technology may be most strongly felt by parents, most of whom report worrying that their kids spend too much time in front of screens. Parental anxiety stems from the inability to control all the content and people one’s kids encounter online, along with heavily publicized research on mental health risks. Jean Twenge presented a correlation between screen time and teen unhappiness, along with the co-occurrence of mobile phone adoption and increased depressive symptoms, loneliness, and suicidality among teens in the United States, as a call to action. Parents were encouraged to set firm screen-time limits, and these limits were even formalized in medical recommendations. Subsequent analyses of the same data set and meta-analyses find very small associations of teen well-being with social media and phone use. Since most of the studies on this topic are correlational, there is no certainty about causality or the absence of confounding factors. Alongside cautionary findings are ethnographic and survey studies that illustrate the importance of social media and digital communication for teens’ social development and well-being.

The takeaway is not that social media or phones are benign. It is that they can’t be studied as a singular thing. They are experienced differently depending in part on factors such as social-emotional vulnerability, socioeconomic status, and gender. The feelings of connection and exclusion social media are amplified for kids who report social-emotional well-being. Similarly, kids from lower-income families are more likely to encounter bullying and other hurtful experiences online. Finally, teenage girls may be more likely than boys to use social media in a way that leads to negative social comparison and teenage girls with depressive symptoms tend to increase their social media use over time.

Sweeping panic about phones and social media is probably unwarranted and unhelpful, but there are issues for parents to address. For example, parents should talk with kids about their interpretations of streams of social media images, reminding them that these are curated “highlight
reels” rather than realistic representations of their friends’ lives. Threats to their kids’ privacy cannot be managed by parents alone (see ref 25 for needed policy changes), but parents can help their kids manage these risks. Rather than shielding their children from privacy infractions and other online harm, parents can help kids learn to anticipate risks and take actions to recover from negative events.26

An alternative to parental restrictions, such as rigid screen-time limits, are parenting approaches based on connection. Sonia Livingstone and Alicia Blum Ross share observations from a multiyear project, Parenting for a Digital Future, of families who use technologies in accordance with values, for example, promoting creative expression and learning.27,28 As these families use technology in ways they think are intrinsically valuable, there is less handwringing about how much time is spent on these activities.27 In addition, they tend to share decision-making, negotiate rather than impose policies, listen to children’s views, and share “digital pleasures,” such as games, music, and taking photos.27 Mimi Ito, director of the Connected Learning Lab at the University of California, Irvine, suggests parents learn the games and other technologies used by their kids so that they can play them together and talk about them. Ito points out that kids should be enlisted as collaborators to generate solutions for technology concerns both in the household and society.27

I have been impressed by how some of the parents and kids I’ve interviewed have communicated about technology, and how they have drawn on technology to facilitate communication. Things as simple as contracts

**Figure 1.** A father streams video to his daughter’s remote piano teacher.
have allowed some families to set norms for phone use. I’ve also been struck by parents who share self-help apps to either process conflict with a child or to help a child manage stress. One woman told me about how she used an anger management app with her son. She opened the app when she sat down with him to talk with him about a disruption he had caused at school. Together they swiped through the images of fire that represented stages of anger and conflict. She told him how ashamed she was to get a call from his school, and he described how mad he had been at the teacher who punished him merely for playing. While pointing to the images in the app and sharing their feelings, they started to see one another’s perspectives. In another example, a young man used smart lights to resolve a conflict with his parents: they wanted to know where he was in the evenings, but he found this to be burdensome and invasive. He devised a compromise in which the colors of the lights at home automatically changed depending on how far away he was (using IFTTT - If This Then That), giving his parents the information they wanted while preserving his feeling of autonomy.

The flexibility and experimentation in these examples may become increasingly important qualities of parenting as technologies work their way into more facets of daily life. Writer John C. Havens imagines disturbing future scenarios in which kids prefer to have stories read to them by robots than their parents, also depicted in the television show _Humans_, and smart home devices turn against parents, rating their fitness to raise children. Such scenarios convey the urgency of prioritizing human relationships over those with machines. Rather than training kids to be polite to Alexa, perhaps parents should de-emphasize Alexa as an entity. More importantly, they should find ways to use conversational agents and other household technologies to strengthen parent-child communication. For example, some parents find that using timers on Alexa or Google Home eases tension about time limits: their kids are less apt to argue with the smart speaker, particularly if they help determine the allotted time. Other parents use these timers to help their kids manage homework or other tasks. One mom described a scaffolding approach in which she works with her teenage son to develop a plan for his homework and estimate the time required for each part of an assignment. Then her son proceeds on his own, setting timers on Alexa as he starts each chunk of work. This system helps him stay focused and has allowed him to take on more independence with his schoolwork. His mom can step back from micromanaging, which they both appreciate. Timers might also help parents listen as teens work out solutions to their problems, for example, by committing to spend 10 minutes acting as a sounding board and resisting the urge to advise.

**Romantic relationships**

Banksy’s image, “Mobile Lovers,” of a man and woman locked in an embrace, but each looking toward their phones, speaks to concerns that phones have eroded intimacy. Many see themselves in that image and in the frequently reported survey findings that people would rather go without sex than their phones, that phones are the last thing they touch at night and the first thing they glance at in the morning, and so on. For some, this misplacement of intimacy onto a device follows a slippery slope of distraction, and for others, it offers an intentional escape from relationship pressures. One woman described how she and her husband each crawl into bed with their laptops and phones. Exhausted from work and getting her two young kids fed and to sleep, she is too tired to care if he is watching porn. The escape to devices feels essential in these moments, even though she realizes it may not serve their relationship well over time.

There are also ways that technologies can enhance a couple’s connection. This can involve using technologies as they were designed or pushing them beyond their intended use. Long-distance couples rely on texting, video calling, and other technologies. Some couples toss images back and forth throughout the day, others “hang out” on platforms like FaceTime for hours at a time, not necessarily talking but just being together, apart. Other couples repurpose technologies, such as smart lights, not designed for communication. One couple, who lived in different cities because of their jobs, set up smart lights in each of their apartments. Periodically the woman came home to find her home colorfully lit up and immediately felt the affection of her partner. Research in the area of Intimate Computing has explored how everyday objects such as beds and teacups can mirror the behaviors and physiology of a remote partner and even how the lights and sounds can be synchronized across homes. Periodically, consumer products emerge based on these ideas, such as jewelry that allows one to sense the heartbeat of a romantic partner from afar.

Technology works its way into how couples negotiate conflict as well as how they express affection. One woman I
spoke to prefers texting for working through disagreements with her partner because arguments heat up quickly in their face-to-face interactions. In texts, she can make her points without interruption. Self-tracking apps can also play a role. One man had a long-standing conflict with his wife over childcare responsibilities and had been feeling resentful. In the course of tracking his moods, he started thinking about how his wife was feeling. He expressed genuine curiosity in her feelings, which allowed them to approach other topics in a considerate, collaborative way. Some people get creative with addressing reoccurring conflicts, drawing on technologies that are not typically marketed for communication. For example, one woman used smart lights as an ambient cue. She was at work one afternoon when her partner texted that he was bringing home a colleague for dinner. Impromptu hosting was not something she enjoyed. From the app on her phone, she changed a smart light in the window to a bold red, knowing that would grab her partner’s attention when he came home. Later that night, they talked about the light and how they could socialize in ways that worked for both of them. Through the light, this woman externalized her anger and opened a dialogue that in the past had been met with defensiveness. Now it was understood that the conflict, like the light, could easily change.

Many of the same technologies can hurt or help a relationship. Location sharing, for example, can be used to coordinate plans or to surveil someone. Similarly, changing someone else’s environment through their smart speakers or smart lights could feel like a hug or a frightening invasion. To have a positive role in a relationship, technologies need to be used with sensitivity and awareness about how they might affect another person. Contracts stipulating the terms of technology use, now common between parents and children, may also have value for couples. This should be an ongoing conversation about how technologies can be used to support a relationship.

**Caregiving**

Many adults find themselves caring for elderly parents at a distance. Increased lifespans and decreased birthrates have made it more likely that their parents, particularly their mothers, will be living on their own. Living alone allows independence, but it can make it more likely that an injury or illness goes undetected. Many older adults become cut off from social activities and community life, particularly if they have mobility restrictions. Loneliness is common in later life and poses risks for chronic diseases that are comparable to smoking or obesity.

Technologies have been developed to address some needs of remote caregivers and their elderly parents, such as medication prompting and fall detection. Loneliness may be a harder problem to tackle. The solutions are not as obvious as offering social support. Loneliness involves sensitivity to rejection and protective withdrawal, where individuals avoid the very situations that could be rewarding. Working one’s way out of loneliness involves participating in communities and finding ways of helping other people.

Some of the well-publicized technologies for loneliness, companion robots, shortcut this complexity by offering human surrogates. Take Paro, the robot baby seal developed by Takanori Shibata in 2001 as a companion for older adults. Paro is responsive to touch and can make eye contact. Sherry Turkle, who observed elders interacting with Paro in a nursing home, noted that some elders found comfort in the robot’s illusion of caring. Turkle raises the concern of authenticity: “What is the value of interactions that contain no understanding of us and that contribute nothing to a shared store of human meaning?”

The question of how to catalyze social interaction rather than replace it drove my research in the early 2000s. My colleagues at Intel and I developed a range of concepts for older adults and caregivers, including one that was like a Fitbit for social interaction. This display of social contact, generated by data from sensors, phone activity, and a journal, looked like a map of a solar system. The elder was represented by a circle in the center, around which rotated smaller circles representing family members and friends. In interviews with elders and caregivers who used the display in their homes for a field study, I learned how the displays worked their way into conversations between family members, offering them a way to talk about loneliness. One caregiver, busy with her own children and work, had been frustrated with her mother’s social passivity. But over the course of these conversations about the display, she became more understanding of her mother’s reluctance to invest in new friendships. The display gave them a vocabulary and license to address an otherwise taboo topic of loneliness, and these conversations, in turn, prompted her mother to initiate family visits and begin volunteering.
One of the simplest but most profound prototypes that my colleagues and I developed was a light that turned on in an elder’s home when her daughter or son returned home from work. Similarly, a light in the caregiver’s home turned on when their mother or father was sitting in a favorite chair. We imagined the light might give reassurance to caregivers and help elders know when a caregiver was available for a phone call. But the value was more subtle than that. The light evoked a visceral connection. One participant described this indication that her daughter was home as “a warm vibe.”

