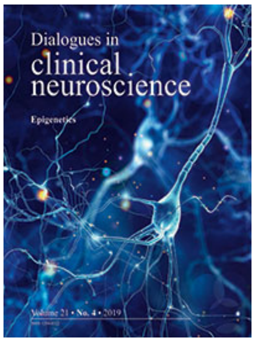

Dialogues in Clinical Neuroscience

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tdcn20

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

Martin Korte

To cite this article: Martin Korte (2020) The impact of the digital revolution on human brain and behavior: where do we stand?, Dialogues in Clinical Neuroscience, 22:2, 101-111, DOI: 10.31887/DCNS.2020.22.2/mkorte

To link to this article: https://doi.org/10.31887/DCNS.2020.22.2/mkorte

Published online: 01 Apr 2022.

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.

Dialogues Clin Neurosci. 2020;22(2):101-111. doi:10.31887/DCNS.2020.22.2/mkorte

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.

Author affiliations: Department of Cellular Neurobiology, Zoological Institute, TU Braunschweig, Germany; Helmholtz Centre for Infection Research, Neuroinflammation and Neurodegeneration Group, Braunschweig, Germany. **Address for correspondence:** Martin Korte, Prof Dr, TU Braunschweig, Zoological Institute, Dept. Cellular Neurobiology, Spielmannstraße 7, 38106 Braunschweig, Germany (email: m.korte@tu-bs.de)

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[1-3]; in psychological problems, from depression to anxiety and sleep disorders[4,5]; and in influencing the level of text comprehension while reading on screens.[6,7] 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.[7-9] 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.[9] In addition, the language scientist Naomi Baron, cited in an article by Makin,[10] 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.[1] 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.[11] 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.[11] 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.

> Neurons learn to represent artificial devices via processes of activity-dependent synaptic plasticity…, [illustrating] that, indeed, our sense of self can be altered by electronic technologies to incorporate external devices

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[12,13] 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.[14] For example, string instrument players have more cortical neurons of the somatosensory cortex allotted to the fingers they use in playing the instrument.[15] This so-called "cortical plasticity of sensory representation" is not limited to musicians; for example, it also occurs with often-repeated grasp movements.[16] As repeated finger movements occur with use of touchscreen smartphones, Gindrat et al[12,13] 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 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 al[18] 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 MRI[24,25] (*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 Grossee et al[26] and Skeide and Friederici.[27] 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 conclude[25]: "Given that screen-based media use is ubiquitous and increasing in children in home, childcare, and school settings, these findings suggest the need for

