

Written evidence submitted by Prof Iroise Dumontheil, Prof Denis Mareschal, Prof Ori Ossmy and Prof Sam Wass (NDC0014)

The Impact of Digital Technologies on Brain Development in Childhood and Adolescence

Science, Innovation and Technology Committee Neuroscience

Evidence submitted by the Birkbeck-UCL Institute of Education *Centre for Educational Neuroscience* (CEN; <https://www.educationalneuroscience.org.uk/>). We are a non-profit academic centre that combines the strengths of Birkbeck, University of London's *Centre for Brain and Cognitive Development* and the UCL *Institute of Education* – to provide the foundation for a national Centre for Educational Neuroscience. Together our objective is to develop this emerging discipline, using our combined strength in neuroscience, child development, psychology, and education research. Our goal is to establish a dialogue between researchers and educationalists to further translations of research into practice to improve education and well-being across the lifespan.

This document was put together by the following members of the CEN: Prof Iroise Dumontheil, Prof Denis Mareschal, Prof Ori Ossmy and Prof Sam Wass.

- Professor Iroise Dumontheil is Deputy *Director of the Cognitive Neuroscience Hub* at the *Melbourne School of Psychological Sciences*, University of Melbourne. She is an expert in the study of factors of individual differences in cognitive and brain development during late childhood and adolescence and a co-investigator of the Study of Cognition, Adolescents and Mobile Phones (SCAMP).
- Professor Denis Mareschal is *Deputy Director of the CEN* and the *Director of the Centre for Brain and Cognitive Development* at *Birkbeck University of London*. He is an expert in Developmental Cognitive Neuroscience and Artificial Neural Networks as models of learning across human development.
- Professor Ori Ossmy is *Director of the Physical Cognition Lab* in the *Centre for Brain and Cognitive Development, Birkbeck University of London*. He is an expert in using new technologies, convergent analytic and imaging technologies to explore the micro-developmental mechanisms of perceptual and cognitive development.
- Professor Sam Wass is *Director of the Institute for the Science of Early Years and Youth* at the *University of East London*. He is an expert in the early years, especially child concentration and child stress related to digital technology use.

Executive Summary

(A) Mobile Phones, Social Media use and the Developing Adolescent Brain

Adolescence is a sensitive period for the development of mental health disorders, in particular socio-emotional disorders including anxiety, depression and eating disorders. One possible factor at play is the increasing use of mobile digital technology by children and adolescents. The *Study of Cognition, Adolescents and Mobile Phones* (SCAMP) was set-up to examine the impacts of mobile phone and digital technology use on mental health, cognition, and behavioural development in the UK. Overall, while associations between digital technology use and adolescent well-being are on the negative side, they are small. *The type of use matters*: procrastination and passive use are related to more negative effects, while social and active use are related to more positive effects

Adolescence is a period of social transition, with heightened social sensitivity and maturation of brain networks supporting social interactions, allowing adolescent to adapt to their social environment. Importantly, within this cohort, those who reported more social media use also reported better peer relationships but also more positive affect and less negative affect and loneliness when interacting face-to-face compared to online.

Sleep is essential for adolescent development and maintenance of daily brain and cognitive functions. Although the studies are not causal, they suggest that limiting the use of mobile phones and social networking sites at night and encouraging adolescents to have a better sleep hygiene may be important targets to limit the potential negative influence of these practices on well-being and mental health.

Importantly, the data currently available provide correlational evidence rather than causal evidence.

(B) The Impact of Pace-of-Information in screen interactions on Early Years brain development

Young brains are also much slower than adult brains. Consequently, optimal learning for young brains comes from content that is relatively slow-paced, repetitious and predictable. There are two distinct brain pathways through which the makers of screen content can engage and sustain young children's attention. The first is use slow-paced material to target comprehension-driven attention networks. The second is to use fast-paced movement and sound to capture children's attention, targeting brain mechanisms that automatically attract our attention to things that are moving in our environment. Increasingly, evidence shows that the ***makers of screen content are relying on fast-paced attention capture, rather than slow-paced comprehension-driven attention.***

Overall, the findings are consistent with a model in which early-life exposure to poorly designed screen content which is fast-paced and unpredictable triggers short- and long-term over-activation of the brainstem and sympathetic nervous system. This physiological hyper-activation has accompanying effects on emotional/behavioural dysregulation and long-term mental health (e.g., anxiety). However, it is also important to understand that this evidence remains correlational rather than causal in humans.

(C) The Impact of Virtual Reality and Immersive Technologies on Developing Brains

Immersive technologies such as Virtual Reality (VR) are not simply another kind of screen. By replacing much of the user's sensory world, coupling perception to head and body movement,

heightening presence, and often introducing mismatches between visual, vestibular, and proprioceptive signals, they engage core neural systems involved in multisensory integration, executive control, attention, emotion, spatial cognition, and social processing. Do these immersive technologies systematically shape experience-dependent plasticity in ways that matter for developing systems of sensorimotor calibration, executive control, emotional regulation, and social cognition? Immersive environments can increase perceptual and cognitive load, which may be particularly demanding for children whose executive systems are still maturing. Taken together, the current evidence does not support strong claims of lasting harm from ordinary short-term use of VR but more research is required. ***This field lacks technology-specific longitudinal, brain-focused, developmentally stratified evidence.***

(D) The impact of AI-enhanced technologies on early development

Despite the rapid changes in young children's exposure to AI during the most significant period of brain and behavioural development, ***the current "state-of-play" around AI-mediated technology use in UK families is largely unknown, nor do we understand the benefits or problems associated with AI use for child motor and cognitive development, or developing parent-child relationship.*** This creates a critical blind spot in the national conversation, limiting our understanding of both the challenges and opportunities of AI in early childhood.