These subtle forms of connection are important to keep in mind as we consider the needs of caregivers and their elderly parents. Technologies specifically designed for older adults living alone and products such as home security cameras, marketed in part for remote monitoring of elders, tend to focus on health monitoring. Detecting falls and tracking medication adherence are part of caregiving, but ongoing communication is equally important. With sensitivity and reciprocity, caregivers can find ways of using many technologies, even those designed for remote monitoring, to stimulate conversations about daily life and challenges such as loneliness.

Clinician-patient relationships

Next, I explore how therapists and other clinicians can guide their patients in using a range of technologies, including mental health apps, and how they can get the most benefit from technologies that are part of their practice, such as videoconferencing. Therapists should try to appreciate the nuances of how individuals adapt technology to work through relationship challenges, discussed in previous sections. Conversation about a patients’ use of technology may surface issues for discussion, highlight patterns that would otherwise be hard to see, and illustrate the contexts of a patient’s struggles.

Therapists have the opportunity to guide patients as they use apps, wearables, and other technologies designed for emotional well-being and use these as adjuncts to therapy. Presuming privacy regulations take effect to restrict the exchange of user data, mental health apps and wearables offer a promising means to extend therapy into daily life. Mood tracking, whether by self-report or sensors, may illuminate patterns that would otherwise be hard to detect and prompt patients to recall events that occurred between sessions. Micro-interventions, such as prompts to practice perspective-shifting and other cognitive exercises, can help patients apply therapy to cope with personal and professional stressors as they arise.

Ideally, mental health apps will extend help to the many people who do not have access to treatment. In keeping with this view, most consumer health apps are designed as a standalone form of self-help. The efficacy and long-term appeal of these consumer apps have not yet been demonstrated, however. Advances in functionality and adaptive learning might allow these apps to sustain the attention of end-users. But it also possible that the premise of individual use is flawed. It runs counter to the social basis for most popular apps and to the idea that progress in psychotherapy is dependent on the alliance between patient and therapist. Individuals can certainly bond with technologies, as was reported with the artificial intelligence (AI) therapist, Woebot, but human dialogue about one’s data and use of the interventions remains important. In a field test of a mobile therapy app, some participants got more value from the app as they discussed it with family or other close contacts, for example. Mental health apps may attract more sustained use when they prompt supportive interpersonal dialogue. Clinicians could engage in such dialogue, collaborating with patients as they use apps to track therapy-related goals, whether those are consumer apps or ones developed for use with a therapist. I suspect that clinicians could also help patients tailor apps to their particular needs, for example, by scheduling prompts for interventions around anticipated stressors.

Therapists should attend to how patients can use a wide range of technologies, not just mental health apps, to support their goals and values. For example, therapists can listen for ways in which patients actively communicate with friends or compare themselves negatively with others on social media. They can encourage patients to reflect on their emotional states as they are using different apps and adjust their use accordingly. They can also explore how the social media and productivity tools that are already a part of patients’ lives can aid self-reflection. One woman I interviewed described how she preferred Excel spreadsheets to mood apps for reflecting on her grief. In Excel, she could use her own words and images, which was far more helpful to her than an emotion checklist. Similarly, one man I spoke with found that he could manage his anger at work by setting a
time delay on his outbound email messages. This gave him a window of time to rephrase a potentially hurtful message. Other people I’ve interviewed have used games to help themselves and others suffering from social anxiety. For example, one woman drew an isolated relative back into the family fold through Words with Friends, a game that highlighted her strong vocabulary and gave her a comfortable way to interact with family members. Instagram and Reddit are also used to seek emotional support, sometimes with anonymous, secret, or temporary accounts to describe stigmatizing experiences and find similar others.59,60 These examples of individuals adapting everyday technologies as mental health tools are elaborated in Left to Our Own Devices.30 Ideally, therapists will help patients sort through ways of using diverse technologies as adjuncts to therapy.

Videoconferencing and other tools used by a therapist can similarly be optimized for connection. With video, therapists can see into a patient’s home where there are cues to routines, interactions, and personality.52 One physician described to me how video allowed her to appreciate the extent of a patient’s hoarding and social phobia. She could see how clutter covered every inch of the woman’s home and physically blocked her from leaving. There is also opportunity to build trust by sharing cues about oneself. With her telemedicine patients, this same clinician experimented with different ways of positioning the camera. Initially, it focused on her against a blank white wall. Then she changed where she sat so that an old wooden armoire and plants appeared in the background. Patients were set at ease by these trappings, and as they commented on them, drew connections to their own homes and families. By revealing more of herself, she felt that she created more reciprocity and trust, which allowed for better care.30

Virtual reality (VR) and augmented reality (AR), studied for treating a range of mental health concerns,53,54 can also be used collaboratively. In VR treatment, patients typically experience simulations, for example of a feared situation, as they are coached by a therapist in the same physical room. In an approach designed to extend access to treatment, a patient’s avatar interacts with a preprogrammed therapist avatar in a simulated environment.55 Interactions with others in a shared virtual environment can be powerful,56 and I have seen how a shared experience of AR/VR in a medical context, specifically, a surgeon and patient jointly examining a hologram of the patient’s anatomy, strengthened trust and enhanced treatment.30 By extension, it may be helpful in some situations for individuals with mental-health concerns to experience simulations simultaneously with clinicians or other patients. It may also help for patients to discuss their experiences with VR and AR in forums, as individuals with social anxiety have shared their use of the AR game, Pokémon Go.57

Perhaps the most profound shift in the clinical relationships will be in the area of assessment. Digital phenotyping, involving analysis of data from digital devices, including speech, voice, location, activity, and interaction data, may give precision to mental health diagnoses.58 Additionally, social media activity, including the sentiment of text and even the gradient of images, has been associated with different emotional states.59,60 These digital and social media analyses may lead to a much more nuanced and empirically based classification of mental illness and more precise means of evaluating interventions. These same analyses are fraught with privacy concerns, from targeted advertising to profiling that could cause social or professional harm. Emotional surveillance may also undermine mental health by interfering with individuals’ feeling of control over what they keep private and what they share. These risks need to be considered along with the potential benefits of assessing mental health through digital traces.

Conclusion

In this review, I have examined how technology can be used intentionally to enhance parenting, caretaking, romantic, and clinical relationships. This connection-oriented technology use differs to some degree across these types of relationships. To connect with children and support their autonomy, parents can engage with the games and social media their kids are using. Through that engagement, they may find openings to talk about kids’ interests, friendships, and anxieties. Caregivers of elderly adults can use technology not just for health monitoring but also to prompt conversations. Romantic partners can creatively use digital communication to bridge conflict and physical distance. And by talking with patients about how they use mental health apps, social media, and other technology, therapists may be able to see patterns that otherwise wouldn’t be obvious.

There are also common principles across the relationship types. First, prioritizing a relationship over technology
sometimes requires deviating from the intended use of technology. In some of the examples above, individuals used smart lights for emotional communication and leveraged popular games to cope with social anxiety. Second, technologies meant for their individual use can be brought into relationships and used jointly. Whether it’s a mother using a self-help app with a child to process an argument or a clinician joining a patient in an immersive AR simulation, interactive use can foster connection. As these examples show, respect for the privacy of the other person is critical to cultivating a close connection. The focus is on sharing rather than surveillance.

These principles may have value for researchers as well as end-users. The parents, caregivers, couples, and clinicians described above use technology as a bridge. When they examine others’ data or share technology, they try to understand the needs and struggles of another person. Researchers should similarly try to learn about individuals’ motivations for specific interactions. Longitudinal analysis of communication, location, mood, and activity from phones is allowing contextually rich assessment of sociability and well-being. A situated understanding of interpersonal motivations and struggles will complement that research, shedding light on how individuals can change the way they engage with technologies, and how the technologies themselves should change, to support important relationships.

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Promises and risks of web-based interventions in the treatment of depression

Ulrich Hegerl, MD, PhD; Caroline Oehler, MS

Major depression (MD) is a highly prevalent and severe disorder with many patients having no access to efficient treatments such as pharmaco- and psychotherapy. Web-based interventions promise to be a method to provide resource-efficient and widespread access to psychotherapeutic support. Meta-analyses summarizing studies that use face-to-face psychotherapy as a comparator provide evidence for equivalent antidepressant efficacy. Web-based interventions seem to be particularly efficacious when they are accompanied by some form of professional guidance. However, they are also associated with a variety of possible risks (eg, suicidal crises can be overlooked) and unwanted effects (eg, increase in rumination and somatization due to self-monitoring) that are so far under-studied. Although some naturalistic studies yield smaller effect sizes than randomized controlled trials (RCTs), well-designed interventions with adequate guidance have been shown to be successfully integrable into routine care.
To fully utilize the potential of web-based interventions, it is important to apply strategies that enhance user engagement and adherence.

Web-based interventions can be divided into those that are offered with some form of professional guidance and those that are completely self-guided. In the outpatient setting, guidance can, for example, be provided by general practitioners (GPs), psychiatrists, psychotherapists, or assistants specialized in providing support for online interventions. The guiding health care professional introduces the patient to the intervention, offers assistance at follow-up appointments, and asks about the patient’s experiences in working with the intervention. In order to be able to provide high-quality guidance, guides have to be familiar with the interventions themselves. For the iFightDepression tool, an e-learning platform is offered, which allows the guides to get acquainted with the iFightDepression tool. Other web-based interventions are accompanied by guidance without face-to-face appointments via asynchronous communication methods (eg, email or text messages) or synchronous communication methods (eg, using the telephone). For web-based elements that are interwoven with regular face-to-face treatment, the term “blended therapy” was coined. Web-based interventions can also be differentiated based on their position in the whole therapeutic concept. Some are conceived as alternatives to regular treatment with antidepressants and face-to-face psychotherapy and as first options in a stepped-care approach, others (eg, the iFightDepression tool) are seen as self-management tools and meant to be used as an addition to regular treatment. Unguided intervention should be considered with a critical eye, as it is a problematic message that people affected by a serious condition such as depression can treat themselves on the internet. There is the risk that such tools are used by patients as an alternative to professional guideline-oriented treatment. In addition, evidence for the efficacy of unguided interventions is questionable (see below). Therefore, guided interventions should be preferred.

Whereas the typical intervention that is currently being researched is accessible online using the browser of a computer, tablet, or smartphone, a rising number of apps are published in both the Apple App Store and the Android Market (Google Play). In a systematic review conducted in 2015, 117 were identified that claimed to offer CBT or behavioral activation (BA) for people suffering from depression. Only 10.3% of these seemed to be consistent with evidence-based principles, and none offered efficacy or effectiveness studies. Safety or privacy policies were often missing. Another study, using more lenient search criteria, identified 1054 apps claiming to be helpful in dealing with depression in 2014. Since this field is developing partic-
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Usually rapidly, the current number will be several times higher. Smartphone applications offer many of the advantages of browser-based internet interventions and are even more accessible. Smartphones are among the most rapidly adopted innovations from recent years. They also have the advantage of being the main tool to access the internet in many developing countries, expanding the potential global impact of web-based interventions to alleviate the burden of MD. Furthermore, smartphone applications offer unique functionalities—eg, sending push notifications—and are often used as a planning device, which makes them ideal to support changes in habit. Considering these features, it is very likely that their importance in the implementation of web-based interventions will increase significantly.

