

The “online brain”: how the Internet may be changing our cognition

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The impact of the Internet across multiple aspects of modern society is clear. However, the influence that it may have on our brain structure and functioning remains a central topic of investigation. Here we draw on recent psychological, psychiatric and neuroimaging findings to examine several key hypotheses on how the Internet may be changing our cognition. Specifically, we explore how unique features of the online world may be influencing: a) attentional capacities, as the constantly evolving stream of online information encourages our divided attention across multiple media sources, at the expense of sustained concentration; b) memory processes, as this vast and ubiquitous source of online information begins to shift the way we retrieve, store, and even value knowledge; and c) social cognition, as the ability for online social settings to resemble and evoke real-world social processes creates a new interplay between the Internet and our social lives, including our self-concepts and self-esteem. Overall, the available evidence indicates that the Internet can produce both acute and sustained alterations in each of these areas of cognition, which may be reflected in changes in the brain. However, an emerging priority for future research is to determine the effects of extensive online media usage on cognitive development in youth, and examine how this may differ from cognitive outcomes and brain impact of uses of Internet in the elderly. We conclude by proposing how Internet research could be integrated into broader research settings to study how this unprecedented new facet of society can affect our cognition and the brain across the life course.

Key words: Internet, cognition, attention, memory, social structures, social media, addiction, virtual reality

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The Internet is the most widespread and rapidly adopted technology in the history of humanity. In only decades, Internet use has completely re-invented the ways in which we search for information, consume media and entertainment, and manage our social networks and relationships. With the even more recent advent of smartphones, Internet access has become portable and ubiquitous to the point at which the population of the developed world can be considered “online”^{1–3}.

However, the impact that this new channel for connection, information, communication, and screen time is having on our brains and cognitive functioning is unclear. Prior to the Internet, a large body of research had convincingly demonstrated that the brain is somewhat malleable to environmental demands and stimuli, particularly with regards to learning new processes, due to its capacity for neuroplasticity⁴. Various scenarios have been observed to induce long-term changes in the neuronal architecture of the human brain, including second-language acquisition⁵, learning new motor skills (such as juggling)⁶, and even formal education or exam preparation⁷. The widespread use of the Internet across the globe has introduced, for many, the necessity and opportunity to learn a myriad of new skills and ways to interact with society, which could bring about neural changes. As an example, even simple interactions with the Internet through the smartphone’s touchscreen interface have been demonstrated to bring about sustained neurocognitive alterations due to neural changes in cortical regions associated with sensory and motor processing of the hand and

thumb⁸. Beyond this, the Internet also presents a novel platform for almost-endless learning of new information and complex processes, relevant to both the online and offline world⁹.

Along with neuroplastic mechanisms, other environmental and biological factors can also cause changes in the brain’s structure and function, resulting in cognitive decline¹⁰. In aging samples, for instance, there is evidence to indicate that age-related cognitive decline may be partly driven by a process of atrophy. Some studies have shown that adopting a less engaging lifestyle across the lifespan may accelerate loss of cognitive function¹¹, due to lower “cognitive reserve” (the ability of the brain to withstand insult from age and/or pathology)¹². Some emerging evidence indicates that disengaging from the “real world” in favor of virtual settings may similarly induce adverse neurocognitive changes. For example, a recent randomized controlled trial (RCT)¹³ found that six weeks of engaging in an online role playing game caused significant reductions in grey matter within the orbitofrontal cortex – a brain region implicated in impulse control and decision making. However, the study did not address the extent to which these results were specific to online gaming, rather than general internet usage. Nonetheless, this raises the possibility that various types of Internet usage could differentially affect the brain and cognitive processes – in both adverse and beneficial ways. This may be of particular relevance to the developing brains of children and adolescents, as many cognitive processes (particularly those relevant to higher executive functions and social cognition)

are not entirely innate, but rather are strongly influenced by environmental factors¹⁴.

Although only recently emerging, this possibility has led to a substantial body of research empirically investigating the multiple potential pathways through which the Internet could affect our brains' structure, function, and cognitive development. Specifically, the bulk of existing research can be separated into three specific domains, examining how the internet is affecting: a) attention (i.e., how the constant influx of online information, prompts and notifications competing for our attention may encourage individuals to displace their concentration across multiple incoming media streams – and the consequences this may have for attentional-switching versus sustained-attention tasks); b) memory and knowledge (i.e., the extent to which we rely on the Internet as our primary informational resource, and how unique properties of online information access may affect how we process new memories and value our internal knowledge); c) social cognition (along with the personal and societal consequences of increasingly embedding our social networks, interactions, and status within the online world).