Because implementations of AI are rapidly evolving, future research should focus on the impact of the fundamental capacities of AI-enhanced technologies to (i) enable *adaptive systems*, (ii) *possess perceived agency*, and (iii) *uncover hidden patterns in large-scale data*, rather than current specific technologies themselves.

This is generally true of most contemporary digital technologies. Consequently, **to be future proofed policy should focus on the critical functional features of a technology, rather than the specific implementations that exist today.**

(E) Mobile Phones, Social Media use and the Developing Adolescent Brain

A.1 Adolescence and mental health disorders

Adolescence is a sensitive period for the development of mental health disorders, in particular socio-emotional disorders including anxiety, depression and eating disorders (Rapee et al., 2019). There is evidence of a 10% increase in common mental disorders, including anxiety, depression and stress, in young adults in the UK, based on health care records, and a 19% increase in psychological distress symptoms, with fastest rise in mental ill-health in deprived areas (Dykxhoom, 2025). While this increases likely reflect a wide range of factors, including increased awareness and acceptance of mental health issues, one possible factor at play is the increasing use of technology by children and adolescents.

The *Study of Cognition, Adolescents and Mobile Phones* (SCAMP) is led by Prof. Mireille Toledano at Imperial College London and was set-up to examine the impacts of mobile phone and digital technology use on mental health, cognition, and behavioural development. More than 6,000 secondary school pupils from more than 30 schools in Greater London were initially recruited when they were 11–12-year-olds (in 2014–2016) and a subsample was tested again when they were 13–15-years-old (in 2016–18). In the SCAMP data, weekday and weekend self-reported social networking sites use on mobile phones and other devices was linearly associated with lower self-reported health-related quality of life (which included both physical

and mental health symptoms) in females, but not in males, and increased behavioural difficulties (including peer problems, conduct problems, emotional problems and hyperactivity) in both genders in 11–12-year-olds (Jenkins et al., 2020). Longitudinally, adolescents who used social networking sites for more than 3 hours per day when they were 11–12 years old (11% of the sample), compared to 0–30 min per day (58%), reported higher levels of symptoms of anxiety and depression when they were 13–15 years old (Shen et al., 2026). Importantly, *this evidence is correlational, so it is possible that greater use of social networking sites has a negative impact on physical and mental health, but it is also possible that those children with poorer physical and mental health spend more time using social networking sites, or that there are bidirectional associations.*

The *Adolescent Brain and Cognitive Development* (ABCD) study is a USA-based larger cohort study starting at age 9–10 years. The ABCD study has provided some insights into the potential impact of screen use in early adolescence. Analyses of baseline and 2-year follow-up data indicate that higher self-reported total screen time was associated with more mental health symptoms, with strongest associations for depressive, conduct, somatic and attention-deficit/hyperactivity symptoms (Nagata et al., 2024). Specific screen use showing the greatest associations with depressive symptoms included video chat, texting, videos, and video games. There was no evidence of moderation of these associations by sex, however screen time was associated with higher depressive, oppositional defiant and attention-deficit/hyperactivity symptoms in white adolescents but not black adolescents.

Overall, while associations between digital technology use and adolescent well-being are on the negative side, they are small. The type of use matters: procrastination and passive use are related to more negative effects, while social and active use are related to more positive effects (Dienlin & Johannes, 2020).

A.2 Adolescence and socio-cultural development

Adolescence is a period of social transition, with heightened social sensitivity and maturation of brain networks supporting social interactions, allowing adolescent to adapt to their social environment (Blakemore & Mills, 2014). The increasing share of online social interactions necessarily has an impact of adolescents' brain and cognitive development underlying social interactions. In the UK a passive monitoring study in 2024–2025 found that in a representative sample of 692 children, 8–14-year-olds spent an average of 3 hours a day online across smartphone, table or computer, with 52% of this time spent on YouTube and Snapchat (Ofcom, 2025). In a nationally representative US samples, it was found that adolescents in the 2010s spent an hour less a day engaging in in-person social interactions compared to adolescents in the late 1980s, that, at the cohort level, feelings of loneliness increased sharply after 2011, and that adolescents low in in-person social interaction and high in social media use reported the most loneliness (Twenge et al., 2019). Importantly, within cohort, *those who report more social media use also report better peer relationships* (Paulich et al., 2021; Twenge et al., 2019). In an experience sampling study, it was found that adolescents reported less positive affect when alone compared to when interacting online, but also more positive affect and less negative affect and loneliness when interacting face-to-face compared to online (Achterhof et al., 2022).

A.3 Sleep as a potential key mediator of the negative effects of technology use in adolescence

Sleep is essential for adolescent development and maintenance of daily brain and cognitive functions. Adolescence is characterised by a high prevalence of sleep deficits and delayed bedtime, due to both biological maturation and environmental factors (Crowley et al., 2007).

Data from a Scottish study (Woods & Scott, 2016) and the SCAMP study (Shen et al., 2026) indicate that social networking sites use, especially at nighttime, is associated with insufficient and poor sleep quality, as well as poorer well-being and mental health. As sleep problems are well-documented risk factors for poor mental health in adolescents (Scott et al., 2021; Shen et al., 2021), sleep is likely an important mediator of the impact of technology use, and in particular social media use, on adolescents' well-being and mental health. This was directly tested in the SCAMP longitudinal data, and it was found that the association between high levels of social networking site use at age 11-12 years old and anxiety and depression symptoms at age 13-15 years old was partly accounted by those 11-12-year-olds not sleeping for long enough (particularly on weekdays), and taking a while to fall asleep. While *these analyses are not causal, they suggest that limiting the use of mobile phones and social networking sites at night and encouraging adolescents to have a better sleep hygiene may be important targets to limit the potential negative influence of these practices on well-being and mental health.*

A.4 How does this vary with characteristics including age, sex, socioeconomic background, ethnicity, and others?