Evidence for antidepressant efficacy

Up to now, more than 100 studies on the antidepressant efficacy of digital interventions have been published, most of them with positive results. A recent meta-analysis on 40 studies of CBT delivered through the internet found an overall effect size of $g=0.502$ directly after the completion of the interventions. However, when evaluating the evidence provided by this field of research, it is crucial to consider a fundamental methodological problem: it is difficult to “blind” the patient concerning the control condition in psychological interventions. As a consequence, participants randomized into the control condition might even experience nocebo effects (nocebo being the negative side of placebo, describing negative expectations that lead to negative effects) through their awareness of receiving the ineffectual condition. But even if an active control is provided, the patient might recognize that she is “only in the control group” and might react with frustration and disappointment. This effect was, for example, visible in a randomized controlled trial (RCT) on primary care patients with milder forms of depression. In this trial, an active control condition, consisting of supervised self-help groups and psychoeducation, lead to an outcome that was significantly worse than pill-placebo. It has been convincingly shown that, more than the kind of intervention itself, the choice of the control condition determines the observed

### Table I. Description of the six core workshops of the iFightDepression tool.

<table>
<thead>
<tr>
<th>NAME OF WORKSHOP</th>
<th>COGNITIVE BEHAVIORAL THERAPY–BASED CONTENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Thinking, feeling, and doing</td>
<td>Information about how thoughts, emotions, and behavior are interconnected. Objective: monitoring of daily activities and corresponding mood changes to identify ways to improve daily routines.</td>
</tr>
<tr>
<td>2) Sleep and depression</td>
<td>Introduction of sleep diary. Objective: explore possible connections between patients’ bedtimes and changes in mood.</td>
</tr>
<tr>
<td>3) Planning and doing enjoyable things</td>
<td>Instruction to plan ahead and to integrate at least one positive activity into the daily routine. Objective: to restore or establish the balance between duties and leisure activities.</td>
</tr>
<tr>
<td>4) Getting things done</td>
<td>Training of problem-solving abilities. Objective: break down one task into small steps and plan ahead when and how to complete it.</td>
</tr>
<tr>
<td>5) Identifying negative thoughts</td>
<td>Introduction of the “ABC model” and automated negative thought patterns. Objective: identify one’s own negative thoughts habits.</td>
</tr>
<tr>
<td>6) Changing negative thoughts</td>
<td>Generate alternative thoughts to the ones listed in workshop 5. Objective: change thought patterns to more helpful and realistic ones.</td>
</tr>
</tbody>
</table>
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Taking these methodological considerations into account, it is apparently difficult to draw any conclusion from studies with a waiting list (WL) or treatment as usual controls (TAU) concerning antidepressant efficacy. Still, most of the evidence collected on web-based interventions for depression so far comes from such studies. Only eight of the 40 studies of the meta-analysis mentioned above did not rely on WL or TAU as control condition.

In that sense, the best evidence on the efficacy of web-based interventions for depression comes from noninferiority trials that use face-to-face psychotherapy as an active comparator. A first small meta-analysis of such trials (based on in total 429 patients from five studies) indicates that web-based interventions have efficacy that is similar to face-to-face interventions. All included trials compared web-based interventions (lasting 6 to 10 weeks) with some form of face-to-face intervention, two of them using group interventions as comparator. Overall, Andersson et al found a between-group effect size of Hedge’s $g=0.12$ that numerically even favored the web-based interventions but did not differ statistically significantly from zero. It has to be noted that the face-to-face interventions were often matched in duration to the web-based intervention and are therefore comparable to them, but do not necessarily resemble a full psychotherapy as provided in routine care.

It is well established that interventions incorporating some kind of guidance by a health-care professional have significantly larger antidepressant effects than unguided intervention, with the greatest improvements found in trials using face-to-face guidance, followed by telephone guidance, and support using text only (email or messages within the intervention tool). Thus far, most scientific evidence has been collected on browser-based interventions and, although the apparent validity of transferring the interventions from browser to application is very high, it is still worth looking at the evidence base. A review by Firth et al aggregated data from 18 RCTs on 22 smartphone apps for depression, mainly including patients suffering from mild to moderate depression. They found small to medium effect sizes when compared with active ($g=0.22$) and inactive ($g=0.56$) control conditions. In this meta-analysis, studies that used interventions that involved app usage as well as human support yielded smaller effect sizes. This contradicts the result consistently found in other web-based interventions that human support or guidance boosts the antidepressant effects of the intervention. The authors of the meta-analysis hypothesize that this result is due to the fact that apps not relying on guidance have been designed more comprehensively and to be user-friendly. Therefore, the result might be an artifact of differences in usability and comprehensive design of the apps.

It is important to keep in mind that, although web-based interventions and face-to-face psychotherapy seem to have comparable antidepressant effects, this does not imply that they have the same value for the patient. In face-to-face psychotherapy, the chance that suicidal and other critical developments are detected by the psychotherapist are higher than in e-mental health approaches, even when some kind of guidance is provided. There might be other more subtle positive effects associated with a direct interaction with the psychotherapist that are hard to quantify. Such effects are likely to depend on the skills and personality of the psychotherapist. On the other hand, receiving an intervention with only minimal personal contact also reduces the possibility of negative effects related to unfavorable personal interactions. In this context, it might be of some anecdotal interest to know that in 1898, Sigmund Freud had 50 documented patients in his private practice. Four committed suicide, two immediately after leaving the cabinet of Freud (personal communication by the Freud biographer Christfried Toegel).

**Risks and negative effects**

As is known for pharmaco- and psychotherapy as first-line treatment options for depression, every active ingredient or intervention also has the potential to induce negative or unwanted effects. A thorough exploration of possible unwanted effects gives users and prescribers the opportunity to consider them in their choice of treatment. Web-based interventions are associated with a variety of risks and possible negative and unwanted effects. This topic is so far largely unstudied, but could, corresponding to the possible negative effects of psychotherapy, include the following aspects:

(i) The **interventions can be used in an incorrect manner**. For example, patients could perceive web-based intervention as an alternative treatment that replaces or delays guideline-oriented treatment. This could happen even though the
intervention might have been designed only as an add-on to regular treatment. GPs or other health professionals could misdiagnose depression and offer an intervention designed for depression to patients with other disorders, eg, obsessive compulsive disorder (OCD) or schizoaffective disorders, where the intervention is unlikely to be helpful or might even be detrimental. Furthermore, most web-based interventions are designed for patients with milder forms of depression. If patients with severe or even delusional depression are confronted with a web-based intervention, negative reactions such as increases in despair and self-blaming could occur. On the other hand, due to the often highly structured form of web-based interventions, treatment fidelity is usually high, and the treatment is delivered in a much more standardized way, avoiding a risk present in traditional psychotherapy.

(ii) The intervention can be offered to the right patients, but guidance is provided with insufficient intensity or quality. As in any psychosocial intervention, the interpersonal relationship can be both a negative and positive factor. So far, this factor has not been sufficiently investigated.

(iii) Even when used in the correct manner, symptom deterioration can occur during the use of web-based interventions. Since it is hard to disentangle if deterioration is directly related to the web-based intervention or results from the random variance due to uncertainties in the assessment of depression and the independent fluctuations of depression severity, reliable deterioration rates are used as an approximation. Reliable deterioration is based on reliable change scores and gives an estimate of how many participants’ symptoms deteriorated, corrected for the reliability of the measure used. This, however, still leaves open the question of causality and natural fluctuations in symptom severity. In an individual patient data meta-analysis, Ebert et al\(^2\) found a risk of 3.36% for reliable deterioration in the intervention group, compared with 7.5% in the control conditions. In this analysis, participants with a lower educational level who were randomized into the intervention group were found to have a comparable risk of experiencing a significant deterioration as participants in the control condition. Especially patients with a lower level of education seem to need more intensive support when working with a web-based intervention. As an amendment to these results, Karyotaki et al\(^3\) analyzed the risk of reliable deterioration in self-guided interventions for depression. In 16 trials with altogether 3805 participants, they found that 5.6% of participants in the intervention groups and 9.1% in the control groups experienced reliable symptom deterioration without the characteristics of the participants predicting the risk of deterioration. So far, web-based interventions seem to be comparable to psychotherapy with respect to reliable deterioration. In a meta-analysis on 18 studies researching psychotherapy for depression, a median deterioration rate of 4% was found, with single rates as high as 10%\(^4\).

(iv) The delivery format brings further specific risks that are not routinely measured in RCTs. Patients might feel stressed by the tight treatment schedule, become frustrated by technical problems, or feel uneasy because of the limited possibility to contact a health care professional\(^5\).

(v) Still more difficult to measure are subtle changes and unwanted effects that might be caused by the regular use of web-based health interventions, electronic devices, and self-monitoring. In a study that added daily self-monitoring via a guided app to the medical treatment in a specialized clinic, patients in the intervention group who reported alleviated symptoms of depression at baseline tended to deteriorate further than the control group\(^6\). The authors hypothesize that especially for patients with a higher initial score of depression, the daily confrontation with self-ratings of depression might have accentuated the symptoms and possibly increased worrying. Regular use of monitoring apps might even induce obsessive self-monitoring or strengthen somatization tendencies through constant direction of attention toward one’s symptoms.

(vi) A further risk associated with web-based intervention is that the chance of detecting suicidal crises is likely to be smaller than with traditional approaches because direct personal contact is reduced. Considering the so far limited evidence for the antidepressant effects of web-based interventions, more research on and sensible consideration of possible unwanted effects are needed.