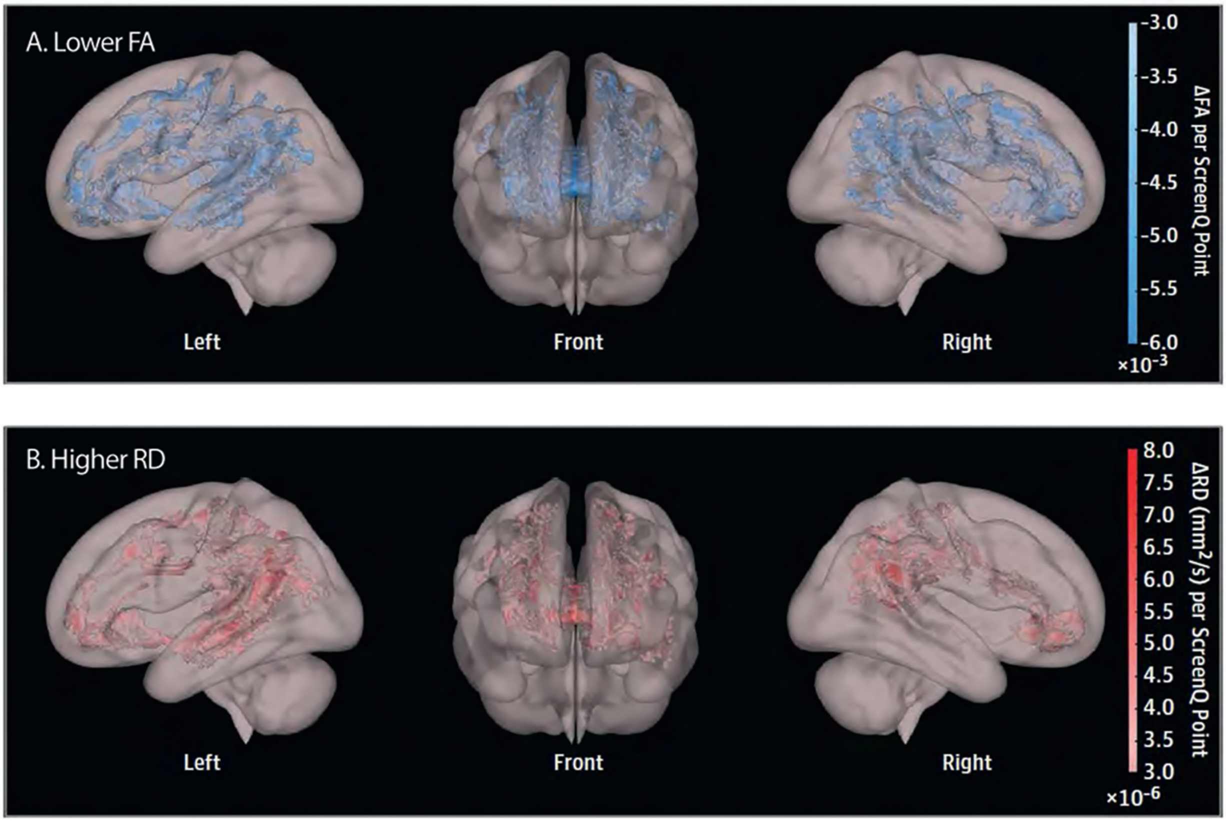

Figure 1. Diffusion tensor magnetic resonance imaging of brain in preschoolers, showing associations between use of screen-based media and white-matter integrity. White-matter voxels exhibit a statistically significant correlation between ScreenQ scores (which indicate screen-based media use, ie, how intensive digital media have been used) and lower fractional anisotropy (FA; A), as well as higher radial diffusivity (RD; B); both indicate fiber tract in the analysis of whole-brain images. All data were controlled for household income level and child age ($P<0.05$, familywise error–corrected). The color code depicts the magnitude or slope of correlation (change in the diffusion tensor imaging parameter for every point increase in ScreenQ score). Adapted from ref 24: Hutton JS, Dudley J, Horowitz-Kraus T, DeWitt T, Holland SK. Associations between screen-based media use and brain white matter integrity in preschool-aged children. *JAMA Pediatr.* 2019;e193869. doi:10.1001/jamapediatrics.2019.3869. Copyright © American Medical Association 2019

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.[28] 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