There is considerable evidence of individual differences in technology use. For example, in the baseline SCAMP data, 10-11 year-olds with black or mixed ethnicities had lower odds of owning a mobile phone ownership but higher levels of mobile phone call frequency and duration than those of white ethnicity, and those of from independent schools or who parental occupations were classified as 'higher managerial, administrative and professional' had higher odds of owning a mobile phone than those from state schools or with parents with other occupations (Toledano et al., 2018). In the ABCD data, lower neighbourhood quality (e.g. higher social vulnerability and higher area deprivation) was associated with higher screen time in 9–10-year-olds (Nagata et al., 2026).

A.5 Is the evidence around the impact of digital devices on the development of children and adolescents adequate?

Despite the ubiquity of technology use by adolescents, there are *limited longitudinal studies* that examine associations between technology use and cognitive development and mental health during development.

Because of the large sample and longitudinal follow-up needed, *there are even fewer studies directly measuring impacts on brain development.* The ABCD study has brain data, and a stream of analyses are being published, although at the moment they tend to only include the first two timepoints (9 to 12 years old); moreover, findings obtained in a US cohort may not necessarily apply to the UK, in particular when considering moderating effects of socio-economic status or ethnicity.

Key limitations of existing research are that:

- The data provide correlational evidence rather than causal evidence.
- There are a lot of possible confounding factors, such as socio-economic status, genetic risk for poor mental health, physical health, parenting, which are rarely all taken into account.

- Technologies, software and behaviour change rapidly, e.g. switch from phone calls with a device held at the ear vs. messaging with a device held in the hands, switch from Facebook to Instagram to TikTok, earlier and earlier use of smartphones by children.
- The samples taking part in the existing research do not tend to be representative of the population.
- Most current research is based on self- or parent-reported technology use rather than objectively measured data. While self-reported use adequately distinguishes between high and low use (e.g. Mireku et al., 2018), objective measures may be needed to obtain a more accurate picture of associations between technology use and cognitive development and mental health.

Where is more research needed on their impact?

- While directly measuring impacts on brain structure and brain function is costly, behavioural, cognitive and self- or parent/carer/teacher-reports of well-being can provide important markers of brain development.
- Comparing data before and after changes in policy (such as the recent social media ban for under 16s adopted by Australia or the recent push in Finland to return to the use of physical books in schools), and between countries, could provide important causal evidence of the impact of technology use, as well as evidence of the impact different policies could have on technology use in childhood and adolescence.
- Similarly, on a smaller scale, studies could be done assessing the impact of delaying the use of laptops at school, or banning the use of mobile phones at schools, or interventions.
- Studies often attempt to control for factors like socio-economic status or ethnicity and report differential technology use according to these factors, but more research is needed to investigate the extent to which these factors associate may moderate the impact of technology use on cognitive development and mental health.
- More research is also needed on how to more objectively measure technology use in children and adolescents, to avoid reliance on self- or parent-reports only, with the collection of not only duration/frequency of use measures, but also the type of use, for example passive vs. social and active use (Dienlin & Johannes, 2020).

(F) The Impact of Pace-of-Information in screen interactions on Early Years brain development

B.1 Young brains learn best from content that is slow-paced and predictable

Our brains are prediction machines (Clark, 2013). For each word that we read, and each time we move our eyes while we watch TV, our brains generate a prediction for what we will see – and then test how our expectations conform to what we experienced (Friston & Kiebel, 2009). This process of generating and testing predictions is how we learn (Howwy, 2013). Everybody learns best in situations where we can accurately predict what is going to happen in advance sometimes, but not always. In neuroscience, this is known as the Goldilocks zone (Kidd et al, 2012)

Young brains, which lack prior knowledge and experience, process information differently to older brains (Wass & Goldberg, 2025). A situation that is predictable to an experienced adult brain is unpredictable for an inexperienced child's brain. For that reason, the Goldilocks zone for young children lies in situations that are **repetitious and predictable** – such as peekaboo, pressing a button over and over again to make a toy pop up, or reading the same book repeatedly. These tend to be the types of learning situations that young learners seek out (Smith et al, 2011).

Young brains are also much slower than adult brains. For example, an adult brain can distinguish up to ten separate visual events per second, but a 15-month-old's brain is **ten times slower** than that (Farzin et al, 2011). Anything that has been and gone in less than a second is too fast for them to process.

In summary, *optimal learning for young brains comes from content that is relatively slow-paced, repetitious and predictable.*

B.2 Early years screen content has been getting more fast-paced and unpredictable in recent years

There are two distinct brain pathways through which the makers of screen content can engage and sustain young children's attention. The first is to target **comprehension-driven attention** networks (Buschman & Kastner, 2015). To do this, content needs to be slow-paced, simple and pitched at a developmentally appropriate level. Many adults find well-made early years TV to be almost comically slow - but that is the point: slow pacing, clear speech, hyper-articulated facial expressions and emotions, and simple structure give young children the clarity and time they need to process and understand what is happening (Wass & Smith, 2015).