Acceptance, adherence, and its predictors

The satisfaction in participants of trials on web-based treatments of depression has been stated to be high\(^7\) and convenience, low cost, privacy, and the ability to proceed at one’s own pace have been named as advantages of web-based interventions\(^8\). In contrast with this, acceptance among the
public seems to be limited. In a review on four studies, most participants reported lower intentions to use media-assisted treatment (via apps or webpages) than medication or face-to-face treatment.39 Also, the perceived helpfulness was higher for the latter methods than for e-health interventions. A survey conducted among a wide group of European mental health stakeholders found the acceptance to be higher for blended treatments than for stand-alone solutions.30 For Germany, the German Depression Foundation assessed opinions about web-based interventions in 2017, both in the general public (N=2009) and in a sample of people with lived experience (N=990). Whereas over half of the participants in both samples reported being critical of web-based interventions for data protection reasons, the proportion of people stating that these interventions might provide helpful support was much higher in the sample of people with lived experience (59.7% vs 39.5%). Also, almost half of the public sample felt that these interventions might be dangerous, whereas only 18% of the people with lived experience did so. It seems that patients themselves might be more ready than the general public to try out new interventions using the internet as an adjunct. Still, only around 20% in both groups said that web-based interventions might be an alternative to face-to-face psychotherapy.31

Another problem that has been described in several instances, especially for routine care, is the low level of adherence to web-based interventions, with meta-analysis reporting dropout rates as high as 74% for unsupported interventions.32 The most prominent example is a large pragmatic trial (N=691) conducted with depressed patients in primary care in the UK, in which two web-based interventions were compared with TAU by the GP.33 The adherence in the British sample was very low: only around 80% of the participants started using the intervention. The most frequent number of sessions completed was one, with only around 17% of the participants completing the online interventions. Low adherence in turn limits the benefit each individual can draw from the intervention,34 and it has been shown that completion rate influences the effect sizes one can expect to find in a study.31

To fully utilize the potential of web-based interventions, it is therefore important to apply strategies that enhance user engagement and adherence. This could on the one hand be accomplished through changes in the way the intervention is delivered. Among others, adherence to web-based inter-
ventions is influenced by guidance, whereby this relationship partly explains the superior effects of guided versus unguided interventions. The optimal time that should be spent on guidance to maximize the interventions effect is still a matter of discussion.35 Other successful strategies for improving adherence could include using persuasive system design elements36 and adding choice, cost, and reminders to the intervention,37 with reminders probably being the most potent feature to increase both adherence and effectiveness.38

On the other hand, patient characteristics have been found to predict the adherence and success of web-based interventions. Another strategy to optimize usage could be to select patient groups that will probably adhere or provide additional guidance to groups that usually show lower adherence rates. Possible predictors can be sociodemographic variables such as age and gender, on the one hand, and beliefs and expectations on the other. In an individual patient data meta-analysis on self-guided interventions for depression, male gender, lower educational level, and being younger predicted higher chances of nonadherence.39 Treatment credibility and a positive working alliance with the intervention have been associated with a reduced probability of dropout and higher probability of reliable symptom improvement,40 and Mira et al41 found that higher initial expectations were related to greater improvements in all measures. The later result was confirmed in a systematic review.42

**Conclusion**

Web-based interventions are developed and researched at an accelerating speed. But the often-postulated good evidence for the efficacy of web-based interventions for depression requires a critical review: most of the studies conducted so far have used WLs and TAU groups as control conditions, which might artificially enhance their effect sizes due to nocebo effects in the control condition. RCTs comparing web-based interventions and face-to-face treatment in noninferiority designs have yielded the best evidence on efficacy available thus far. A first meta-analysis on this type of study found that web-based interventions had a similar antidepressant effect to face-to-face interventions if they are offered with professional guidance.

Fields for further research are potential negative and unwanted effects of web-based interventions. Whereas
first studies have shown similar deterioration rates as seen in traditional psychotherapy, other possibilities such as the opportunity to detect suicidal crises have not been quantified so far and should be the focus of future research. One of the most relevant barriers to fully exploit the potential of web-based interventions in routine care is a low rate of adherence, especially if the interventions are provided as stand-alone offers without any support. But if they are designed incorporating persuasive elements, eg, frequent reminders as well as regular guidance, at best in a face-to-face setting, they can lead to a significant decrease in symptoms of depression, even in routine care.\(^{43,44}\)

Digital interventions can be considered to be a promising means to meet the increasing demand for psychotherapeutic interventions worldwide. Especially in the treatment of depression, a highly prevalent, severe, and at the same time undertreated disorder, they are likely to play an increasingly important role in the future. \(\blacksquare\)

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Virtual reality as a clinical tool in mental health research and practice

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Virtual reality (VR) is a potentially powerful technology for enhancing assessment in mental health. At any time or place, individuals can be transported into immersive and interactive virtual worlds that are fully controlled by the researcher or clinician. This capability is central to recent interest in how VR might be harnessed in both treatment and assessment of mental health conditions. The current review provides a summary of the advantages of using VR for assessment in mental health, focusing on increasing ecological validity of highly controlled environments, enhancing personalization and engagement, and capturing real-time, automated data in real-world contexts. Considerations for the implementation of VR in research and clinical settings are discussed, including current issues with cost and access, developing evidence base, technical challenges, and ethical implications. The opportunities and challenges of VR are important to understand as researchers and clinicians look to harness this technology to improve mental health outcomes.

Keywords: assessment; digital technology; mental disorders; mental health; psychiatry; virtual reality

Introduction

Developments in virtual reality (VR) have the potential to radically transform the landscape of assessment in mental health. Immersive VR involves wearing an enclosed head-mounted device (HMD) that displays three dimensional images on a screen so that the person is fully immersed in a virtual environment (eg, Figure 1). Images are continuously rendered relative to the position of the head and can capture movements of the body, allowing users to explore and interact with objects and avatars (digital agents) in the virtual space. These virtual environments are either programmed using specialist software to create computer-generated, photorealistic images, or filmed with specialized cameras to create 360-degree videos of real-world scenes that can be replayed within VR. Together, these capabilities make it possible for researchers and clinicians to observe and record individuals in highly controlled and near-natural environments, in real time.

VR has been applied for the delivery of exposure-based treatments, whereby individuals can experience feared situations or contexts in a safe and controlled manner, without leaving the clinical setting. Indeed, VR exposure treatments have proven effective across a range of mental health conditions. A number of reviews have been written on the topic of VR-based treatments for psychiatric conditions more broadly. Freeman et al conducted a systematic review in 2017, finding 154 studies on VR treatments for a range of mental health disorders. Further reviews...
have been published on VR treatments for schizophrenia, anxiety disorders, and mental disorders more generally. Evidence for the efficacy of VR treatments is noted within these reviews; however, the methodological quality of studies is generally low and the implementation of VR treatments beyond research settings is yet to be examined. Exposure therapy is notably dominant within this literature, highlighting how the ability of VR to recreate real-world environments has been leveraged to target the mechanism underpinning exposure. However, in general, innovation has not moved far from this approach, with more novel clinical applications of VR yet to be explored. One such application of VR within treatment is its use as a clinical assessment tool, a topic of relatively limited discussion within the literature. Clinical assessment is an integral element of mental health treatment, from diagnosis to treatment planning and monitoring. As such, the aim of this review is to orient the reader to the clinical application of VR as an assessment tool within mental health research and practice. The specific capabilities that underlie the utility of VR for clinical assessment is provided, as well as examples from high-quality research studies, finishing with a discussion of current considerations and limitations in the field.

Benefits of virtual reality for assessment

From symptoms and cognition to functioning and capacity, the measurement of psychological phenomena is central to research and practice in mental health. Although we can have confidence in current assessment instruments to a certain degree, there are many threats to reliability and validity. Differences between the assessment context (e.g., a lab or clinic) and the real world generate multiple sources of potential bias, threatening the accuracy of results. Real-world assessments are possible, but can be costly and time consuming, and access can be limited by location and mobility. VR may overcome many of these limitations through the ability to generate highly controlled, real-world experiences.

Enhancing ecological validity

With technological advances over the past decade in particular, VR has become increasingly immersive. By immersing individuals in real-world situations through VR, it is possible to conduct assessments that more closely emulate what happens in daily life. This capability overcomes the issue of ecological validity, that is, the degree to which the findings of research studies generalize to real-world settings. Research has consistently shown that individuals respond to virtual environments as if they were experiencing them in real life. Virtual environments are known to produce physiological changes consistent with emotional responses to real-world scenarios and have the ability to elicit symptoms such as paranoia, cravings, anxiety, and fear. A meta-analysis of nine randomized controlled trials comparing VR exposure with in vivo exposure for phobias found equivalent effects for both interventions, suggesting similar processes occur. Experiences in VR have also been found to elicit predictable behaviors, with one study finding that people with higher levels of paranoia kept a greater interpersonal distance from avatars within a virtual environment, which was considered a reflection of perceived trust and social threat. These findings highlight one of the main advantages of VR within mental health: the ability to simulate experiences in everyday life.

Whereas validation studies are still lacking, research has demonstrated that VR-based assessments can perform...
comparatively to assessments conducted in the real world. Gorini et al. examined emotional reactions to food in a virtual kitchen, a real kitchen, and in photographs, among individuals with eating disorders. They found that both real and virtual exposure to food cues elicited the same emotional reactions, which were greater than those elicited by the photographs. VR also enables access to situations and experiences previously difficult to attain in research, such as hard to reach or dangerous environments. For example, VR has been used in neuroimaging research to study brain activation in naturalistic scenarios, a method previously impossible from inside the scanner. Furthermore, since recent developments have resulted in VR becoming completely mobile, assessments do not need to occur within the clinic or lab, allowing people to access them remotely. The possibility to deliver automated assessments in people’s homes, independent from a clinician, is an exciting opportunity to increase efficiency, improve accessibility, and reduce cost.

Control and manipulation of the virtual environment
VR offers the ability to control and manipulate features of the environment that can be used to test and assess relevant variables, such as eliciting paranoia in social situations or examining responses to cues within the environment. Experimental control is a cornerstone of psychological research, enabling direct comparison between conditions to determine causal relationships between variables. Strong methodological rigor can be achieved in VR through careful manipulation of variables across conditions in virtual environments. For example, Veling et al. randomized participants with psychosis, siblings, and health controls to conditions with varying levels of social stress within a virtual environment. They found a dose-response relationship between social stress and paranoia, which was associated with psychosis liability, supporting the theory that social stress may account for the relationship between the environment and psychosis. Another example comes from Freeman et al. who examined experiences of paranoia and perceptions of social rank within a virtual underground train. Participants were placed in two conditions: one where they were taller than others on the train and another where they were shorter. Findings showed that under the condition where they were shorter, participants had a more negative view of themselves relative to others and greater levels of paranoia. The differences in paranoia were fully mediated by social comparison, suggesting that negative views of the self, relative to others, may drive feelings of mistrust.

Sufficient evidence has accumulated to support the benefits of VR for a variety of assessment purposes in mental health

Another capability of VR is that individuals are able to interact with objects within the system, rather than simply observing or imagining different scenarios. This not only enhances ecological validity, as interaction is inherent to the real world, but also allows researchers to examine behaviors of individuals within the virtual environment and their impact by manipulating different contingencies. Previously, this type of research was only possible using actors or “confederates” who performed certain roles within situations, which was costly and limited in ecological validity. Furthermore, the controlled nature of the experience enables greater reproducibility relative to field studies where the environment is constantly changing. These capabilities have important implications for social psychology, but also for identifying differences characteristic of mental disorders. For example, previous studies have demonstrated that exposure of each participant to the same virtual scenario can allow controlled examination of the determinants of paranoid ideation.