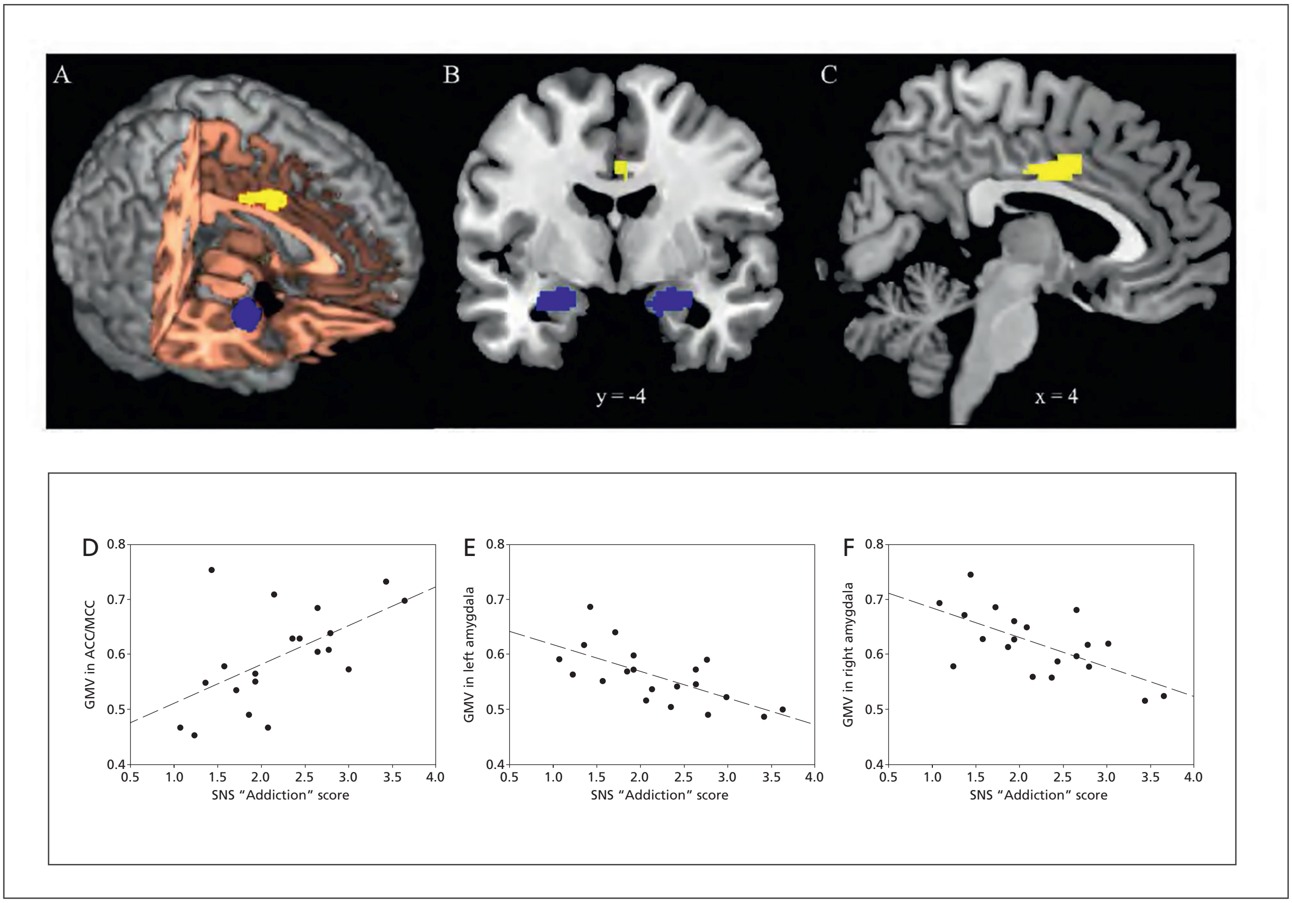

Figure 2. Magnetic resonance imaging of the human brain and analysis showing correlation between gray-matter volume (GMV) and social-networking site (SNS) addiction score. Depicted is the visualization of the voxel-wise–based morphometry (VBM) exemplified in three different views: (A) rendered brain; (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.

(DMN), and cerebellar association. 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.[29] 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 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*).[30,31] This suggests an important interplay between actual social experiences in online social networks and brain development.[32] 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.[33] 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.[34] 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.[34]

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.[35,36] 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[37]; for a review, see ref 38. Other studies, including one by Maguire[39] in London taxi drivers, and studies in pianists (as mentioned above)[14] and jugglers[40] 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").[41,42]

On the cellular level, this phenomenon has been named synaptic plasticity, reviewed by Korte and Schmitz.[35] 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).[35,43,44] 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.[41] 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.[45] 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[46] 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,[25] 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.[48] 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.[49] 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.[50] 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[51,52] (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/multitasking 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.[54] 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.[54] Adolescents in particular might be at risk.[55] 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[56] and D'Hondt et al.[57]

It is also noteworthy that some studies found a correlation between brain anatomy alterations and social networking site (SNS) addiction.[58] 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,[59] 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.[60-62] 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.[63] This works partly because neurons learn to represent artificial devices via processes of activity-dependent synaptic plasticity.[63] 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 algorism 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 Carr[65]). 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).[6,67] 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.[6] This demonstrates that multitasking, a rapidly growing behavioral trend, is associated with a distinct approach to fundamental information processing. Uncapher et al[6] 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 Turkle[5] 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 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.[69] 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.[69] 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,[70,71] 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. ■

Acknowledgments/Disclosures: The author declares no potential conflict of interest. I thank Dr Marta Zagrebelsky for critical comments on the manuscript.

References

1. Swing EL, Gentile DA, Anderson CA, Walsh DA. Television and video game exposure and the development of attention problems. *Pediatrics*. 2010;126(2):214-221.

2. Christakis DA, Zimmerman FJ, DiGiuseppe DL, McCarty CA. Early television exposure and subsequent attentional problems in children. *Pediatrics*. 2004;113(4):708-713.

3. Moisala M, Salmela V, Hietajarvi L, et al. Media multitasking is associated with distractibility and increased prefrontal activity in adolescents and young adults. *NeuroImage*. 2016;134:113-121.