Another approach is to use **fast-paced movement and sound to capture children's attention**, targeting brain mechanisms that *automatically attract* our attention to things that are moving in our environment (Itti & Baldi, 2009). These mechanisms have developed, we think, because as early humans, movement used to signal threat (e.g. predators) or opportunities (e.g. food), so we have evolved to pay instant attention to movement. Although no longer needed from a survival perspective, this automatic tendency to pay attention to movement remains – and is exploited to capture children's attention to screens. This attention capture is *immediate, involuntary, and does not require understanding of the content being viewed.*

Increasingly, evidence shows that *the makers of screen content are relying on fast-paced attention capture, rather than slow-paced comprehension-driven attention* (Koolstra et al., 2004). This is because comprehension-driven attention is subjective and slow to develop – it *builds gradually over repeated viewings* (Barr et al., 2007) – whereas *movement-driven attention capture is universal and instantaneous.*

B.3 Exposure to fast-paced and unpredictable screen content associates with brainstem/physiological dysregulation – short- and long-term

Using screens to placate a dysregulated child is effective in the short term: *watching screens associates with immediate reductions in negative as well as positive mood expression in children* (Haverson et al., 2026). We are generally less emotional when screens are on. Short-term, children's bad moods going into screen use predicts bad moods after screens are turned

off (Coyne et al., 2022). And, long-term, increased use of devices to calm bad moods predicts long-term increases in emotional reactivity (Radesky et al, 2023) and increased behavioural and emotional dysregulation- even after controlling for demographic covariates.

Why is this the case? It is suggested that faced with situations that are *too fast-paced and unpredictable*, our brains shift into '*high alert*' mode, to mobilise rapid target detection– an automatic, evolutionary reaction to being in situations that are unpredictable, and so might be dangerous. Changes in the brainstem trigger overall increases in arousal and wakefulness, and the sympathetic ('fight or flight') nervous system becomes active.

Evidence shows that exposure to fast-paced screen content leads to short-term increases in brainstem arousal (Lissak, 2018) and increased sympathetic nervous system activity with expected knock-on effects on behaviour (e.g. impaired inhibitory control). Evidence from animal research suggests that long-term exposure to fast-paced screen content causally increases long-term brainstem arousal (Christakis et al, 2018). There is no direct evidence from humans that exposure to fast-paced screen content increases brainstem arousal over longer time-frames. However, there is evidence that viewing screen content increases long-term behavioural and emotional dysregulation; and, over long time-frames, incidence of affective disorders such as anxiety (Huang et al. 2025; Tang et al., 2021). Behavioural/emotional dysregulation in children and anxiety in adults are both associated with brainstem hyper-arousal and overactivation of the sympathetic nervous system.

Overall, these findings are consistent with a model in which *early-life exposure to poorly designed screen content which is fast-paced and unpredictable triggers short- and long-term over-activation of the brainstem and sympathetic nervous system*. This physiological hyper-activation has *accompanying effects on emotional/behavioural dysregulation and long-term mental health* (e.g. anxiety). However, it is also important to understand that this evidence remains correlational rather than causal in humans.

B.4 Recommendations for future research

- Direct measurements of long-term brain stem hyperarousal in children because of high paced digital media use needs to be observed in humans to confirm this Theory of Change.
- Establishing causal relations between the pace of information in digital content and long-term mental health outcomes needs to be evaluated using causal longitudinal and cohort analysis methods.

(G)The Impact of Virtual Reality and Immersive Technologies on Developing Brains

C.1 What is special about immersive technologies?

Immersive technologies such as Virtual Reality (VR) are not simply another kind of screen. By replacing much of the user's sensory world, coupling perception to head and body movement, heightening presence, and often introducing mismatches between visual, vestibular, and proprioceptive signals, they engage core systems involved in multisensory integration,

executive control, attention, emotion, spatial cognition, and social processing. For that reason, immersive technologies merit distinct scrutiny in childhood and adolescence.

From a developmental neuroscience perspective, the key question is not whether VR “changes the brain” in some generic sense. All learning changes the brain. The real question is *whether immersive technologies systematically shape experience-dependent plasticity in ways that matter for developing systems of sensorimotor calibration, executive control, emotional regulation, and social cognition*. This matters especially in childhood because the brain is still under construction. Prefrontal systems that support inhibition, self-monitoring, and reality checking mature over a long developmental period, while multisensory and motor systems are also still being calibrated across childhood and adolescence.

C.2 Prefrontal Regulation and Immersive Presence

One of the clearest brain-based findings relevant to policy comes from Baumgartner et al. (2008), who used fMRI to examine “presence” inside an immersive virtual environment. In adults, presence was modulated by dorsolateral prefrontal mechanisms that appeared to regulate immersive experience. In children, these regulatory patterns were not evident, alongside evidence of relative immaturity in the relevant prefrontal regions. The implication is not that VR is necessarily harmful, but that *the same immersive experience may place different demands on the developing brain than on the mature brain*. In practice, children may be less able to down-regulate highly salient or emotionally compelling virtual experiences, with possible consequences for attention, arousal, memory, and behavioural control (Baumgartner et al., 2008).

C.3 Multisensory Integration and Sensorimotor Calibration

Another major aspect of using immersive technologies with children concerns multisensory integration and sensorimotor calibration. VR can alter the normal relationship between vision, proprioception, and vestibular input. Valori et al. (2020) showed that younger children were less accurate than older children and adults in proprioceptive tasks, and that immersive VR disrupted visuo-proprioceptive performance when visual information was present. Miehlbradt et al. (2021) similarly found that immersive VR interfered with default head–trunk coordination strategies in young children. These findings are important because they point not only to discomfort, but to interference with developing brain systems that support balance, posture, body representation, and coordinated action. *The most plausible concern is therefore not immediate injury, but repeated perturbation of sensory-motor systems that are still being calibrated.*

C.4 Executive Control and Inhibitory Regulation

Executive control provides a third important issue. Bailey et al. (2019) found that 4- to 6-year-olds showed poorer inhibitory control in a VR version of a task than in a television version, while also showing stronger socially responsive behaviour towards the virtual character. This suggests that immersive environments may amplify salience and social pull, thereby increasing demands on frontal systems that support inhibition and self-regulation. More recently, Dina et al. (2025) showed that immersive virtual environments can also be used productively as scientific tools: in a CAVE-based Go/No-Go task paired with fNIRS, young children showed activation in the left inferior frontal gyrus, a region closely associated with inhibitory control. Together, these studies suggest that immersive environments can both alter the behavioural expression of executive control and provide a more naturalistic platform for measuring its neural development.