As such, the enhanced environmental control and interactivity of VR allows for standardization of otherwise dynamic variables, ensuring a consistent assessment experience, both over time and across individuals.

Personalization and tailoring
Because virtual environments are computer-generated or recorded, it is also possible to program tailored VR experiences that match individual needs, abilities, or preferences (eg, slowing down a sequence, using text or audio instructions, minimizing distraction). Rizzo et al. developed a VR-based exposure therapy for posttraumatic stress disorder (PTSD) that enabled the therapist to customize various features of a combat scenario most relevant to the trauma experienced by soldiers. Since effective treatment of PTSD requires exposure to cues of highly idiosyncratic experiences, customization of the virtual environment is an important feature. Such customization also has important
utility for assessment purposes, though very little research has examined this to date. For example, functional analysis involves the examination of how symptoms change in relation to different triggers and responses. VR could be used to examine changes in symptoms across different situations and in relation to certain cues, for example visual, auditory, and olfactory, allowing precise insight into the determinants of relevant clinical events. Gatti et al describe a VR protocol whereby clinicians were able to customize the virtual environment with personally relevant cues to alcohol craving and behaviors for the purposes of clinical formulation. The ability to perform psychiatric assessment via personalized tests and tasks meaningful to the individual and their situation is powerful but is currently understudied within VR.

Real-time, automated data capture
The benefits of using technology for automatic data capture has been well recognized. Mobile apps for tracking symptoms and other clinically relevant information over time has been a major area of progress in digital mental health, with findings suggesting that they are feasible and acceptable to individuals. Researchers are starting to consider how data collected from devices such as smartphone apps and VR might be clinically informative. Patterns in data collected from technology devices, such as movement, speech, and geolocation, have been associated with changes in symptoms and may even be used to predict relapse among people with psychosis.

It is possible to capture data automatically from users during VR experiences. Eye-tracking software can be integrated with VR, capturing a source of data commonly used to identify markers of psychiatric disorders and cognition. It is also possible to measure behaviors within the virtual environment, such as decisions about how to navigate and interact with different objects and agents. Capturing the temporal relationship between variables in real time (ie, how thoughts, emotions, and behaviors unfold in relation to changes in the environment), makes it possible to test hypothesized processes and causal interactions. Furthermore, physiological measures commonly used as objective indicators of psychological states, such as heart rate and galvanic skin response, can be recorded and synced with virtual content or even eye gaze. Mühlberger et al developed a VR-delivered behavioral avoidance test (VR-BAT) to assess fear in specific phobia while automatically collecting heart rate, skin conductance, subjective rating of discomfort, and stimulus-approach distance. Results indicated that the physiological measures were good predictors of fear intensity. Others have begun to investigate integrating more sophisticated biosensors, such as wireless electroencephalography (EEG), with VR to assess psychologically relevant constructs such as emotional state, with the aim to feed the data back to clinicians for enhanced decision making or even within VR itself as biofeedback.

Increasing engagement
Another benefit of delivering clinical evaluation via VR is the potential to enhance an individual’s engagement with the test or assessment. Traditional testing procedures undertaken in mental health can be lengthy, repetitive, and/or laborious, which may impact individual performance, especially for measures of attention or memory. Therefore, replacing traditional assessment with more engaging, meaningful, or enjoyable methods has substantial appeal. This is particularly important given that symptoms such as poor concentration and lack of motivation are common across mental health conditions. This application of VR may also be of benefit in young people experiencing mental illness, a population where digital technologies are common and their use for mental health is promising.

VR may enhance engagement with clinical evaluations through the immersive, realistic, enjoyable environments enabled by the technology. The term “presence” has been used in VR research to refer to the subjective experience of being in a place or environment, even when one is physically situated in another. The feeling of presence is influenced by the degree of immersion, defined as the extent to which the system generates sensory stimulation consistent with sensorimotor experience (eg, images are updated as the head moves). Sense of presence has traditionally been linked to an individual’s level of engagement and motivation. As such, high rates of presence and immersion reported within investigations of clinical uses of VR point to the ability of the technology to enhance engagement with clinical evaluation. However, it is currently difficult to create VR environments with a high level of realism, which can create a strong aversion to the experience.

VR could further increase engagement with clinical evaluation by adding elements of digital games to the assessments, a process known as “gamification.” Incorporating features of games, such as rewards and feedback, within VR may
engage individuals more fully in the evaluation process, limiting distractions that may compete for attention. Pollak et al.\(^5\) reported that young participants (aged 9 to 17) rated a VR attention-deficit/hyperactivity disorder (ADHD) assessment significantly more enjoyable than a computerized test of attention. The affordances inherent within VR technology have the potential to increase engagement with clinical evaluation for all individuals across presenting disorders, potentially improving the reliability and validity of the assessments.

**Applications of VR for assessment in clinical research studies**

Owing to the ecological validity, immersive capabilities, and ease of standardized data collection as discussed above, the field has begun to explore the use of VR for the assessment of clinically relevant outcomes. To date, these have fallen into three main areas: social functioning, cognition, and symptomatology. Social functioning can be assessed using automatic data capture such as eye gaze, proximity to VR avatars, and recording of responses to simulated social situations.\(^25,56\) Across studies, individuals with mental health conditions known to impact social functioning differed from control participants on VR-recorded measures. Cognition was among the first outcomes to be assessed with early-stage VR programs,\(^61-63\) focusing on memory and executive function, commonly assessed using maze navigation and attention tasks. For example, response to a VR-administered continuous performance task assessed attention and response inhibition in children and teens with ADHD compared with controls.\(^64\) Finally, VR environments have also been used to elicit and assess symptoms, such as paranoid ideation in the general population,\(^19,65\) individuals at risk for psychosis,\(^32,37\) those with a first-episode psychosis,\(^57\) and individuals with long-standing persecutory delusions.\(^56\) Other symptoms such as auditory hallucinations,\(^67\) disordered eating,\(^68\) addiction,\(^69\) and phobia\(^47\) have also been studied using VR.

**Considerations and limitations**

Whereas VR offers exciting opportunities to advance multiple areas of mental health, it is important to remain cautiously optimistic. Mirroring broader issues within the field of digital mental health, the following are major areas where caution is needed.

**Cost and access**

Although VR has been around for several decades, only recently has the technology advanced to the point of commercial readiness. A major milestone occurred in 2010 with the release of the *Oculus Rift*, a relatively affordable VR device directed at consumers. Prior to this, VR technology mainly existed behind the closed doors of software companies and specialized research labs.\(^1\) Over the past decade, we have seen rapid technological advancement and proliferation of the marketplace, with various companies offering a range of devices suited to different consumers and budgets. Critical to VRs viability, 2019 saw the release of the fully mobile HMD *Oculus Quest*.\(^70\) Mobile HMDs can be run without a cable connecting them to a computer, overcoming earlier problems with mobility and ease of use. It is now easier to imagine VR becoming commonplace in clinics, hospitals, and people’s homes because it is easier to set up and more convenient to use. However, the cost of these devices is still prohibitive for many, with the most recent version of the *Oculus Quest* costing around US $400. The biggest limiting factor to the implementation of VR into clinical practice at present is the lack of evidence-based VR programs that can be bought off the shelf and used by clinicians and researchers. A number of labs around the world are developing their own software packages and testing them, but they are not yet commercially available. The few commercially available products developed by software companies have not been tested to show whether they are safe and effective. Additionally, because the technology is advancing so rapidly, hardware becomes outdated quickly and proprietary issues limit the availability of VR applications across newer platforms. Consequently, we are yet to see VR have the same market penetration as smartphones, with only a small proportion of consumers currently owning these devices. Some clinicians have integrated VR into their practice,\(^71\) but again we are yet to see these treatments become widely available despite good evidence base for some approaches, particularly exposure therapy for anxiety disorders.\(^2\) In comparison, there has been a more steady increase in the use of VR within mental health research.\(^72\) The slow integration of VR into clinical care is due to many factors. These include a lack in infrastructure to support the technology within services, absence of training and standardized evidence-based VR packages, the learning curve and costs associated with adopting new technologies, and more broadly, fears that technology may hinder engage-
ment or even replace mental health professionals’ roles. For these reasons, it is imperative that new VR applications, and in fact any digital technology, are designed with considerations for the systems and context in which they will be implemented.

Developing evidence base
Traditionally, medical research is painstakingly slow at developing new evidence. Research is costly, time consuming, and in many ways, inefficient. This is particularly problematic in digital mental health, where research operates at a much slower pace compared to technology development. Therefore, research often lags behind in providing the evidence base necessary to justify the hype surrounding many technologies. As a result, the marketplace is largely dominated by mental health technologies that lack the evidence to substantiate their claims. VR is no exception, with a booming market of HMDs, games, and applications ready for consumer use.

In addition to the complexities in developing and validating new VR technologies, it is also difficult to maintain them. Updates to software and hardware require ongoing maintenance costs that are not afforded in the traditional funding model offered by research grants. Potential solutions are still unfolding; however, currently, it is rare for the technologies and applications developed by researchers to be widely available for consumers and clinicians. They are also often developed in isolation, with collaboration across research centers lacking. Better partnerships across institutions as well as with commercial companies may offer solutions to this problem, but until this time, clinicians and researchers may find themselves frustrated by the lack of readily available VR assessment tools.

Technical requirements and issues
Technology can be complex and unstable, with teams of experts required for effective development and maintenance. Anyone interested in developing new VR applications for research should be warned that considerable technical, design, and computational expertise is required. Enhancing ecological validity is a major offering of VR; however, the degree of immersion necessary to generate the sense of presence is a matter of ongoing research. Features that affect this sense of immersion include the display parameters of the VR system (eg, frame rate and resolution), design features (eg, realism of visual objects), and multisensory feedback. An interesting phenomenon related to this that is often observed in VR is termed the “uncanny” valley. This refers to the way in which humanoid characters in a virtual world can elicit a feeling of unease or revulsion if they look very human-like but are imperfect (eg, their breathing movements are not realistic), reducing the overall realism of the environment. Interestingly, avatars with more cartoon-like feature might overcome this problem as they are easily accepted and do not seem to elicit the same sense of unease as more real-like humanoids. Clearly, the design of reliable and immersive VR experiences is complex. This, combined with the computing power and hardware required to build and run VR experiences, is a challenge for those in the field.