4. Hoge E, Bickham D, Cantor J. Digital media, anxiety, and depression in children. *Pediatrics*. 2017;140(suppl 2):S76-S80.

5. Turkle S. *Alone Together: Why We Expect More from Technology and Less from Each Other*. New York, NY: Basic Books; 2011.

6. Uncapher MR, Lin L, Rosen LD, et al. Media multitasking and cognitive, psychological, neural, and learning differences. *Pediatrics*. 2017;140(suppl 2):S62-S66.

7. Kerr M, Symons S. Computerized presentation of text: effects on children's reading of informational material. *Read Writ*. 2006;19:1-19.

8. Mangen A, Walgermo B, Brønnick K. Reading linear texts on paper versus computer screen:

effects on reading comprehension. *Int J Educ Res.* 2013;58:61-68.
9. Mangen A, Olivier G, Velay JL. Comparing comprehension of a long text read in print book and on Kindle: where in the text and when in the story? *Front Psychol.* 2019;10:38.
10. Makin S. Searching for digital technology's effects on well-being. *Nature.* 2018;563(7733):S138-S140.
11. Ophir E, Nass C, Wagner AD. Cognitive control in media multitaskers. *Proc Natl Acad Sci U S A.* 2009;106(37):15583-15587.
12. Gindrat AD, Chytiris M, Balerna M, Rouiller EM, Ghosh A. Use-dependent cortical processing from fingertips in touchscreen phone users. *Curr Biol.* 2015;25(1):109-116.
13. Gindrat AD, Chytiris M, Balerna M, Rouiller EM, Ghosh A. Smartphone use shapes cortical tactile sensory processing from the fingertips [article in French]. *Med Sci (Paris).* 2015;31(4):363-366.
14. Elbert T, Pantev C, Wienbruch C, Rockstroh B, Taub E. Increased cortical representation of the fingers of the left hand in string players. *Science.* 1995;270(5234):305-307.
15. Pantev C, Engelien A, Candia V, Elbert T. Representational cortex in musicians. Plastic alterations in response to musical practice. *Ann N Y Acad Sci.* 2001;930:300-314.
16. Byl NN, Merzenich MM, Jenkins WM. A primate genesis model of focal dystonia and repetitive strain injury: I. Learning-induced dedifferentiation of the representation of the hand in the primary somatosensory cortex in adult monkeys. *Neurology*. 1996;47:508 -520.
17. Webster EK, Martin CK, Staiano AE. Fundamental motor skills, screen-time, and physical activity in preschoolers. *J Sport Health Sci.* 2019;8(2):114-121.
18. Gomez J, Barnett M, Grill-Spector K. Extensive childhood experience with Pokémon suggests eccentricity drives organization of visual cortex. *Nat Hum Behav.* 2019;3(6):611-624.
19. Mishkin M, Ungerleider LG, Macko KA. Object vision and spatial vision: two cortical pathways. *Trends Neurosci.* 1983;6:414-417.
20. Carrier LM, Spradlin A, Bunce JP, Rosen LD. Virtual empathy: positive and negative impacts of going online upon empathy in young adults. *Comput Human Behavr.* 2015;52:39-48.
21. James C, Davis K, Charmaraman L, et al. Digital life and youth well-being, social connecte dness, empathy, and narcissism. *Pediatrics.* 2017; 140(suppl 2):S71-S75.
22. Choudhury S, McKinney KA. Digital media, the developing brain and the interpretive plasticity of neuroplasticity. *Transcult Psychiatry.* 2013;50(2): 192-215.
23. Lahiry S, Choudhury S, Chatterjee S, Hazra A. Impact of social media on academic performance and interpersonal relation: a cross-sectional study among students at a tertiary medical center in East India. *J Educ Health Promot.* 2019;8:73.
24. Hutton JS, Dudley J, Horowitz-Kraus T, DeWitt T, Holland SK. Associations between home literacy environment, brain white matter integrity and cognitive abilities in preschool-age children. *Acta Paediatr.* 2019 December 18. Epub ahead of print. doi:10.1111/apa.15124.
25. Hutton JS, Dudley J, Horowitz-Kraus T, DeWitt T, Holland SK. Associations between screen-based media use and brain white matter integrity in preschool-aged children. *JAMA Pediatr.* 2019:e193869.
26. Grosse Wiesmann C, Schreiber J, Singer T, Steinbeis N, Friederici AD. White matter maturation is associated with the emergence of Theory of Mind in early childhood. *Nat Commun.* 2017;8:14692.
27. Skeide MA, Friederici AD. The ontogeny of the cortical language network. *Nat Rev Neurosci.* 2016; 17(5):323-332.
28. Hutton JS, Dudley J, Horowitz-Kraus T, DeWitt T, Holland SK. Differences in functional brain network connectivity during stories presented in audio, illustrated, and animated format in preschool-age children. *Brain Imaging Behav.* 2020;14(1):130-141.