C.5 Social Brain Engagement

The same logic applies to the social brain. Bulgarelli et al. (2023) used child friendly wearable neuroimaging technology (fNIRS) with preschoolers and showed that child-friendly immersive VR paradigms can engage frontal and temporo-parietal regions relevant to social processing. This does not show that VR changes social development in any simple or direct way, but it does show that immersive contexts can recruit neural systems central to social cognition. That makes immersive technologies developmentally significant and ***strengthens the case for studying impact of immersive technologies separately rather than treating them as equivalent to conventional screens.***

C.6 Immersive Technologies and Neurodiversity

The difference between VR and conventional screen technologies becomes especially important in neurodevelopmental conditions such as ADHD, autism spectrum disorder, and developmental coordination disorder. The significance of immersive technology is not simply that it may make assessment more engaging, but that immersive environments can expose brain-relevant processes under conditions that more closely approximate daily life. In ADHD, virtual classrooms and real-world-like VR tasks have revealed heightened susceptibility to distractors, altered gaze allocation, and links between attentional symptoms and the sampling of visual information (Neguț et al., 2017; Mangalmurti et al., 2020; Merzon et al., 2022). In Autism, immersive paradigms have been used to examine interpersonal distance regulation and repetitive movement in ways that may better capture multisensory, motor, and social processes than static laboratory tasks (Gessaroli et al., 2013; Alcañiz Raya et al., 2020; Simões et al., 2020). In Developmental Coordination Disorder, VR-based interventions have shown promise for motor performance, but they also expose a central weakness in the literature: most studies still measure outcomes more readily than the continuous sensorimotor dynamics and neural mechanisms from which those outcomes arise (EbrahimiSani et al., 2020). Finally, Muszynska et al. (2025) showed that children with ADHD performed more poorly on switch than non-switch trials in a whole-body object-interception task, and that the magnitude of these switching costs was related to children's impulsivity and inattention, further illustrating how immersive paradigms can reveal executive-control differences in ecologically valid settings.

C.7 Cognitive Load, Sensory Conflict, and Short-Term Safety

Greater immersion is not automatically better for learning. ***Immersive environments can increase perceptual and cognitive load, which may be particularly demanding for children whose executive systems are still maturing.*** They can also introduce sensory conflict, cybersickness, visual fatigue, and disruption of balance or coordination, all of which are brain-relevant because they arise from the way immersive displays interact with perceptual and sensorimotor systems. Hoffman et al. (2008) and Shibata et al. (2011) showed that stereoscopic displays can create vergence–accommodation conflicts that contribute to visual discomfort, while Rushton and Riddell (1999) raised the possibility that developing visual systems may be especially sensitive to such demands. Chang et al. (2023) reviewed EEG studies of cybersickness and concluded that brain-based measurement of VR-related discomfort is advancing, though the evidence remains dominated by adult samples. By contrast, Silva et al. (2025) found that moderate, time-limited VR exposure in 10–12-year-olds did not produce clear negative effects on a range of visual, physical, and cognitive measures. ***Taken together, the current evidence does not support strong claims of lasting harm from ordinary short-term use of VR,*** but neither does it justify complacency.

C.8 Recommendations for Future Research

Immersive technologies deserve serious attention in any neuroscience account of digital childhoods because they engage the brain differently from conventional digital media. They act directly on systems for perception, action, salience, and self-regulation, all of which are still developing across childhood and adolescence. The strongest current evidence points to *particular relevance for prefrontal control, multisensory calibration, and sensorimotor function*. There is also promising evidence that immersive technologies can become valuable tools for education and developmental neuroscience when used carefully (Cherry et al., 2024). But the present evidence base remains too limited to support broad claims about long-term developmental effects on the brain.

The field lacks technology-specific longitudinal, brain-focused, developmentally stratified evidence. Most existing studies are short-term, cross-sectional, or feasibility-oriented. We still know too little about *whether repeated immersive exposure alters trajectories of brain development across months and years. We also lack sufficiently precise comparisons across device types and use contexts*. Head-mounted displays are not equivalent to projection-based immersive environments, and entertainment use is not equivalent to educational or clinical use. These distinctions matter both scientifically and for policy.

Future studies should:

- distinguish clearly between device properties, content properties, and patterns of use.
- compare immersive and non-immersive versions of the same tasks,
- should measure brain-relevant outcomes such as cognitive load, inhibitory control, visuo-vestibular integration, and social processing.
- follow children longitudinally over development to establish causality

(H)The impact of AI-enhanced technologies on early development

Young children growing up in the UK are already affected by AI. They can interact with virtual assistants like *Amazon Alexa*TM, play with smart toys like *Galaxy Kid*TM that allows young children to speak with ‘AI Chat Buddies’ that adapt to their language level, and are monitored by smart mats that can detect potential medical problems. Such advances hold transformative potential for supporting early child development through “smart” toys, intelligent tutoring systems, and individualised parenting support (Zhang et al., 2022; Wang et al., 2022; McStay et al., 2021). Despite this potential, AI-based tools could critically risk replacing key ‘real world’ interactions, reducing opportunities for self-initiated learning, algorithmic discrimination, amplifying technological poverty, and algorithms that monetise attention or drive early addictive-like behaviours (Asai, 2020; Holmes et al., 2022). ***We rapidly need to generate empirical data on the impact of AI during this critical period of child and brain development to optimise the balance of risk and benefits and ensure a prosperous future society.***