Ethical issues
A number of reviews and commentaries have been written about the ethical landscape of digital mental health. Common themes across this literature include privacy, confidentiality, transparency, security, and ownership of data. These issues are also relevant to VR, especially when the application involves the collection of personal information and is accessed via the Internet. VR brings about more specific ethical challenges, however. More conceptually, the blurring of realities may have undue consequences on how we relate to and understand the world, perhaps especially so for conditions such as psychosis where reality distortion is already a challenge. As discussed previously, research has demonstrated that experiences in VR can have the same impact as if they occurred in the real world, necessitating considerable caution when conducting VR experiments designed to manipulate behavior. Some have commented on the dangers of enabling continual access to alternate realities, potentially perpetuating escape from the discomfort of the real world. The side effects of VR—namely, eye strain, cybersickness, and reality distortion—are also important considerations, and limited research exists on their long-term effects. In considering these factors, Madary and Metzinger, and Rizzo and Schulheis, provide recommendations for the ethical use of VR within research, drawing on general principles underpinning respect for rights and protection from harm.

Conclusion
Sufficient evidence has accumulated to support the benefits of VR for a variety of assessment purposes in mental health. VR elicits similar psychological and physiological reactions.
to real-world environments, extending the reach of current assessments beyond the lab or clinic. Superior capabilities for experimental manipulation and controlled exposure could significantly advance the field of mental health by improving methodological rigor, as well as enabling more accurate and individualized assessment. Automatic data capture of behaviors and signals from VR experiences can reveal important insights that might improve our understanding of mental health conditions and inform more tailored treatments. Advances in hardware, software, and research evidence has progressed in recent years; however, more studies are clearly needed to establish the reliability and validity of VR-based assessments, and issues with access to these resources and ethics require attention, thought, and research as the field develops.

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Brain health consequences of digital technology use

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Emerging scientific evidence indicates that frequent digital technology use has a significant impact—both negative and positive—on brain function and behavior. Potential harmful effects of extensive screen time and technology use include heightened attention-deficit symptoms, impaired emotional and social intelligence, technology addiction, social isolation, impaired brain development, and disrupted sleep. However, various apps, videogames, and other online tools may benefit brain health. Functional imaging scans show that internet-naive older adults who learn to search online show significant increases in brain neural activity during simulated internet searches. Certain computer programs and videogames may improve memory, multitasking skills, fluid intelligence, and other cognitive abilities. Some apps and digital tools offer mental health interventions providing self-management, monitoring, skills training, and other interventions that may improve mood and behavior. Additional research on the positive and negative brain health effects of technology is needed to elucidate mechanisms and underlying causal relationships.

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Keywords: emotional intelligence; digital technology; internet; media; neural activation; online searching

Introduction

During the past three decades, digital technology has transformed our daily lives. People at every age are now taking advantage of the vast amounts of available online information and communication platforms that connect them with others. This technology helps us to generate, store, and process enormous amounts of information and interact with each other rapidly and efficiently.

Most adults use the internet daily, and nearly one out of four report being online most of the time. Because of this transformation to an online world, neuroscientists have begun focusing their attention on how digital technology may be changing our brains and behavior. The emerging data suggest that constant technology use impacts brain function and behavior in both positive and negative ways. For example, older individuals suffering from cognitive decline could use the internet to access information to help them remain independent longer; however, many seniors with cognitive complaints are reluctant or unable to adopt new technologies. Our group’s functional magnetic resonance imaging (MRI) research tracking neural activity during simulated internet searches suggests that simply searching online may represent a form of mental exercise that can strengthen neural circuits. By contrast, the persistent multitasking that is characteristic of most technology users impairs cognitive performance. In this review, we highlight some of the research suggesting potential benefits and possible risks of using digital technology.
Potential harmful effects of digital technology use

Reduced attention
Multiple studies have drawn a link between computer use or extensive screen time (e.g., watching television, playing videogames) and symptoms of attention-deficit hyperactivity disorder (ADHD). A 2014 meta-analysis indicated a correlation between media use and attention problems.\(^5\) A recent survey of adolescents without symptoms of ADHD at the start of the study indicated a significant association between more frequent use of digital media and symptoms of ADHD after 24 months of follow-up.\(^6\) Although most of the research linking technology use and ADHD symptoms has involved children and adolescents, this association has been identified in people at any age.\(^7\)

The reason for the link between technology use and attention problems is uncertain, but might be attributed to repetitive attentional shifts and multitasking, which can impair executive functioning.\(^8\) Moreover, when people are constantly using their technology, they have fewer opportunities to interact offline and allow their brain to rest in its default mode.\(^9\)

Impaired emotional and social intelligence
Because of concern that a young, developing brain may be particularly sensitive to chronic exposure to computers, smartphones, tablets, or televisions, the American Academy of Pediatrics has recommended that parents limit screen time for children aged 2 years or younger, when the brain is particularly malleable.\(^10\) Spending extensive periods of time with digital media translates to spending less time communicating face to face.\(^11\)

Kirsh and Mounts\(^12\) explored the hypothesis that playing videogames would interfere with the ability to recognize emotions conveyed through facial expressions. They examined the effects of playing videogames on recognition of facial expressions of emotions in 197 students (ages 17 to 23 years). Participants played violent videogames before watching a series of calm faces morph into either angry or happy faces. Participants were asked to quickly identify the emotion while the facial expression changed. The authors found that happy faces were identified faster than angry faces, and that playing violent videogames delayed happy-face recognition time.

Our team at the University of California, Los Angeles (UCLA)\(^13\) hypothesized that preteens restricted from screen-based media would have more opportunities for face-to-face interactions, which would improve their ability to recognize nonverbal emotional and social cues. We studied 51 schoolchildren who spent five days at an overnight nature camp where television, computers, and smartphones were forbidden, and compared them with 54 school-based matched controls who continued their usual media practices (4 hours of screen time per day). At baseline and after 5 days, participants were assessed for their ability to recognize emotions from photographs of facial expressions and videotaped scenes of social interactions (without verbal cues). After 5 days, the nature camp participants restricted from screen time demonstrated significantly better recognition of nonverbal emotional and social cues than participants who continued their usual daily screen time. These findings suggest that time away from screen-based media and digital communication tools improves both emotional and social intelligence.

Technology addiction
Although not formally included in the *Diagnostic and Statistical Manual of Mental Disorders*,\(^14\) excessive and pathological internet use has been recognized as an internet addiction, which shares features with substance-use disorders or pathological gambling. Common features include preoccupations, mood changes, development of tolerance, withdrawal, and functional impairment.\(^15,16\) The global prevalence of internet addiction is estimated at 6%, but in some regions such as the Middle East the prevalence is as high as 11%.\(^17\) Students with internet addiction are more likely to suffer from ADHD symptoms than from other psychiatric disorders.\(^18\) You and colleagues\(^16\) reported that schoolchildren with internet addiction experienced significantly greater symptoms of inattention, hyperactivity, and impulsivity than non–internet-addicted students. Panagiotidi and Overton\(^19\) reported greater ADHD symptoms in adults aged 18 to 70 years with internet addiction: predictors of addiction included younger age, playing massively multiplayer online role-playing games, and spending more time online. Despite consistent associations between ADHD symptoms and internet addiction, a causal relationship has not been confirmed. It is possible that people with ADHD symptoms have a greater risk for developing technology addiction, but an alternative explanation is that extensive technology use from addictive behavior causes ADHD symptoms.
Surgeons who played videogames more than 3 hours each week made 37% fewer surgical errors [and] were 27% faster in response times... than surgeons who do not play videogames

Social isolation
Ninety percent of young adults in the United States use social media platforms such as Facebook, Twitter, Snapchat, and Instagram, and most visit these sites at least daily.20 Paradoxically, social media use is linked to social isolation (ie, a lack of social connections and quality relationships with others),21 which is associated with poor health outcomes and increased mortality.1

Primack and colleagues20 studied 1787 young adults (ages 19 to 32 years) and found that using social media 2 or more hours each day doubled the odds for perceived social isolation compared with use less than 30 minutes each day. Similar associations between perceived social isolation and social media use were observed in 213 middle-aged and older adults.22 Possible explanations for such findings include reduced offline social experiences and the tendency to make upward social comparisons based on highly curated social media feeds that produce unrealistic expectations of oneself.1 Future research should explore casual explanations for such relationships and seek ways to address the needs of people who may benefit from social media–based interventions, such as geographically isolated individuals.

Adverse impact on cognitive and brain development
Screen time may also adversely impact cognitive and brain development. In a recent review, children under age 2 were reported to spend over 1 hour each day in front of a screen; by age 3, that number exceeded 3 hours.23 Increased screen time (and less reading time) has been associated with poorer language development and executive functioning, particularly in very young children,24 as well as poorer language development in a large cohort of minority children.25 In infants, increased screen time was one of several factors that predicted behavioral problems.26 For infants 6 to 12 months, increased screen time was linked to poorer early language development.27 In children of preschool age and older, digital media directed toward active learning can be educational, but only when accompanied by parental interaction.23

Recent research has examined the effects of media exposure on brain development. In a study of children aged 8 to 12 years, more screen and less reading time were associated with decreased brain connectivity between regions controlling word recognition and both language and cognitive control.24 Such connections are considered important for reading comprehension and suggest a negative impact of screen time on the developing brain. Structurally, increased screen time relates to decreased integrity of white-matter pathways necessary for reading and language.28 Given the growing prominence of screen use among even very young children at stages when brain plasticity is greatest, there is significant concern about the cognitive and brain development of the current generation of screen-exposed children that requires greater understanding.

Sleep
Recent studies indicate that screen exposure disrupts sleep, which can have a negative effect on cognition and behavior. Daily touch-screen use among infants and toddlers was shown to negatively impact sleep onset, sleep duration, and nighttime awakenings.29 In adolescents, more time using smartphones and touch screens was associated with greater sleep disturbances, and tablet time was associated with poor sleep quality and increased awakenings after sleep onset.30 In adults, increased smartphone use was associated with shorter sleep duration and less efficient sleep.31 Poor sleep quality is associated with brain changes, such as reduced functional connectivity and decreased gray-matter volume, as well as an increased risk for age-associated cognitive impairment and Alzheimer disease.32,33 It is unclear whether the act of looking at screens or media content disrupts sleep; however, it is well-known that the wavelength of light exposure affects the circadian rhythms that govern sleep. Computer and phone light-emitting diode (LED) screens emit slow wave, blue light that interferes with circadian rhythms. Exposure to LED versus non-LED screens has been shown to produce changes in melatonin levels and sleep quality, and such exposure decreases cogni-
Thus, it is important to recognize the effects of screen time on sleep as a moderator of various negative effects on cognition and brain function.