In this state-of-the-art review, we present the current leading hypotheses of how the Internet may alter these cognitive processes, subsequently examining the extent to which these hypotheses are supported by recent findings from psychological, psychiatric and neuroimaging research. In this way, we aggregate the contemporary evidence arising from multiple fields of research to produce revised models on how the Internet may be affecting our brains and cognition. Furthermore, whereas studies to date have focused upon only specific age groups, we examine the effects of the Internet on the human brain across the entire life course. In particular, we explore how the potential benefits/drawbacks of extensive Internet integration with cognitive processes may differ among children and older adults. Finally, we identify important gaps in the existing literature to present key priorities for future research in order to gain new insights for minimizing detrimental effects of the Internet, while capitalizing on this new feature of our societies to potentially influence neurocognitive processes in a beneficial way.

“DIGITAL DISTRACTIONS”: A HIJACK OF ATTENTION ON THE INFORMATION HIGHWAY?

How does the Internet gain and sustain our attention?

The Internet consumes a considerable chunk of our attention on a day-to-day basis. The vast majority of adults go online daily, and over a quarter report being online “almost constantly”². Within this, one in five American adults are now “smartphone-only” Internet users¹. Importantly, the introduction of these Internet-enabled mobile devices has also reduced the “digital divide” previously experienced by lower and middle income countries¹⁵. The amount and frequency of Internet usage is even more pronounced amongst younger people. Most adults today witnessed the beginning of the

transition from “Internet-free” to “Internet-everywhere” societies. However, younger generations (termed “digital natives”¹⁶) have been brought up entirely within a “connected world”, particularly in developed countries. Consequently, digital natives are often the first to adopt new online technologies as they arise¹⁶, and engage extensively with all existing features of the Internet. For instance, 95% of US teens have access to a smartphone, and 45% are online “almost constantly”³.

Multiple factors are driving the rapid uptake and extensive usage of Internet-enabled technologies across the globe. This is partly due to the Internet now being unavoidable, ubiquitous, and a highly functional aspect of modern living. For instance, Internet use is now deeply entwined with education, travel, socializing, commerce, and the majority of workplaces. Along with pragmatic uses, the Internet also offers an endless array of recreational and entertainment activities, through podcasts, e-books, videos, streaming movies and gaming. However, the ability of the Internet to capture and hold attention is not solely due to the quality of media content available online. Rather, it is also driven by the underlying design and presentation of the online world. One such example is the self-evolving “attraction mechanism”; whereby aspects of the Internet that fail to gain attention are quickly drowned out in the sea of incoming information, while the successful aspects of the adverts, articles, apps or anything that does manage to capture our attention (even superficially) are logged (through clicks and scrolls), noticed (through online shares), and subsequently proliferated and expanded upon. Alongside this, leading technology companies have been accused of intentionally capitalizing on the addictive potential of Internet, by studying, testing, and refining the attention-grabbing aspects of their websites and applications (“apps”) to promote extremely high levels of engagement, without due concern for user well-being¹⁷.

Furthermore, even when not using the Internet for any specific purpose, smartphones have introduced widespread and habitual “checking” behaviours, characterized by quick but frequent inspections of the device for incoming information from news, social media, or personal contacts¹⁸. These habits are thought to be the result of behavioural reinforcement from “information rewards” that are received immediately on checking the device¹⁹, potentially engaging the cortico-striatal dopaminergic system due to their readily available nature²⁰. The variable-ratio reinforcement schedule inherent to device checking may further perpetuate these compulsive behaviours²¹.

Cognitive consequences of the attention-grabbing Internet

The unprecedented potential of the Internet to capture our attention presents an urgent need for understanding the impact that this may have on our thought processes and well-being. Already, education providers are beginning to perceive detrimental effects of the Internet on children’s attention, with over 85% of teachers endorsing the statement that “today’s digital

technologies are creating an easily distracted generation²². The primary hypothesis on how the Internet affects our attentional capacities is through hyperlinks, notifications, and prompts providing a limitless stream of different forms of digital media, thus encouraging us to interact with multiple inputs simultaneously, but only on a shallow level, in a behavioural pattern termed “media multi-tasking”^{23,24}.

The seminal study by Ophir et al²³ was among the first to explore the sustained impact of media multi-tasking on cognitive capacities. This was a cross-sectional study of individuals who engaged in “heavy” (i.e., frequent and extensive) media multi-tasking compared to those who did not. Cognitive testing of the two groups produced the then-surprising finding that those involved in heavy media multi-tasking performed worse in task-switching tests than their counterparts – contrary to the authors’ expectation that the “extra practice” afforded by frequent media multi-tasking would confer cognitive benefit in task-switching scenarios. Closer inspection of findings suggested that the impeded task-switching ability in heavy media multi-tasking individuals was due to their increased susceptibility to distraction from irrelevant environmental stimuli²³.