The rapid pace of learning in the first five years of life is driven by children’s expanding abilities to actively explore the world around them. Neuroconstructivist¹ theories posit that through their own actions, children learn about the causal relationships between physical objects (what happens when I drop my rattle?), the labels we use for objects, and what other people find rewarding. How are these processes impacted by AI, which has the power to allow adaptation of input to each individual? How does this impact learning about own agency, or

the regularities that govern the real world? How do children differentiate what is real from what is computer-generated? We will deliver new empirical information on the impact of AI on children through a series of studies co-designed with parents and families.

Despite the rapid changes in young children's exposure to AI during the most significant period of brain and behavioural development (Mareschal et al, 2007) , there is currently no evidence related to this issue. ***The current "state-of-play" around AI-mediated technology use in UK families is largely unknown, nor do we understand the benefits or problems associated with AI use for family dynamics, or developing parent-child relationship (Croeser et al., 2019)*** This creates a critical blind spot in the national conversation, limiting our understanding of both the challenges and opportunities of AI in early childhood.

Because implementations of AI are rapidly evolving, future research should focus on the impact fundamental capacities of AI-enhanced technologies to (i) enable *adaptive systems*, (ii) *possess perceived agency*, and (iii) *uncover hidden patterns in large-scale data*, rather than current specific technologies themselves.

19 April 2026

References

- Achterhof, R., Kirtley, O. J., Schneider, M., Hagemann, N., Hermans, K. S. F. M., Hiekkaranta, A. P., Lecei, A., Lafit, G., & Myin-Germeyns, I. (2022). Adolescents' real-time social and affective experiences of online and face-to-face interactions. *Computers in Human Behavior*, 129, 107159.
- Alcañiz Raya, M., Marín-Morales, J., Minissi, M. E., Teruel Garcia, G., Abad, L., and Chicchi Giglioli, I. A. (2020). Machine learning and virtual reality on body movements' behaviors to classify children with autism spectrum disorder. *Journal of Clinical Medicine*, 9(5), 1260.
- Asai, R. (2020). AI and ethics for children: How AI can contribute to children's wellbeing and mitigate ethical concerns in child development. In M. Arias-Oliva, et al (Eds.) *Societal Challenges in the Smart Society*, pp 459-466.
- Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. *Annual Review of Neuroscience*, 28(1), 403-450.
- Bailey, J. O., Bailenson, J. N., Obradović, J., and Aguiar, N. R. (2019). Virtual reality's effect on children's inhibitory control, social compliance, and sharing. *Journal of Applied Developmental Psychology*, 64, 101052.
- Barr, R. (2010). Transfer of learning between 2D and 3D sources during infancy: Informing theory and practice. *Developmental Review*, 30(2), 128-154.
- Barr, R., Muentener, P., Garcia, A., Fujimoto, M., & Chavez, V. (2007). Repetition enhances imitation from television during infancy. *Developmental Science*, 10(5), F31-F38.

Baumgartner, T., Speck, D., Wettstein, D., Masnari, O., Beeli, G., and Jäncke, L. (2008). Feeling present in arousing virtual reality worlds: prefrontal brain regions differentially orchestrate presence experience in adults and children. *Frontiers in Human Neuroscience*, 2, 8.

Blakemore, S.-J., & Mills, K. L. (2014). Is adolescence a sensitive period for sociocultural processing? *Annual Review of Psychology*, 65, 187–207.

Bulgarelli, C., Pinti, P., Aburumman, N., and Jones, E. J. H. (2023). Combining wearable fNIRS and immersive virtual reality to study preschoolers' social development: a proof-of-principle study on preschoolers' social preference. *Oxford Open Neuroscience*, 2, kvad012.

Buschman, T. J., & Kastner, S. (2015). From behavior to neural dynamics: an integrated theory of attention. *Neuron*, 88(1), 127-144.

Chang, E., Billinghamurst, M., and Yoo, B. (2023). Brain activity during cybersickness: a scoping review. *Virtual Reality*, 27, 2073–2097.

Cherry, L., Soderberg, C., Haertter, J., & Ossmy, O. (2024). Extended reality in STEM: a modernised educational tool for children. *Journal of Human Centered Technology*, 3(2), 10-20.

Christakis, D. A., Ramirez, J. S. B., Ferguson, S. M., Ravinder, S., & Ramirez, J. M. (2018). How early media exposure may affect cognitive function: A review of results from observations in humans and experiments in mice. *Proceedings of the National Academy of Sciences*, 115(40), 9851-9858.

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and brain sciences*, 36(3), 181-204.

Croeser, S., & Eckersley, P. (2019). Theories of Parenting and Their Application to Artificial Intelligence. *Proceedings of the 2019 AAAI/ACM Conference on AI, Ethics, and Society*. p. 423–428

Crowley, S. J., Acebo, C., & Carskadon, M. A. (2007). Sleep, circadian rhythms, and delayed phase in adolescence. *Sleep Medicine*, 8(6), 602–612.

Dienlin, T., & Johannes, N. (2020). The impact of digital technology use on adolescent well-being. *Dialogues in Clinical Neuroscience*, 22(2), 135.

Dina, L.-M., Pinti, P., and Smith, T. J. (2025). Measuring neurodevelopment of inhibitory control in children using naturalistic virtual reality. *Scientific Reports*, 15, 26944.