**Brain-health benefits of digital technology**

Despite these potential harmful brain-health effects of digital technology, emerging evidence points to several benefits for the aging brain in particular, including opportunities for brain-strengthening neural exercise, cognitive training, and the online delivery of mental-health interventions and support (Table I).

**Neural exercise**

*Internet-savvy versus internet-naive adults*

Functional neuroimaging allows scientists to observe regional neural activity during various mental tasks. Our group was the first to explore neural activity using functional MRI while research volunteers performed simulated internet searching. Previous studies suggested that mentally challenging tasks, such as searching online, may benefit brain health and even delay cognitive decline. We focused on internet searching because it is so common among people of all ages.

We assessed patterns of brain neural activation in 24 cognitively normal middle-aged and older adults (ages 55 to 76 years): 12 of them had minimal internet search experience (net-naive group), and 12 had extensive experience (net-savvy group). In addition to the internet-search task, we used a control task of reading text on a computer screen formatted to simulate a printed book layout.

We found that text reading activated brain regions controlling language, reading, memory, and visual abilities (left inferior frontal, temporal, posterior cingulate, parietal, and occipital regions), and the magnitude and extent of activation were similar in the net-naive and net-savvy groups. During internet searching, net-naive subjects displayed activation patterns similar to those observed while reading text. However, net-savvy subjects demonstrated significant activity in neural signal intensity in additional regions controlling decision-making, complex reasoning, and vision (frontal pole, anterior temporal region, anterior and posterior cingulate, and hippocampus). During the internet-search task, the net-savvy group displayed a more than twofold increase in the extent of activation in the major regional clusters compared with the net-naive group (21 782 versus 8646 total activated voxels).

These findings suggest that searching online may be a form of brain neural exercise. Other research indicates that after several months, daily computer-game playing leads to reduced cortical neural activity. Our other research indicates that memory training, along with healthy life-

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*Table I*. Health-promoting digital technology strategies for the aging brain.
style behaviors (eg, physical exercise, healthy diet), leads to reduced dorsal prefrontal cortical metabolism after 2 weeks. Such findings suggest that task repetition over time leads to lower neural activity during the task, which could reflect greater cognitive efficiency after mental training.

One model that could explain such findings is that novel and stimulating mental experiences, such as searching on the internet, initially lead to minimal activation before the internet user discovers strategies for solving the unfamiliar mental challenge. After such insights, a broader neural network is engaged. After repeated sessions, the initially novel mental task becomes routine and repetitive, no longer posing a mental challenge. The lower activity observed may thus reflect a more efficient neural response. These results also suggest that previous internet-search experience may alter the brain’s responsiveness in neural circuits controlling decision-making and complex reasoning. The net-savvy volunteers showed increased activation during the internet-search task, which suggests that internet searching may remain a novel and mentally stimulating process even after continued practice.

**Internet training and brain function**

We also used functional MRI to record brain neural activity during simulated internet-search tasks in 12 net-naive and 12 net-savvy subjects before and after internet training. Based on our previous findings, we hypothesized that net-naive volunteers would recruit a larger frontal lobe network after internet training and that net-savvy volunteers would show either no increase or a decrease in activation after training because of greater cognitive efficiency due to training.

The training consisted of brief instructions on how to search online along with practice sessions (1 hour per day for a week). To increase motivation, participants were told that they would be quizzed on their knowledge of assigned search topics after the experiment.

During their first session, net-naive subjects recruited a neural network that included the superior, middle, and inferior frontal gyri, as well as the lateral occipital cortex and occipital pole. During the second session (after internet training), additional regions in the middle and inferior frontal gyri were recruited only in the net-naive group. By contrast, during their first scan session, the net-savvy subjects recruited a cortical network that, though overlapping with that of the net-naive subjects, showed more extensive regions of activation (Figures 1 and 2). This cortical network included regions that control mental activities supporting tasks required for internet searches, including decision-making, working memory, and the ability to suppress nonrelevant information. Moreover, net-savvy participants showed a pattern of activation that was reduced after the training. This reduction is consistent with our hypothesis that the brain becomes more efficient and possibly habituates to the internet task over time. Overall, these findings suggest that internet searching for relatively short periods of time can change brain-activity patterns in middle-aged and older adults.

Other groups have explored the effects of internet-search training on brain structure and function. Dong and associates studied the influence of short-term internet-search training on white-matter microstructure via diffusion tensor imaging. After 6 training days, they found that the 59 participants (mean age 21 years) showed increased fractional anisotropy (diffusion tensor imaging scans) in the right superior longitudinal fasciculus and within that region, decreased radial diffusivity. These findings suggest that short-term internet-search training may increase white-matter integrity in the right superior longitudinal fasciculus, which could result from increased myelination.
Shapira and colleagues\(^4\) assessed the psychological effects of learning computer and internet-search methods. They offered a course to 22 older adults (mean age 80 years), who were compared with 26 participants engaged in other activities. The investigators reported significant improvements in the intervention group in measures of life satisfaction, depression, loneliness, and self-control after 4 months, whereas the control group showed declines in each of these measures. These findings suggest that computer and internet training contribute to older adults’ well-being and sense of empowerment.

White and associates\(^4\) performed a randomized controlled trial assessing the psychosocial impact of internet access to older adults during a 5-month period. The intervention group (n=29) received 9 hours of training (6 sessions over 2 weeks) and experienced less loneliness, less depression, and more positive attitudes toward computers than controls (n=19) who were not regular internet users.

Cognitive training

**Memory ability**

Findings showing that mental stimulation and cognitive training improve memory in older adults\(^4\),\(^4\) have led to the development of several memory apps and computer games. Miller and associates\(^5\) explored whether computerized brain-training exercises (Dakim Brain Fitness) improved cognitive performance in older adults without dementia (mean age of 82 years). Subjects were randomized into an intervention group (n=36) that used a computer program 5 days a week for 20 to 25 minutes each day, or a waitlist control group (n=33). Neuropsychological testing at baseline, 2 months, and 6 months showed that the intervention group improved significantly in delayed memory, and the control group did not. Moreover, participants who played the computer program for at least 40 sessions over 6 months improved in immediate memory, delayed memory, and language. These findings point to the potential benefit of cognitive training using a computerized, self-paced program.

In a meta-analysis of computerized cognitive training, investigators found an overall moderate effect on cognition in mild cognitive impairment across 17 trials.\(^4\) Small to moderate effects were reported for global cognition, attention, working memory, and learning abilities.

**Multitasking skills**

Multitasking has been defined as performing two simultaneous tasks, which is only possible when the tasks are automatic, but it can also refer to rapid switching between tasks. Research has shown that such task switching increases error rates.\(^5\) Multitasking is common thanks to widespread technology use, and multiple studies point to its negative impact on cognitive performance.\(^5\) However, certain computer games may enhance multitasking, one of the cognitive domains that declines in a linear fashion across the lifespan.\(^5\)

Anguera and colleagues\(^5\) trained volunteers (ages 60 to 85 years) over 4 weeks using a videogame called NeuroRacer, in which players control a car on a winding road while responding to signs that randomly appear. Out of 46 participants, 16 were trained in multitasking (both driving and sign reading), 15 in single-tasking mode (active controls; either sign reading or driving), and 15 received no training (no-contact controls). Only the multitasking training group showed significant improvements in performance scores, which not only exceeded that of untrained individuals in their twenties but was maintained for 6 months without additional training. Moreover, the multitasking training

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**Figure 2. Overlay of pre-training and post-training scanning sessions.** Transaxial (left images) and coronal (right) views for pre-training (blue) and post-training (red) sessions showing increase in frontal activity (arrows) after training in the internet-naive group.
improved other cognitive skills, including working memory and divided and sustained attention.

**Working memory and fluid intelligence**
Fluid intelligence refers to the capacity to reason and think flexibly and requires working memory, the ability to retain information over a brief period of time. Investigators have found that training in working memory may improve fluid intelligence.\(^{50,51}\) Jaeggi and associates\(^{52}\) used a training program (n-back task) to investigate the effects of working-memory training on fluid intelligence. Healthy subjects (n=70) were randomized into working-memory training groups that were further randomized according to number of training sessions (8, 12, 17, or 19 days), or a control group that received no training. All subjects received pre- and post-testing on a measure of fluid intelligence at the same time intervals. The four groups not only showed significant improvements in working memory, but also on tests of fluid intelligence. Moreover, results demonstrated that the longer the training period, the greater the improvement in fluid intelligence. These results indicated successful transfer of improved working memory to improved fluid intelligence measures with a dose-dependent training effect.

**Visual attention and reaction time**
Videogames have been popular for decades, and many gamers who began playing in the 1980s have continued to play through adulthood. Despite potential negative health effects of excessive playing (eg, attention deficits, social withdrawal, increased risk of obesity), recent research suggests potential benefits, such as improved visual attention processing, spatial visualization, reaction time, and mental rotation. Green and Bavelier\(^{53}\) have shown that playing action videogames more than 4 days per week (at least 1 hour each day) for 6 months enhances visual attention (ie, the ability to recognize and process visual information), spatial attention over the visual field, and task-switching abilities.

Rosser and colleagues\(^{54}\) examined a potential link between action videogaming and laparoscopic surgical skills and suturing. Surgeons who played videogames more than 3 hours each week made 37% fewer surgical errors, were 27% faster in response times, and scored 42% better in measures of laparoscopic and suturing skills than surgeons who do not play videogames. Moreover, the most experienced players in specific videogames (Super Monkey Ball 2, Star Wars Racer Revenge, and Silent Scope) made 47% fewer errors and performed 39% faster. These findings suggest that playing action videogames can improve cognitive and motor skills that improve surgical skills and lower error rates in the operating room.

**Other mental health interventions**
Technological advances have brought about novel approaches for delivering mental health support and interventions in the form of apps for smartphones or tablets, as well as through telepsychiatry. Internet-based mental health interventions offer the advantages of accessibility, cost-effectiveness, and anonymity. Between 2009 and 2015, the National Institute of Mental Health awarded more than 400 grants totaling $445 million for technology-enhanced mental-health interventions to further investigate roles for technology in preventing and treating mental disorders.\(^{55}\)

Investigators have studied the efficacy of various online mental health interventions. For example, Peter and colleagues\(^{56}\) found that an online, 4-week intervention using cognitive behavioral therapy for insomnia reduced depression and insomnia ratings at levels comparable to traditional face-to-face interventions. Segal and associates\(^{57}\) evaluated the effectiveness of treating residual depressive symptoms with a web-based program that delivers mindfulness-based cognitive therapy. They found that use of this program in addition to usual depression care significantly improved depression and functional outcomes compared with usual depression care alone.