Since these initial findings, the effects of media multi-tasking on cognition have come under increasing scrutiny, because the increasingly diverse forms of entertainment and activities available through the online world can further our capabilities (and temptation) of engaging in media multi-tasking²⁵, even on single devices. For instance, Yeykelis et al²⁶ measured participants’ media multi-tasking between different types of online media content while using just one device (personal laptops), and found that switches occurred as frequently as every 19 seconds, with 75% of all on-screen content being viewed for less than one minute. Measures of skin conductance during the study found that arousal increased in the seconds leading up to media switching, reaching a high point at the moment of the switch, followed by a decline afterward²⁶. Again, this suggests that the proclivity for alternating between different computer windows, opening new hyperlinks, and performing new searches could be driven by the readily available nature of the informational rewards, which are potentially awaiting in the unattended media stream. Supporting this, the study also found that, whereas switching from work-related content to entertainment was associated with increased arousal in anticipation of the switch, there was no anticipatory arousal spike associated with entertainment to work-content switches²⁶.

The growing concern around the increasing amount of media multi-tasking with the spread of ubiquitous Internet access has resulted in further empirical studies. These have produced conflicting findings, with some failing to find any adverse effects on attention²⁷, and others indicating that media multi-tasking may even be linked to increased performance for other aspects of cognition, such as multisensory integration²⁸. Nonetheless the literature, on balance, does seem to indicate that those who engage in frequent and extensive media multi-tasking in their day-to-day lives perform worse in various cognitive tasks than those who do not, particularly for sustained attention²⁵.

Imaging studies have shed light onto the neural differences which may account for these cognitive deficits. Functionally, those who engage in heavy media multi-tasking perform poorer in distracted attention tasks, even though exhibiting greater activity in right prefrontal regions²⁹. As right prefrontal regions are typically activated in response to distractor stimuli, the observed increases in recruitment of these regions alongside poorer performance suggests that heavy media multi-taskers require greater cognitive effort to maintain concentration when faced with distractor stimuli²⁹. Structurally, high levels of Internet usage³⁰ and heavy media multi-tasking³¹ are associated with decreased grey matter in prefrontal regions associated with maintaining goals in face of distraction (such as the right frontal pole and anterior cingulate cortex). However, the findings to date must be interpreted with caution, as various confounding factors may be affecting the results of these cross-sectional imaging studies. Although the differences persist when controlling for general digital media use and other simple confounders (age, gender, etc.), further research is required to examine if the observed neural differences are specifically attributable to heavy vs. light media multi-tasking, or in fact driven by broader differences in lifestyle between the two groups.

Given the amount of time that people now spend in media multi-tasking via personal digital devices, it is increasingly relevant to consider not only sustained changes which arise in those who engage in large amounts of media multi-tasking, but also the acute effects on immediate cognitive capacities. A meta-analysis of 41 studies showed that engaging in multi-tasking was associated with significantly poorer overall cognitive performance, with a moderate-to-large effect size (Cohen’s $d = -0.71$, 95% CI: -0.86 to -0.57). This has been confirmed by more recent studies, further showing that even short-term engagement with an extensively hyperlinked online environment (i.e., online shopping for 15 minutes) reduces attentional scope for a sustained duration after coming offline, whereas reading a magazine does not produce these deficits³².

Overall, the available evidence strongly indicates that engaging in multi-tasking via digital media does not improve our multi-tasking performance in other settings – and in fact seems to decrease this cognitive capacity through reducing our ability to ignore incoming distractions. Much of the multi-tasking investigations so far have been focusing on personal computers. However, smartphone technologies may even further encourage people to engage in media multi-tasking through high rates of incoming prompts from emails, direct messages and social media notifications occurring while both using and not using the device. Thus, along with determining long-term consequences of media multi-tasking, future research should examine how the constant multi-tasking made possible by Internet-enabled mobile devices may impact daily functioning through acute but high frequency effects.

Furthermore, both the immediate and chronic effects of media multi-tasking are relatively unexplored in children and adolescents, who are the prime users of such technologies³³ and are at a phase of development that is crucial for refining

higher cognitive abilities¹⁴. The first longitudinal study of media multi-tasking in young people has recently found that frequent multi-tasking behaviours do predict the development of attentional deficits specifically in early adolescents, but not in older teens³⁴. Additionally, extensive media multi-tasking during childhood and adolescence could also negatively impact cognitive development through indirect means, by reducing engagement with academic and social activities, as well as by interfering with sleep³⁵, or reducing the opportunity to engage in creative thinking^{36,37}. Clearly, further research is necessary to properly measure the effects of ubiquitous computing on children's cognitive development, and to find practical ways for ameliorating any detrimental impact this may be having.

“iFORMATION”: NEUROCOGNITIVE RESPONSES TO ONLINE INFORMATION GATHERING

The Internet and transactive memory

In response to the question “How has the Internet changed your life?”, some common answers include finding new friends, renewing old friendships, studying online, finding romantic relationships, furthering career opportunities, shopping, and travel³⁸. However, the most common answer is people stating that the Internet has “changed the way in which they access information”³⁸. Indeed, for the first time in human history, the majority of people living in the developed world have access to almost all factual information in existence literally at their fingertips.