29. Wolf M, Ullman-Shade C, Gottwald S. The emerging, evolving reading brain in a digital culture: implications for new readers, children with reading difficulties, and children without schools. *J Cogn Educ Psych.*11(3):230-240.
30. Pfeifer JH, Blakemore SJ. Adolescent social cognitive and affective neuroscience: past, present, and future. *Soc Cogn Affect Neurosci.* 2012;7(1): 1-10.
31. Kanai R, Bahrami B, Roylance R, Rees G. Online social network size is reflected in human brain structure. *Proc Proc Biol Sci.* 2012; 279(1732):1327-1334.
32. Meshi D, Tamir DI, Heekeren HR. The emerging neuroscience of social media. *Trends Cogn Sci.* 2015;19(12):771-782.
33. Crone EA, Konijn EA. Media use and brain development during adolescence. *Nat Commun.* 2018;9(1):588.
34. Anderson CA, Shibuya A, Ihori N, et al. Violent video game effects on aggression, empathy, and prosocial behavior in eastern and western countries: a meta-analytic review. *Psychol Bull.* 2010;136(2):151-173.
35. Korte M, Schmitz D. Cellular and system biology of memory: timing, molecules, and beyond. *Physiol Rev.* 2016;96(2):647-693.
36. Takeuchi T, Duszkiewicz AJ, Morris RG. The synaptic plasticity and memory hypothesis: encoding, storage and persistence. *Philos Trans R Soc Lond B Biol Sci.* 2014;369(1633):20130288.
37. Engert F, Bonhoeffer T. Dendritic spine changes associated with hippocampal long-term synaptic plasticity [see comments]. *Nature.* 1999; 399(6731):66-70.
38. Yuste R, Bonhoeffer T. Morphological changes in dendritic spines associated with long-term synaptic plasticity. *Ann Rev Neurosci.* 2001;24: 1071-1089.
39. Maguire EA, Gadian DG, Johnsrude IS, et al. Navigation-related structural change in the hippocampi of taxi drivers [see comments]. *Proc Natl Acad Sci U S A.* 2000;97(8):4398-4403.
40. Draganski B, Gaser C, Busch V, Schuierer G, Bogdahn U, May A. Neuroplasticity: changes in grey matter induced by training. *Nature.* 2004; 427(6972):311-312.
41. Hebb DO. *The Organization of Behavior. A Neuropsychological Theory.* New York, NY: Wiley; 1949.
42. Katz LC, Shatz CJ. Synaptic activity and the construction of cortical circuits. *Science.* 1996;274(5290):1133-1138.
43. Martin SJ, Grimwood PD, Morris RG. Synaptic plasticity and memory: an evaluation of the hypothesis. *Annu Rev Neurosci.* 2000;23:649-711.
44. Kandel ER, Dudai Y, Mayford MR. The molecular and systems biology of memory. *Cell.* 2014;157(1):163-186.
45. Magee JC, Grienberger C. Synaptic plasticity forms and functions. *Annu Rev Neurosci.* 2020 February 19. Epub ahead of print. doi:10.1146/annurev-neuro-090919-022842.
46. Sajikumar S, Morris RG, Korte M. Competition between recently potentiated synaptic inputs reveals a winner-take-all phase of synaptic tagging and capture. *Proc Natl Acad Sci U S A.* 2014;111(33):12217-12221.
47. Cabeza R, Albert M, Belleville S, et al. Maintenance, reserve and compensation: the cognitive neuroscience of healthy ageing. *Nat Rev Neurosci.* 2018;19(11):701-710.
48. Kuhn S, Lorenz RC, Weichenberger M, et al. Taking control! Structural and behavioural plasticity in response to game-based inhibition training in older adults. *Neuroimage.* 2017;156:199-206.
49. Kuhn S, Brass M, Gallinat J. Imitation and speech: commonalities within Broca's area. *Brain Struct Funct.* 2013;218(6):1419-1427.
50. Klingberg T. Training and plasticity of working memory. *Trends Cogn Sci.* 2010;14(7):317-324.
51. Shah TM, Weinborn M, Verdile G, Sohrabi HR, Martins RN. Enhancing cognitive functioning in healthly older adults: a systematic review of the clinical significance of commercially available computerized cognitive training in preventing cognitive decline. *Neuropsychol Rev.* 2017;27(1):62-80.
52. Pallavicini F, Ferrari A, Mantovani F. Video games for well-being: a systematic review on the application of computer games for cognitive and emotional training in the adult population. *Front Psychol.* 2018;9:2127.
53. Katz B, Shah P, Meyer DE. How to play 20 questions with nature and lose: reflections on 100 years of brain-training research. *Proc Natl Acad Sci U S A.* 2018;115(40):9897-9904.
54. Brand M, Young KS, Laier C, Wolfling K, Potenza MN. Integrating psychological and neurobiological considerations regarding the development and maintenance of specific Internet-use disorders: an Interaction of Person-Affect-Cognition-Execution (I-PACE) model. *Neurosci Biobehav Rev.* 2016;71:252-266.
55. Rehbein F, Kliem S, Baier D, Mossle T, Petry

