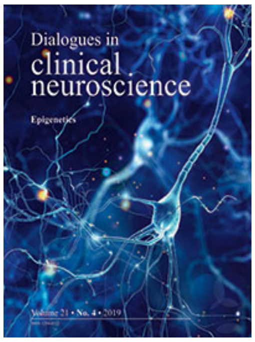

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Original article

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.[1] 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.[2] 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.[3] By contrast, the persistent multitasking that is characteristic of most technology users impairs cognitive performance.[4] In this review, we highlight some of the research suggesting potential benefits and possible risks of using digital technology.

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Potential harmful effects of digital technology use

Reduced attention

Multiple studies have drawn a link between computer use or extensive screen time (eg, 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.

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 colleagues[20] 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.

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

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 cognitive performance.[34] 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.[3] Previous studies suggested that mentally challenging tasks, such as searching online, may benefit brain health and even delay cognitive decline.[35,36] We focused on internet searching because it is so common among people of all ages.[37]

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.[38] Our other research indicates that memory training, along with healthy life-

STRATEGIES	BRAIN-HEALTH PROMOTING TARGETS
Online searching	Neural activation of circuits controlling decision-making and complex reasoning
Cognitive training games	Global cognition, memory (immediate, delayed, and working), attention, learning abilities
Racecar videogames with distracting road signs	Multitasking skills
N-back task training games	Working memory, fluid intelligence
Action videogames	Visual attention, reaction time, task-switching abilities
Monitoring apps	Heart rate, breathing patterns
Psychotherapy, educational apps	Mood, sleep, social support

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.[36] 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.[39] 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[40] 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.

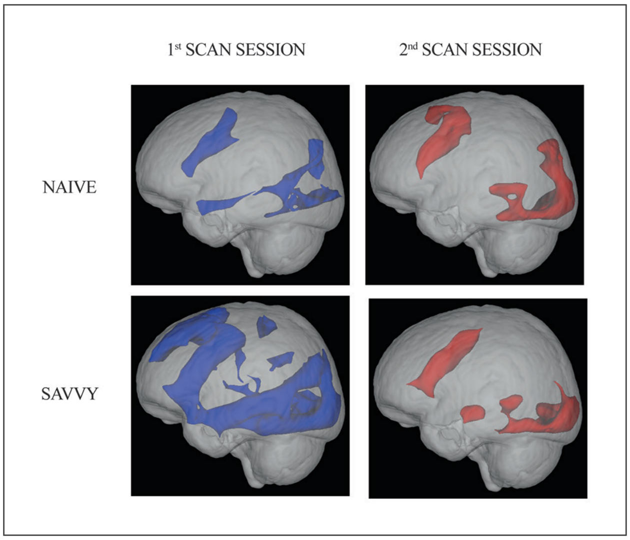

Figure 1. Internet-searching task activations before and after training in internet-naive and internet-savvy subjects. Areas of activation are indicated in blue for baseline and in red for patterns after training.

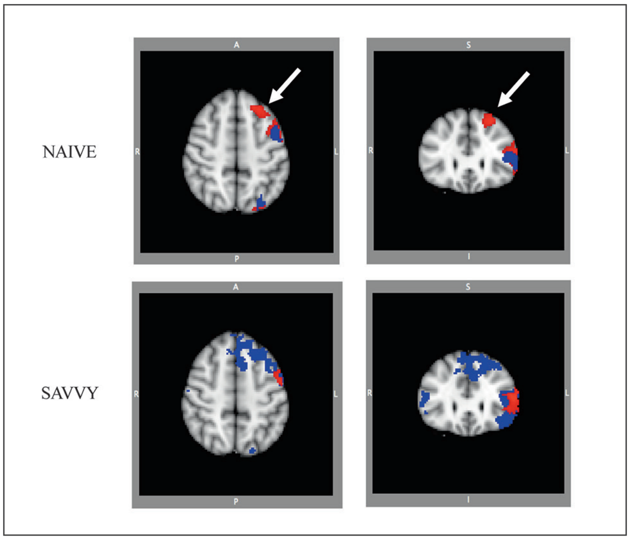

Figure 2. Overlay of pre-training and post-training scanning sessions. Transaxial (left images) and coronal (right) views for pre-training (blue) and post-training (red) sessions showing increase in frontal activity (arrows) after training in the internet-naive group.

Shapira and colleagues[41] 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[42] 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[43,44] have led to the development of several memory apps and computer games. Miller and associates[45] 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 wait-list 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.[46] 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.[47] Multitasking is common thanks to widespread technology use, and multiple studies point to its negative impact on cognitive performance.[48] However, certain computer games may enhance multitasking, one of the cognitive domains that declines in a linear fashion across the lifespan.[48]

Anguera and colleagues[49] 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 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[59] 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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