Along with the obvious advantages, this unique situation also introduces the possibility of the Internet ultimately negating or replacing the need for certain human memory systems – particularly for aspects of “semantic memory” (i.e., memory of facts) – which are somewhat independent from other types of memory in the human brain³⁹. An initial indication of Internet information gathering affecting typical memory processes was provided by Sparrow et al⁴⁰, who demonstrated that the ability to access information online caused people to become more likely to remember where these facts could be retrieved rather than the facts themselves, indicating that people quickly become reliant on the Internet for information retrieval.

It could be argued that this is not unique to the Internet, but rather just an example of the online world acting as a form of external memory or “transactive memory”^{40,41}. Transactive memory has been an integral part of human societies for millennia, and refers to the process by which people opt to outsource information to other individuals within their families, communities, etc., such that they are able to just remember the source of the knowledge, rather than attempting to store all of this information themselves⁴¹. Although beneficial at a group level, using transactive memory systems does reduce an individual's ability to recall the specifics of the externally stored information⁴². This may be due to individuals using transactive memory for “cognitive offloading”, implicitly reducing their

allocation of cognitive resources towards remembering this information, since they know this will be available for future reference externally. This phenomenon has been demonstrated in multiple contexts, including those of team work⁴³ and other “non-Internet” technologies (e.g., photography reducing individuals' memories of the objects they photographed)⁴⁴.

However, it is becoming clear that the Internet actually presents something entirely novel and distinct from previous transactive memory systems^{45,46}. Crucially, the Internet seems to bypass the “transactional” aspect that is inherent to other forms of cognitive offloading in two ways. First, the Internet does not place any responsibility on the user to retain unique information for others to draw upon (as would typically be required in human societies)⁴⁵. Second, unlike other transactive memory stores, the Internet acts as a single entity that is responsible for holding and retrieving virtually all factual information, and thus does not require individuals to remember what exact information is externally stored, or even where it is located. In this way, the Internet is becoming a “supernormal stimulus”⁴⁶ for transactive memory – making all other options for cognitive offloading (including books, friends, community) become redundant, as they are outcompeted by the novel capabilities for external information storage and retrieval made possible by the Internet.

How does a supernormal stimulus interact with normal cognition?

Unfortunately, the rapid methods of acquisition and constant availability of information afforded by the Internet may not necessarily lead to better use of information gained. For instance, an experimental study⁴⁷ found that individuals instructed to search for specific information online completed the information gathering task faster than those using printed encyclopedias, but were subsequently less able to recall the information accurately.

During Internet and encyclopedia information gathering tasks, functional magnetic resonance imaging was used to examine activation in the ventral and dorsal streams. These regions are referred to as the “what” and “where” streams, respectively, due to their indicated roles in storing either the specific content (ventral stream) or external location (dorsal stream) of incoming information⁴⁷. Although there was no difference in activation of the dorsal stream, results showed that the poorer recall of Internet-sought information compared to encyclopedia-based learning was associated with reduced activation of the ventral (“what”) stream during online information gathering. These findings further support the possibility, initially raised by Sparrow et al⁴⁰, that online information gathering, while faster, may fail to sufficiently recruit brain regions for storing information on a long-term basis.

The potential for online searching to produce a sustained impact upon our cognitive processes has been investigated in a series of studies examining pre-post changes following a

six-day Internet search training paradigm. In these studies, young adults were given an hour per day of Internet search tasks, and undertook an array of cognitive and neuroimaging assessments pre- and post-training. Results showed that the six-day Internet search training reduced regional homogeneity and functional connectivity of brain areas involved in long-term memory formation and retrieval (e.g., temporal gyrus)⁴⁸. This indicates that a reliance on online searching may impede memory retrieval by reducing the functional connectivity and synchronization of associated brain regions⁴⁸. Furthermore, when faced with new questions after the six days, the training had increased participants' self-reported impulses towards using the Internet to answer those questions, which was reflected in a recruitment of prefrontal brain areas required for behavioural and impulse control⁴⁹. This increased propensity for relying on Internet searches for gathering new information has been replicated in subsequent studies⁵⁰, and is in keeping with the "supernormal stimulus" nature of the Internet, potentially suggesting that online information gathering quickly trains people to become dependent on this tool when faced with unknown issues.

However, despite the possible adverse effects on regular "offline" memory, the six-days training did make people more efficient at using the Internet for retrieving information, as participants became faster at the search tasks, with no loss of accuracy⁵¹. Search training also produced increases in white matter integrity of the fiber tracts connecting the frontal, occipital, parietal and temporal lobes, significantly more than the non-search control condition⁵². In other studies, cognitive offloading via digital devices has also been found to improve people's ability to focus on aspects that are not immediately retrievable, and thus remember these better in the future⁵³.