Dykxhoorn, J., Solmi, F., Walters, K., Gnani, S., Lazzarino, A., Kidger, J., Kirkbride, J. B., & Osborn, D. P. J. (2025). Common mental disorders in young adults: temporal trends in primary care episodes and self-reported symptoms. *BMJ Mental Health*, 28(1).

EbrahimiSani, S., Sohrabi, M., Taheri, H., Agdasi, M. T., and Amiri, S. (2020). Effects of virtual reality training intervention on predictive motor control of children

Fanselow, M. S. (1994). Neural organization of the defensive behavior system responsible for fear. *Psychonomic Bulletin & Review*, 1(4), 429–438.

Farzin, F., Rivera, S. M., & Whitney, D. (2011). Time crawls: the temporal resolution of infants' visual attention. *Psychological Science*, 22(8), 1004-1010.

Friston, K., & Kiebel, S. (2009). Predictive coding under the free-energy principle. *Philosophical transactions of the Royal Society B: Biological sciences*, 364(1521), 1211-1221.

Gessaroli, E., Santelli, E., di Pellegrino, G., and Frassinetti, F. (2013). Personal space regulation in childhood autism spectrum disorders. *PLoS one*, 8(9), e74959.

Hoffman, D. M., Girshick, A. R., Akeley, K., and Banks, M. S. (2008). Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision*, 8(3), 33.

⁹Holmes, W., Persson, J., Chounta, I-A., Wasson, B., & Dimitrova, V. (2022). *Artificial Intelligence and Education a Critical View Through the Lens of Human Rights, Democracy and the Rule of Law*. Strasbourg. France: The Council of Europe.

Huang, P., Chan, S. Y., Zhou, K. X., Chuah, J., Manahan, A. M. A., Law, E. C. N., ... & Tan, A. P. (2025). Neurobehavioural links from infant screen time to anxiety. *EBioMedicine*.

Itti, L., & Baldi, P. (2009). Bayesian surprise attracts human attention. *Vision research*, 49(10), 1295-1306.

Jenkins, R. H., Shen, C., Dumontheil, I., Thomas, M. S. C., Elliott, P., Rösli, M., & Toledano, M. B. (2020). Social networking site use in young adolescents: Association with health-related quality of life and behavioural difficulties. *Computers in Human Behavior*, 109, 106320.

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks effect: Human infants allocate attention to visual sequences that are neither too simple nor too complex. *PloS one*, 7(5), e36399.

Koolstra, C. M., Van Zanten, J., Lucassen, N., & Ishaak, N. (2004). The formal pace of Sesame Street over 26 years. *Perceptual and motor skills*, 99(1), 354-360.

Kostyrka-Allchorne, K., Cooper, N. R., Kennett, S., Nestler, S., & Simpson, A. (2019). *The Short-Term Effect of Video Editing Pace on Children's Inhibition and N2 and P3 ERP Components during a Visual Go/No-Go Task*. *Developmental Neuropsychology*, 44(4), 385-396.

Lillard, A. S., & Peterson, J. (2011). The immediate impact of different types of television on young children's executive function. *Pediatrics*, 128(4), 644-649.

Lissak, G. (2018). *Adverse physiological and psychological effects of screen time on children and adolescents: Literature review and case study*. *Environmental Research*, 164, 149-157.

Mareschal, D., Johnson, M.H., Sirois, S., Spratling, M., Thomas, M. & Westermann, G. (2007). *Neuroconstructivism, Vol. I: How the brain constructs cognition*. Oxford, UK: Oxford University Press.

- McStay, A. & Rosner G. (2021). Emotional artificial intelligence in children's toys and devices: Ethics, governance and practical remedies. *Big Data & Society*, 1–16.
- Mangalmurti, A., Kistler, W. D., Quarrie, B., Sharp, W., Persky, S., and Shaw, P. (2020). Using virtual reality to define the mechanisms linking symptoms with cognitive deficits in attention deficit hyperactivity disorder. *Scientific Reports*, 10, 529.
- Merzon, L., Pettersson, K., Aronen, E. T., Huhdanpää, H., Seesjärvi, E., Henriksson, L., MacInnes, W. J., Mannerkoski, M., Macaluso, E., and Salmi, J. (2022). Eye movement behavior in a real-world virtual reality task reveals ADHD in children. *Scientific Reports*, 12, 20308.
- Miehlbradt, J., Cuturi, L. F., Zanchi, S., Gori, M., and Micera, S. (2021). Immersive virtual reality interferes with default head–trunk coordination strategies in young children. *Scientific Reports*, 11, 17959.
- Mireku, M. O., Mueller, W., Fleming, C., Chang, I., Dumontheil, I., Thomas, M. S. C., Eeftens, M., Elliott, P., Röösli, M., & Toledano, M. B. (2018). Total recall in the SCAMP cohort: Validation of self-reported mobile phone use in the smartphone era. *Environmental Research*, 161.
- Muszynska, M., Dalton, R., Serino, G., Kumar, S., Pinti, P., Farran, E. K., & Ossmy, O. (2025, September). Using virtual reality and psychophysics to test embodied cognitive flexibility in children with ADHD. In *2025 IEEE International Conference on Development and Learning (ICDL)* (pp. 1-7). IEEE.
- Nagata, J. M., Al-Shoaibi, A. A. A., Leong, A. W., Zamora, G., Testa, A., Ganson, K. T., & Baker, F. C. (2024). Screen time and mental health: a prospective analysis of the Adolescent Brain Cognitive Development (ABCD) Study. *BMC Public Health*, 24(1).
- Nagata, J. M., Helmer, C. K., Memon, Z., Talebloo, J., Ganson, K. T., Testa, A., He, J., Abdel Magid, H. S., Gooding, H. C., & Baker, F. C. (2026). Neighborhood quality and screen use: Findings from the adolescent brain cognitive development study. *Academic Pediatrics*, 26(2), 103164.
- Neguț, A., Jurma, A. M., and David, D. (2017). Virtual-reality-based attention assessment of ADHD: ClinicaVR: Classroom-CPT versus a traditional continuous performance test. *Child Neuropsychology*, 23(6), 692–712.
- Ofcom (2025) Children's Passive Online Measurement.
<https://www.ofcom.org.uk/siteassets/resources/documents/online-safety/research-statistics-and-data/protecting-children/ofcom-childrens-passive-online-measurement.pdf?v=408844>
- Paulich, K. N., Ross, J. M., Lessem, J. M., & Hewitt, J. K. (2021). Screen time and early adolescent mental health, academic, and social outcomes in 9- and 10- year old children: Utilizing the Adolescent Brain Cognitive Development SM (ABCD) Study. *PloS One*, 16(9).
- Rapee, R. M., Oar, E. L., Johnco, C. J., Forbes, M. K., Fardouly, J., Magson, N. R., & Richardson, C. E. (2019). Adolescent development and risk for the onset of social-emotional disorders: A review and conceptual model. *Behaviour Research and Therapy*, 123, 103501.