Several digital mental health applications have been developed or are in development, such as self-management apps that provide user feedback (eg, medication reminders, stress management tips, heart rate, and breathing patterns). Other programs provide skills training using educational videos on anxiety management or the importance of social support. Some applications have the capacity to collect data using smartphone sensors that record movement patterns, social interactions (eg, number of texts and phone calls), and other behaviors throughout the day.

Despite some promising early research, systematic studies demonstrating the efficacy of these emerging apps are limited. A recent review\(^{58}\) indicated that only 3% of downloadable apps had research to justify their effectiveness.
claims, and most of that research was performed by the program developers. Another recent survey\(^9\) of online-technology use to support mental health and well-being indicated that smartphone apps were the most commonly used technology: 78% of respondents used them either alone or in combination with other technologies. The apps that are being used provide guided activities, relaxation, and tracking; social media and discussion forums; and web-based programs to assist in the management of daily stress and anxiety.

Conclusions

Research on the brain-health consequences of digital technology is beginning to elucidate how these novel devices and programs can both help and harm brain function. Their frequent use heightens ADHD symptoms, interferes with emotional and social intelligence, can lead to addictive behaviors, increases social isolation, and interferes with brain development and sleep. However, specific programs, videogames, and other online tools may provide mental exercises that activate neural circuitry, improve cognitive functioning, reduce anxiety, increase restful sleep, and offer other brain-health benefits. Future research needs to elucidate underlying mechanisms and causal relationships between technology use and brain health, with a focus on both the positive and negative impact of digital technology use.

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Digital technology, including its omnipresent connectedness and its powerful artificial intelligence, is the most recent long wave of humanity’s socioeconomic evolution. The first technological revolutions go all the way back to the Stone, Bronze, and Iron Ages, when the transformation of material was the driving force in the Schumpeterian process of creative destruction. A second metaparadigm of societal modernization was dedicated to the transformation of energy (aka the “industrial revolutions”), including water, steam, electric, and combustion power. The current metaparadigm focuses on the transformation of information. Less than 1% of the world’s technologically stored information was in digital format in the late 1980s, surpassing more than 99% by 2012. Every 2.5 to 3 years, humanity is able to store more information than since the beginning of civilization. The current age focuses on algorithms that automate the conversion of data into actionable knowledge. This article reviews the underlying theoretical framework and some accompanying data from the perspective of innovation theory.

Keywords: artificial intelligence; creative destruction; digital age; digital revolution; information; information overload; information society; innovation; technology

New digital wine into the old wineskins of innovation theory

The discussion of digital technology and social change is part of the broader literature of innovation theory. Innovation theory is most commonly based on Schumpeter’s notion of socioeconomic evolution through technological change. The reputed “prophet of innovation” himself gave it an illustrative name: “creative destruction.” Creative destruction works on different levels, reaching from product cycles, over fashion and investment-life cycles (including so-called Kitchin and Juglar cycles), to so-called business cycles. The result is “an indefinite number of wavelike fluctuations which will roll on simultaneously and interfere with one another in the process… of different span and intensity… superimposed on each other.” High-level business cycles (also known as great surges or long waves) are emergent phenomena linked to technological paradigms that modernize the modus operandi of society as a whole, including its economic, social, cultural, and political organization.

Schumpeter extended, theorized, and generalized the work of the Soviet economist Nikolai Kondratieff, who had already identified two cycles of expansion, stagnation, and recession. He identified the key carrier technology of his first industrial revolution (1770-1850) as water-powered mechanization (including mills and irrigation systems, see Figure 1). The following long wave (1850-1900) was enabled by steam-powered technology.
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(including trains and industrial machinery). Kondratieff speculated that around 1900 a new cycle had started, which Schumpeter later called the “Third Kondratieff.” It was characterized by the electrification of social and productive organization, including manufacturing (1900-1940). Schumpeterian economists later added the long wave of motorization (1940-1970s), and the age of information and telecommunications thereafter.

Note that this specific scheme of historical classification promoted foremost by industrial economists could be complemented with other perspectives, including historical advances in medicine, military technology, institution or cultural evolution, or the very nature of communication itself. Independently of the detail of what technology transforms society exactly when, it is common practice in innovation theory to name long-term paradigms of human history after the dominating technological toolset. This practice is borrowed from historians, who commonly subdivide archaeological periodization of early civilizations into the descending sequence of the Stone Age, Bronze Age, and Iron Age (Figure 1). The general notion is that “civilization advances by extending the number of important operations which we can perform without thinking about them.” In order to trigger a great surge in form of a long wave, the automation needs to be driven by a so-called general purpose technology. Those fulfill “the following conditions: (i) clearly perceived low-and descending- relative cost; (ii) unlimited supply for all practical purposes; (iii) potential all-pervasiveness; (iv) a capacity to reduce the costs of capital, labor and products as well as to change them qualitatively.”

The fact that the consecutive long waves have tended to become shorter over the course of history (note that the Stone Age lasted 2 000 000, and the Bronze Age 2000 years) is due to the combinatorial logic of technological innovation (Schumpeter defined innovation as “carrying out New Combinations”). An accumulatively larger repertoire of possibilities leads to exponential progress.

![Figure 1. Schematic presentation of Schumpeterian long waves. GDP, gross domestic product](image-url)
The creative process of societal modernization is at the same time also destructive, and inseparably intertwined with financial bubbles, recession, and social crisis.

Each technological revolution, originally received as a bright new set of opportunities, is soon recognized as a threat to the established way of doing things in firms, institutions, and society at large. The new techno-economic paradigm gradually takes shape as a different “common sense” for effective action in any area of endeavor. But while competitive forces, profit seeking, and survival pressures help diffuse the changes in the economy, the wider social and institutional spheres — where change is also needed — are held back by strong inertia stemming from routine, ideology, and vested interests. It is this difference in rhythm of change, between the techno-economic and the socio-institutional spheres, that would explain the turbulent period.11

In short, the initial euphoria about the (often economic) opportunities is in every cycle followed by a subsequent sobering discovery of the (often societal) downsides. It is well known that the industrial revolutions have contributed much wealth, but also much inequality and many economic problems. The same is true for the current period of digital technology and social change.

The diffusion of the digital paradigm

The most recent period of this ancient and incessant logic of societal transformation was given many names between the 1970s and the year 2000, among them (in chronological order) post-industrial society,24 information economy,25 information society,26 fifth Kondratieff,19 information technology revolution,27 digital age,28 and information age.29 While only time will provide the required empirical evidence to set any categorization of this current period on a solid footing, recent developments have suggested that we are living through different long waves within the continuously evolving information age. Starting with Shannon’s conceptualization of “digital” in 1948 in the area of telecommunication (aka the “bit”),30 the Kuhnian process of scientific puzzle solving31 started by focusing on the problem of communication. The search for Shannon’s limit of utmost communication capacity kept engineers busy for almost half a century, but was eventually solved in the early 1990s (for all practical purposes).32 Since then, broadband communication has been sending entropic information through radio waves and fiber optic cables at the speed of light, which seems to be a fundamental limit to the speed of information transmission in our universe.

As always in technological paradigms, the process of successful technological innovation was closely followed by a process of technological diffusion.33,34 The world was swamped with internet connections and mobile phones in record time.35 The result was the resolution of space-time constraints in global communication29 and the accumulation of vast amounts of stored data, which has more recently been termed “big data.”36 We estimate the beginning of the “digital age” to be in 2002, when the world was first able to store more digital than analog information in its technological tools (Figure 2).37 In the late 1980s, still less than 1% was in digital format, whereas in 2012, 99% of the world’s stored information was digital.38 During these decades, the world’s technological capacity to communicate and store information has grown 25% to 35% per year (doubling every 2.5-3 years — see logarithmic left-hand side axis in Figure 2).38-40

As always, the diffusion of a new paradigm is never instantaneous, but takes place over social networks over time, which inevitably creates a divide between the have and have nots.34 Figure 2 also shows that the resulting digital divide has increasingly been closed internationally. Non-high-income countries provided 16% of the installed bandwidth capacity in the late 1980s but hosted more bandwidth than high-income countries after 2015 (led by China). It is good news that the divide among countries has become smaller. At the same time, within countries and among people worldwide, independent from their nationality, bandwidth capacity continues to correlate strongly with income.41,42 Since income inequality is notoriously
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persistent, it is expected that the digital bandwidth divide has become a systematic and permanent characteristic of modern societies, especially as its focus migrates from minimum connectivity to bandwidth.

The digital growth of information and communication led to the often-lamented information overload for humans, whose mental capacities get crunched in the ambitions of the information economy. At the same time, it led to the much-celebrated “unreasonable effectiveness of data” in discovering actionable knowledge through artificially intelligent machines. The world’s computational capacity has grown three times faster than our information storage and communication capacity (some 80% per year), which enabled us to analyze the provided data in an automated fashion. For many practitioners, artificial intelligence (AI) has become synonymous with data-driven machine learning, including the neural networks of deep learning architectures.

Advancements in the field of AI have been dazzling. AI has not only superseded humans in many intellectual tasks, like several kinds of cancer diagnosis and speech recognition (reducing AI’s word-error rate from 26% to 4% just between 2012 and 2016), but has also become an indispensable pillar of the most crucial building blocks of society. By now, most humans not only trust AI blindly with their lives on a daily basis through anti-lock braking systems in cars (ABS) and autopilots in planes, but also with the filtering of their cultural, economic, social, and political opinions. The electric grid is in the hands of AI; three out of four transactions on the US stock markets are executed by it; and one in three marriages in America begins online. If we were to study any other species that has outsourced almost all of its energy distribution decisions, three-quarters of its resource distribution decisions, and an average one-third of its procreation decision to some kind of intelligent and proactive system, it is unlikely that we would treat them as two distinct and independent systems. We would look at it...
as one inseparable and organically interwoven socio-technological system. From a historical perspective of social change, the merger between biological and AI has already crossed beyond any point of return, at least from the social science perspective of society as a whole. Currently, the downsides of this merger are starting to become obvious, including the loss of privacy, political polarization, psychological manipulation, addictive use, social anxiety and distraction, misinformation, and mass narcissism.33,54

**Amid the third metaparadigm**

Summing up, we can distinguish three different long-term metaparadigms, each with different long waves (Figure 1). The first focused on the transformation of material, including stone, bronze, and iron. The second, often referred to as industrial revolutions, was dedicated to the transformation of energy, including water, steam, electric, and combustion power. Finally, the most recent metaparadigm aims at transforming information. It started out with the proliferation of communication and stored data and has now entered the age of algorithms, which aims at creating automated processes to convert the existing information into actionable knowledge.

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