These findings seem to support the emergent hypotheses that relying on the Internet for factual memory storage may actually produce cognitive benefit in other areas, perhaps by "freeing up" cognitive resources⁵⁴, and thus enabling us to use our newly available cognitive capacities for more ambitious undertakings than previously possible⁴⁵. Researchers advocating this view have pointed to multiple domains of collective human endeavor that have already been transformed by the Internet's provision of supernormal transactive memory, such as education, journalism and even academia⁵⁵. As online technologies continue to advance (particularly with regards to "wearables"), it is conceivable that the performance benefits from the Internet, which are already visible at the societal level, could ultimately become integrated within individuals themselves, enabling new heights of cognitive function⁵⁶.

Unfortunately, however, a more sobering finding with regards to the immediate possibility of ubiquitous Internet access enabling new heights of human intelligence is provided by Barr et al⁵⁷, who observed that analytical thinkers, with higher cognitive capacities, actually use their smartphone less for transactive memory in day-to-day situations compared to individuals with non-analytical thinking styles. Furthermore, the reduced smartphone usage in analytical versus non-analytical thinkers was specific to online information searching, with no

differences in social media or entertainment usages, thus indicating that the differences are likely due to the Internet furthering "cognitive miserliness" among less analytical thinkers⁵⁷.

Alongside this, the increasing reliance on the Internet for information may cause individuals to "blur the lines" between their own capabilities and their devices⁵⁸. In a series of experiments, Fisher et al⁵⁹ investigated how the Internet influences our self-perceived knowledge. Results showed that online searching increases our sense of how much we know, even though the illusion of self-knowledge is only perceived for the domains in which the Internet can "fill in the gaps" for us. The experiments also demonstrated how quickly individuals internalized the Internet's external knowledge as their own – as even immediately after using the Internet to answer the task questions, participants attributed their higher quality explanations to "increased brain activity". More recent studies have shown that illusions of self-knowledge similarly persist when using smartphones to retrieve online information⁵⁸. As individuals become more and more connected with their personal digital devices (which are also always accessible), it seems inevitable that the distinction between self and Internet's abilities will become increasingly elusive, potentially creating a constant illusion of "greater than actual knowledge" among large portions of the population.

Overall, the Internet clearly can provide a "superstimulus" for transactive memory, which is already changing the way we store, retrieve, and even value knowledge. However, with popular online information sources such as Google and Wikipedia less than 20 years old, it is currently not possible to ascertain how this may eventually be reflected in long-term changes to the structure and function of the human brain. Nonetheless, our constant connection with the online world through personal devices (i.e., smartphones), along with the emerging potential for more direct integration through wearable devices, certainly indicates that we are set to become more reliant on the Internet for factual information as time goes on. Also, whereas the studies described above have focused on factual knowledge, the Internet is also now becoming a superstimulus for spatial information (through providing constant access to online maps and global positioning system). As spatial memory is somewhat independent from semantic memory in the human brain⁶⁰, further research should investigate the multitude of ways in which extensive use of these external memory systems may reduce, enhance or alter our cognitive capacities.

ONLINE SOCIAL NETWORKS: FAULTY CONNECTIONS, OR FALSE DICHOTOMY?

Human sociality in the online world

Social relationships and having a sense of connection are important determinants of happiness and stress relief^{61,62}, mental and physical well-being^{63,64}, and even mortality⁶⁵. Over the past decade, the proportion of an individual's social

interactions that take place online within social networking sites (e.g., Facebook, Instagram, Twitter) has grown dramatically^{66,67}, and our connection with these sites is now strongly meshed with the offline world. The real-world implications of this are perhaps best evidenced by the critical role that social media have played in multiple global affairs, including reportedly starting and precipitating the London Riots, the Occupy movement⁶⁸, and even the Arab Spring⁶⁹, along with potentially influencing the outcomes of the UK's European Union Referendum ("Brexit")⁷⁰ and the 2016 US elections⁷¹. Clearly, understanding the shift from real-world interactions into the online social environment (and vice versa) holds significance to almost all aspects of people's lives.

Our motivations towards using social media is broadly similar to the instinctual desires underlying "real world" social interactions, as people are drawn to online sociality in order to exchange information and ideas, along with gaining social support and friendships⁷². However, whether or not these virtual interactions engage the human brain in ways analogous to real-world socialization remains a topic of debate since the turn of the century⁷³. Whereas it would be highly beneficial if social media sites could fulfil the implicit human needs for social connection, it may be that the distinction between online and offline networks is so great that entirely different cognitive domains are involved in navigating these different environments^{74,75}.

How does the online environment affect our fundamental social structures?