Ross, J. A., & Van Bockstaele, E. J. (2021). The locus coeruleus-norepinephrine system in stress and arousal: unraveling historical, current, and future perspectives. *Frontiers in psychiatry*, 11, 601519.

Scott, J., Kallestad, H., Vedaa, O., Sivertsen, B., & Etain, B. (2021). Sleep disturbances and first onset of major mental disorders in adolescence and early adulthood: A systematic review and meta-analysis. *Sleep Medicine Reviews*, 57.

Rushton, S. K., and Riddell, P. M. (1999). Developing visual systems and exposure to virtual reality and stereo displays: some concerns and speculations about the demands on accommodation and vergence. *Ophthalmic and Physiological Optics*, 19, 25–31.

Shen, C., Girela-Serrano, B. M., di Simplicio, M., Spiers, A., Dumontheil, I., Thomas, M. S. C., Rösli, M., Elliott, P., Smith, R. B., & Toledano, M. B. (2026). Social networking site use, depressive and anxiety symptoms in adolescents: evidence from a longitudinal cohort study (SCAMP). *BMC Medicine* 24:1, 24(1), 139.

Shen, C., Mireku, M. O., Simplicio, M. di, Dumontheil, I., Michael, J., Thomas, S. C., Rösli, M., Elliott, P., & Toledano, M. B. (2022). Bidirectional associations between sleep problems and behavioural difficulties and health-related quality of life in adolescents: Evidence from the SCAMP longitudinal cohort study. *JCPP Advances*, 2(3), e12098

Silva, K. S. K., Breeland, N. B., Clark, A. M., Öztekin, İ., and Kelly, R. L. (2025). Effects of virtual reality use in children aged 10 to 12 years. *Frontiers in Virtual Reality*, 6.

Simões, M., Mouga, S., Pereira, A. C., de Carvalho, P., Oliveira, G., and Castelo-Branco, M. (2020). Virtual reality immersion rescales regulation of interpersonal distance in controls but not in autism spectrum disorder. *Journal of Autism and Developmental Disorders*, 50(12), 4317–4328.

Shibata, T., Kim, J., Hoffman, D. M., and Banks, M. S. (2011). The zone of comfort: predicting visual discomfort with stereo displays. *Journal of Vision*, 11(8), 11.

Tang, S., Werner-Seidler, A., Torok, M., Mackinnon, A. J., & Christensen, H. (2021). The relationship between screen time and mental health in children and adolescents: A systematic review of longitudinal studies. *Clinical Psychology Review*, 88, 102067.

Toledano, M. B., Mutz, J., Rösli, M., Thomas, M. S. C., Dumontheil, I., & Elliott, P. (2019). Cohort Profile: The Study of Cognition, Adolescents and Mobile Phones (SCAMP). *International Journal of Epidemiology*, 48(1), 25–261.

Twenge, J. M., Spitzberg, B. H., & Campbell, W. K. (2019). Less in-person social interaction with peers among U.S. adolescents in the 21st century and links to loneliness. *Journal of Social and Personal Relationships*, 36(6), 1892–1913.

Ulrich-Lai, Y. M., & Herman, J. P. (2009). Neural regulation of endocrine and autonomic stress responses. *Nature reviews neuroscience*, 10(6), 397-409.

Valori, I., McKenna-Plumley, P. E., Bayramova, R., Zandonella Callegher, C., Altoè, G., and Farroni, T. (2020). Proprioceptive accuracy in immersive virtual reality: a developmental perspective. *PLOS ONE*, 15(1), e0222253.

Wang, G.E., Zhao, J., van Kleek, M., Shadbolt, N. (2022). Informing Age-Appropriate AI: Examining Principles and Practices of AI for Children. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, Article 536, 1–29.

Wass, S., & Goldenberg, G. (2025). *Take Action on Distraction: The definitive guide to improving attention and focus in the Early Years and Key Stage One*. Bloomsbury Publishing.

Wass, S. V., & Smith, T. J. (2015). Visual motherese? Signal-to-noise ratios in toddler-directed television. *Developmental science*, 18(1), 24-37.

Zhang, Z., Xu, Y., Wang, K. Y., et al. (2022). StoryBuddy: A Human-AI Collaborative Chatbot for Parent-Child Interactive Storytelling with Flexible Parental Involvement. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, Article 218. 1–21.