NM. Prevalence of Internet gaming disorder in German adolescents: diagnostic contribution of the nine DSM-5 criteria in a state-wide representative sample. *Addiction*. 2015;110(5):842-851.
56. Yao YW, Liu L, Ma SS, et al. Functional and structural neural alterations in Internet gaming disorder: a systematic review and meta-analysis. *Neurosci Biobehav Rev*. 2017;83:313-324.
57. D'Hondt F, Billieux J, Maurage P. Electrophysiological correlates of problematic Internet use: critical review and perspectives for future research. *Neurosci Biobehav Rev*. 2015;59:64-82.
58. He Q, Turel O, Bechara A. Brain anatomy alterations associated with Social Networking Site (SNS) addiction. *Sci Rep*. 2017;7:45064.
59. Nicolelis MAL. Are we at risk of becoming biological digital machines? *Nat Human Behav*. 2017;1(1):0008.
60. Widge AS, Zorowitz S, Basu I, et al. Deep brain stimulation of the internal capsule enhances human cognitive control and prefrontal cortex function. *Nat Commun*. 2019;10(1):1536.
61. Polania R, Nitsche MA, Ruff CC. Studying and modifying brain function with non-invasive brain stimulation. *Nat Neurosci*. 2018;21(2):174-187.
62. Lozano AM, Lipsman N, Bergman H, et al. Deep brain stimulation: current challenges and future directions. *Nat Rev Neurol*. 2019;15(3):148-160.
63. Carmena JM, Lebedev MA, Crist RE, et al. Learning to control a brain-machine interface for reaching and grasping by primates. *PLoS Biol*. 2003;1(2):E42.
64. Shokur S, Gallo S, Moioli RC, et al. Assimilation of virtual legs and perception of floor texture by complete paraplegic patients receiving artificial tactile feedback. *Sci Rep*. 2016;6:32293.
65. Carr N. *The Glass Cage. Automation and Us*. New York, NY: W. W. Norton & Co; 2014.
66. Sparrow B, Liu J, Wegner DM. Google effects on memory: cognitive consequences of having information at our fingertips. *Science*. 2011;333(6043):776-778.
67. Brown TI, Uncapher MR, Chow TE, Eberhardt JL, Wagner AD. Cognitive control, attention, and the other race effect in memory. *PloS ONE*. 2017;12(3):e0173579.
68. Dunbar RIM. The anatomy of friendship. *Trends Cogn Sci*. 2018;22(1):32-51.
69. Reeves B, Robinson T, Ram N. Time for the Human Screenome Project. *Nature*. 2020;577(7790):314-317.
70. Ram N, Yang X, Cho M-J, et al. Screenomics: a new approach for observing and studying individuals' digital lives. *J Adolesc Res*. 2019;35(1):16-50.
71. Gijsen V, Maddux M, Lavertu A, et al. #Science: the potential and the challenges of utilizing social media and other electronic communication platforms in health care. *Clin Transl Sci*. 2020;13(1):26-30.