To investigate the neuroimaging correlates of offline and online networks, the seminal study by Kanai et al⁷⁴ collected real-world social network size, online sociality (i.e., Facebook friends) and magnetic resonance imaging scans from 125 participants. Results showed that both real-world social network size and number of Facebook friends were significantly associated with amygdala volume. As this has previously been established as a key brain region for social cognition and social network size⁷⁶, these results present a strong case for the overlap between online and offline sociality in the human brain.

However, those authors also found that the grey matter volume of other brain regions (specifically, posterior regions of the middle temporal gyrus and superior temporal sulcus, and the right entorhinal cortex) were predicted by the numbers of participants' Facebook friends, but held no relationship to their real-world social networks. This suggests that certain unique aspects of social media implicate aspects of the brain that are not central in "real-world" social settings. For instance, the tendency for online networks to encourage us towards holding many weak social connections, involving thousands of face-to-name pairs, could require high associative memory capacities, which is not typically required in real-world networks (as these are comprised of fewer, but more familiar, relationships)⁷⁴. As associative memory formation for name-face pairs involves

the right entorhinal cortex^{77,78}, this could explain the exclusive relationship that this region holds with online social (but not real-world) network size⁷⁴.

Indeed, one key difference which may separate how the brain handles online and offline social networks is the unique capacity afforded by the Internet for people to hold, and simultaneously interact with, millions of "friendships"^{79,80}. Empirical testing of this hypothesis is a most fruitful area of investigation stemming from research into the fundamental similarities and differences between these two social worlds at a biological level⁶⁶. When defining "friendships" under a broad context (people who maintain contact and share an emotional bond)⁶⁶, two patterns are prominent across a diverse range of real-world social networks: a) the average individual has around 150 "friendships" (but this is highly variable between individuals), and b) this is made up of five hierarchical layers, consisting of primary partners, intimate relationships, best friends, close friends, and all friends, which follow a size-scaling ratio of around 3 (i.e., each cumulative layer is 3 times bigger than the last), and therefore have set average (cumulative/inclusive) sizes of 1.5, 5, 15, 50 and 150 respectively⁶⁶. The patterns of the average number of 150 total friendship connections, and the scaling sizes of the five hierarchical layers of relationships making this up, have been found across regions and time periods within various human organizations, ranging from hunter-gatherer societies^{81,82} and historical village populations⁸³, armies⁶⁶, residential camps⁸⁴, to personal networks of modern Europeans⁸⁵.

Thus, given the unprecedented potential that online social networks allow in terms of number of connections, and the varied contexts these take place over^{79,80}, it is imaginable that this extraordinary environment may allow these two apparently set aspects of real-world social networks to be bypassed. However, recent findings have confirmed that user-to-user friendship connections, posting patterns and exchanges within Twitter, Facebook, and even online gaming platforms, all indicate a similar average number of general friendships (around 150, despite high skew), along with maintaining the same scaled sizes of the hierarchical structure of the five distinct friendship layers (as determined by reciprocal communication exchanges)⁸⁶⁻⁸⁹. Therefore, even within the unique realms of online social networks, the most fundamental operations of human social networks appear to remain relatively unchanged^{88,89}. So, it is highly conceivable that the social connections formed in the online world are processed in similar ways to those of the offline world, and thus have much potential to carry over from the Internet to shape "real-world" sociality, including our social interactions and our perceptions of social hierarchies, in ways that are not restricted to the context of the Internet.

The driving forces that sustain the set structural patterns of social networks, even when faced with the immense connective potential of the online world, may be broadly explained by two overlapping mechanisms. First, constraints on social cognition within the human brain seem to carry over across social contexts⁶⁶. For instance, humans struggle to engagingly

interact with more than three individuals simultaneously in the real world, and this limitation on attention also appears to apply online^{90,91}. This evidence is in agreement with the hypothesis that circumventing the cognitive constraints on social relationships may be difficult even when technology affords unnatural opportunities to do so⁸⁸.

The second driver of set boundaries on social activity is that simple underlying factors may produce social constraints, even within online settings. Most obviously, investment in social relationships is limited by time constraints, and this may contribute to the set patterns of both the number and type of social connections^{93,94}. In line with this, analyses across various social contexts have shown that temporal limitations govern the number of social interactions that individuals engage in, and how they distribute these across their different kinds of relationships^{93,94}. Again, these general interaction rates remain similar within online social networks^{87,88}.

The possibility that the parameters on all social networks (online or offline) are governed by basic underlying factors is further supported by research showing that similar structures also exist within simpler social systems, such as animal societies^{66,95}. For instance, the sizes and scaling of hierarchical “friendship” layers found in online and offline human networks are also found in dolphins, elephants, and various primate species⁹⁶, and the phenomena of humans increasing the number and strength of their social networks connections following the death of a friend on Facebook⁹⁷ is also seen in wild birds, which show compensatory up-regulation of their social network connections upon experiencing the loss of a social associate⁹⁸.

Supporting the idea that limited cognitive capacities govern our social structures is research showing that the brain regions predicting individual variation in social network size in humans also do so for macaques⁹⁹. Strong support for simple underlying factors (such as time) governing our general patterning of social interactions can be found in studies demonstrating that entirely computationally simulated systems replicate some of the apparent complexities of human social networks, even under relatively simple rules^{100,101}. Examples include agent-based models generating similar social layering structures as humans when sociality is defined as time-limited¹⁰⁰.

In light of the current evidence regarding how the Internet may have affected human thinking surrounding social networks, it is undeniable that the online environment poses unique potential and context for social activity^{79,80,102,103}, which may invoke some non-identical cognitive processes and brain areas in comparison to the offline world^{74,75}. Nevertheless, aside from these comparatively fine-scale differences, it appears that our brains process the online and offline social networks in surprisingly similar ways, as demonstrated by the shared cognitive capacities and simple underlying factors ultimately governing their fundamental structure^{87,88}. As such, the online social world has very significant implications for not only measuring and understanding human sociality, but also for governing the outcomes of social processes across various aspects of life.

Social cognitive responses to the online social world

Given the evidence above, an appropriate metaphor for the relationship between online and real-world sociality could be a “new playing field for the same game”. Even beyond the fundamental structure, emerging research suggests that neurocognitive responses to online social occurrences are similar to those of real-life interactions. For instance, being rejected online has been shown to increase activity in brain regions strongly linked with social cognition and real-world rejection (medial prefrontal cortex¹⁰⁴) in both adults and children¹⁰⁵⁻¹⁰⁷. However, within the “same old game” of human sociality, online social media is bending some of the rules – potentially at the expense of users¹⁷. For instance, whereas real-world acceptance and rejection is often ambiguous and open to self-interpretation, social media platforms directly quantify our social success (or failure), by providing clear metrics in the form of “friends”, “followers”, and “likes” (or the potentially painful loss/absence of these)¹⁰⁷. Given the addictive nature of this immediate, self-defining feedback, social media companies may even capitalize upon this to maximally engage users¹⁷. However, growing evidence indicates that relying on online feedback for self-esteem can have adverse effects on young people, particularly those with low social-emotional well-being, due to high rates of cyberbullying¹⁰⁸, increased anxiety and depression^{109,110}, and increased perceptions of social isolation and exclusion among those who feel rejected online¹¹¹.

Another process common to human social behaviour in both online and offline worlds is the tendency to make upward social comparisons^{112,113}. Whereas these can be adaptive and beneficial under regular environmental conditions¹¹², this implicit cognitive process can also be hijacked by the artificial environmental manufactured on social media^{113,114}, which showcases hyper-successful individuals constantly putting their best foot forward, and even using digital manipulation of images to inflate physical attractiveness. By facilitating exposure to these drastically upward social comparisons (which would rarely be encountered in everyday life), online social media can produce unrealistic expectations of oneself – leading to poor body image and negative self-concept, particularly for younger people^{107,111,115,116}. For instance, in adolescents (particularly females), those who spent more time on social media and smartphones have a greater prevalence of mental health problems, including depression, than those who spent more time on “non-screen” activities¹¹⁶, with greater than 5 hrs/day (versus 1 hr/day) associated with a 66% increased risk of one suicide-related outcome¹¹⁷.

However, a causal relationship between high levels of social media use and poorer mental health is currently difficult to establish, as there is most likely a complex interaction between several confounding factors, including reduced sleep and in-person social interaction, and increased sedentary behaviour and perceived loneliness^{116,118}. Nonetheless, given the large amounts of social media use observed among young people, future research should thoroughly examine the potentially

detrimental effects that this new setting for sociality may have on health and well-being, along with aiming to establish the driving factors – such that adjustments can be made in subsequent iterations of social media in order to produce more positive outcomes.

Whereas young people with mental disorders may be the most vulnerable to negative input from social media, these media may also present a new platform for improving mental health in this population, if used correctly. In future, social media may also be exploited to promote ongoing engagement with Internet-based interventions, while addressing key (but frequently neglected) targets such as social connectedness, social support and self-efficacy, to aim to bring about sustained functional improvements in severe and complex mental health conditions¹¹⁹. To achieve these goals, online social media-based interventions need to be designed to promote engagement by harnessing, in an ethical and transparent manner, effective strategies used by the industry. For instance, developing technologies which are increasingly adopted by online marketing and tech companies, such as natural language processing, sentiment analyses and machine learning, could be capitalized upon, for example making it possible to identify those at increased risk for suicide or relapse¹²⁰, and rationalizing human driven support to those who need it most at the time they need it¹²¹. In addition, online systems will be able to learn from what helps individuals and when, opening a window into personalized, real time interventions¹²¹.

While the use of online social media-based interventions is in its infancy, pioneering efforts indicate that these interventions are safe, engaging, and have the potential to improve clinical and social outcomes in both patients and their relatives¹²²⁻¹²⁷. That said, online interventions have failed up to now to be adopted by mental health services^{128,129}. The main reasons include high attrition rates, poor study designs which reduce translational potential, and a lack of consensus around the required standards of evidence for widespread implementation of Internet-delivered therapies¹³⁰⁻¹³². Efforts are currently underway to determine the long-term effects of the first generation of social media-based interventions for mental illness via large randomized controlled trials^{133,134}. Alongside this clinical use, developing public health strategies for young adults in the general population to avoid the potential adverse effects and negative aspects of typical social media are also warranted.

CONCLUSIONS AND DIRECTIONS

As digital technologies become increasingly integrated with everyday life, the Internet is becoming highly proficient at capturing our attention, while producing a global shift in how people gather information, and connect with one another. In this review, we found emerging support for several hypotheses regarding the pathways through which the Internet is influencing our brains and cognitive processes, particularly with regards to: a) the multi-faceted stream of incoming information

encouraging us to engage in attentional-switching and “multi-tasking”, rather than sustained focus; b) the ubiquitous and rapid access to online factual information outcompeting previous transactive systems, and potentially even internal memory processes; c) the online social world paralleling “real world” cognitive processes, and becoming meshed with our offline sociality, introducing the possibility for the special properties of social media to impact on “real life” in unforeseen ways.

However, with fewer than 30 years since the Internet became publicly available, the long-term effects have yet to be established. Within this, it seems particularly important that future research determines the impact of the Internet on us throughout different points in the lifespan. For instance, the Internet’s digital distractions and supernormal capacities for cognitive offloading seem to create a non-ideal environment for the refinement of higher cognitive functions in critical periods of children and adolescents’ brain development. Indeed, the first longitudinal studies on this topic have found that adverse attentional effects of digital multi-tasking are particularly pronounced in early adolescence (even compared to older teens)³⁴, and that higher frequency of Internet use over 3 years in children is linked with decreased verbal intelligence at follow-up, along with impeding maturation of both grey and white matter regions¹³⁵.

On the other hand, the opposite may be true in older adults experiencing cognitive decline, for whom the online environment may provide a new source of positive cognitive stimulation. For instance, Internet searching engaged more neural circuitry than reading text pages in Internet savvy older adults (aged 55-76 years)⁹. Furthermore, experimental studies have found that computer games available online and through smartphones can be used to attenuate aging-related cognitive decline¹³⁶⁻¹³⁸. Thus, the Internet may present a novel and accessible platform for adults to maintain cognitive function throughout old age. Building from this, successful cognitive aging has previously been shown to be dependent upon learning and deploying cognitive strategies, which can compensate for aging-related decline in “raw” memory capacities¹³⁹. This has previously been referred to as optimizing internal cognitive processes (e.g., through mnemonic strategies), or taking advantage of cognitive offloading in traditional formats (list making, transactive memory, etc.)¹³⁹. Nonetheless, as Internet-based technologies become more deeply integrated with our daily cognitive processing (through smartphones, wearables, etc.), digital natives could feasibly develop forms of “online cognition” in the aging brain, whereby older adults can increasingly take advantage of web-based transactive memory and other emerging online processes to fulfil (or even exceed) the typical capacities of a younger brain.

Although it is an emerging area of study, the same could apply for social aspects of the online world. Whereas young people seem particularly prone to the rejections, peer pressure, and negative appraisals this world may induce¹⁰⁷, older adults may ultimately be able to harness social media in order to overcome isolation and thus continue to benefit from the

diverse range of physical, mental and neurocognitive benefits associated with social connection⁷³. Viewed collectively, the nascent research in this area already indicates that equivalent types of Internet usage may have differential effects on individuals' cognitive and social functioning depending on their point in the lifespan.

For better or for worse, we are already conducting a mass-scale experiment of extensive Internet usage across the global population. A more fine-scale analysis is essential to gaining a fuller understanding of the sustained impact of this usage across our society. This could include measuring frequency, duration and types of Internet usage as a standard part of national data projects, for instance through collecting Internet data (from either device-based or self-report measures) in "biobank" assessment protocols. Combining this with the extensive genetic, socio-demographic, lifestyle and neuroimaging data gathered by some ongoing projects, researchers could be able to establish the impact of Internet usage on psychological well-being and brain functioning across entire populations (rather than the currently limited study samples), while also controlling for multiple confounders.

Overall, this early phase of the Internet's introduction into our society is a crucial period for commencing rigorous and extensive research into how different types of Internet usage interact with human cognition, in order to maximize our opportunities for harnessing this new tool in a beneficial manner, while minimizing the potentially adverse effects.

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