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Brain connectivity in children is increased by the time they spend reading books and decreased by the length of exposure to screen-based media

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ABSTRACT

Aim: This study compared the time spent using screen-based media or reading on the functional connectivity of the reading-related brain regions in children aged 8–12.

Methods: We recruited 19 healthy American children from a private school in Cincinnati, USA, in 2015-6 after advertising the study to parents. The parents completed surveys on how many hours their children spent on independent reading and screen-based media time, including smartphones, tablets, desktop or laptop computers and television. The children underwent magnetic resonance imaging that assessed their resting-state connectivity between the left visual word form area, as the seed area, and other brain regions, with screen time and reading time applied as predictors.

Results: Time spent reading was positively correlated with higher functional connectivity between the seed area and left-sided language, visual and cognitive control regions. In contrast, screen time was related to lower connectivity between the seed area and regions related to language and cognitive control.

Conclusion: Screen time and time spent reading showed different effects on functional connectivity between the visual word form area and language, visual and cognitive control regions of the brain. These findings underscore the importance of children reading to support healthy brain development and literacy and limiting screen time.

INTRODUCTION

Reading, which is the ability to decode and extract meaning from abstract graphemes, is a relatively new human invention, dating back approximately 5000 years (1). As it is a learned rather than innate skill, successful reading acquisition involves the development and integration of fundamental cognitive abilities supported by dedicated brain areas and networks, such as those for language, visual processing and higher-order executive functions (1). Neuroimaging-based studies have identified that left-lateralised neural components are involved with these networks, in particular the superior temporal, Brodmann areas 20–22 and inferior frontal gyrus Brodmann areas 44 and 45 that support language, the lateral occipital visual-association Brodmann areas 18 and 19 that support imagery (2) and the angular gyrus Brodmann areas 39 and 40 that support multimodal and audio-visual association (3). The left fusiform gyrus Brodmann area 37, also known as the visual word form area, supports the recognition of letters and the groups of letters that make up words (3). Previous studies have confirmed that executive functions play a role in emerging literacy via error monitoring and cognitive control involving the anterior cingulate gyrus Brodmann area 24 (4) and the dorsal attention network, including the inferior parietal sulci and frontal eye fields (5) via functional connections with the visual word form area (6).

Abbreviation
MRI, Magnetic resonance imaging.

Key notes

- Parental surveys and magnetic resonance imaging scans were used to compare the time spent using screen-based media or reading on the functional connectivity of the reading-related brain regions in 19 children aged 8–12.
- Greater reported reading time was associated with increased functional connectivity in the reading-related brain networks in children.
- The results underscore the importance of reading to support healthy brain development and literacy and limiting screen-based media use.

Given the remarkable feat of neuronal recycling for reading (7), a question naturally arises about which factors and experiences help facilitate, and impair, this process during child development. Reciprocal verbal stimulation is particularly important and contributes to wide disparities in language and academic achievement (8). Shared reading, mainly by parents and children, is a potent means to enhance such exposure (9), and the American Academy of Pediatrics recommends that this starts as soon as possible after birth (10). Greater reading exposure has been strongly correlated with increased receptive and expressive language, mastery of print concepts and attitudes towards reading, which in turn predict future reading practices and academic achievement (11). Neuroimaging-based research has provided neurobiological support for these findings, demonstrating positive correlation between the home reading environment and brain activation to support language, imagery and social–emotional skills in preschool children (12). Imaging-based research has also found positive associations between structural and functional neurobiological measures and cognitive outcomes, including reading ability, intelligence quotients and college admission test scores (13,14).

Screen-based media is a far more recent development than reading and has exploded over the past 20 years, fundamentally altering the way humans interact with one another and the world (15). Perhaps more profoundly, this has transformed the way a child learns and explores the environment (16), while their neural infrastructure has not changed (17). Despite recommendations to the contrary (15), 90% of children under the age of two years are regularly exposed to electronic media (18), increasing from one to three hours per day in infancy (16) to over three hours per day by kindergarten and seven and a half hours per day by adolescence (16). By contrast, studies have shown that time that children spend reading traditional books has decreased to between 19 and 28 minutes per day (16,19). The documented negative effects of screen time, which includes the use of screen-based media such as smartphones, tablets, desktop or laptop computers and television, include language delay (20), obesity (21), decreased readiness for kindergarten (22) and other academic problems (23) and exacerbation of attention deficit hyperactive disorder (24). It has been proposed that major drivers of these effects are decreased engagement with grown-up caregivers (25) and the displacement of active endeavours such as reading, homework and creative play (26). Imaging-based studies have also shown neurobiological correlates of screen time in children, including grey matter and white matter cortical atrophy (27), lower cortico-striatal functional connectivity (28) and increased cortical thickness in nonlanguage areas, accompanied by lower intelligence (29). Thus, the American Academy of Pediatrics recommends that screen time be limited to one hour per day in children over 18 months old and that they are encouraged to get involved in constructive alternatives, such as reading (15,30). However, prior to this study, there have been no published reports that have explored the potentially differential effects of screen time and time spent reading on reading-related brain networks in school-age children, during a formative stage of reading and broader cognitive development.

The aim of this study was to examine neural correlates of reported screen time and time spent reading in children aged 8–12 using resting-state, functional magnetic resonance imaging (MRI). Given the major role of the visual word form area in the functional reading network (1), we used this region as the seed area for our analyses. Given the lack of previous studies investigating neural circuits related to screen time in children, we conducted whole-brain analyses, so that we did not exclude potentially important, unexpected contributors. Our decision to study eight–12-year-olds was based on the fact that children in this age range are reasonably expected to be reading fluently (31). Given the known positive effects of reading practice on activation of the visual word form area, and its functional connectivity with the brain circuits that support language and executive functions (6), we hypothesised that time spent reading would be positively correlated with higher functional connectivity between the visual word form area and these circuits. By contrast, given the cognitive risks that have been cited by other studies, we hypothesised that screen time would be correlated with decreased functional connectivity between the visual word form area and these circuits.

METHODS

Participants and demographics

We recruited 19 children (11 females) with a mean age of 9.99 years, a standard deviation of 0.84 and a range of eight–12 years from a private school in Cincinnati, OH, USA, after we advertised the study to their parents. All participants were within the normal range of nonverbal intelligence with no history of neurological, emotional or attention disorders. They were also monolingual English speakers, prescreened for compatibility with MRI, Caucasian and from average socio-economic status households with a median income of $42 000. Informed consent and assent were signed by the parents and children, respectively. This study was part of a larger study that examined the neurobiology of reading, and it was approved by the Cincinnati Children's Hospital Institutional Review Board.

Behavioural measures

All children underwent the Test of Nonverbal Intelligence (32) and a vocabulary task from the Peabody Picture Vocabulary Test (33) to verify normal nonverbal and verbal intelligence, respectively. To control for reading ability, the letter-word and word-attack subtest from the Woodcock–Johnson Tests of Cognitive Abilities (34) was assessed. Attention difficulties were ruled out by administering the Conners Parent Short-form Assessment Report (35).

Reading and screen time

Reading and screen time were measured using items adapted from the validated StimQ-P instrument (36). During their study visit, parents were asked to report approximately how many hours per day their child spent reading for pleasure, such as books, newspapers or any other reading material. Parents were also asked approximately how many hours per day their child spent using screen-based media such as smartphones, tablets, desktop or laptop computer and television.

Imaging

MRI scans were conducted using a Philips Achieva 3T scanner (Philips Medical Systems, Amsterdam, the Netherlands). Participating children were acclimatised to the scanner using established, play-based techniques (37). Head motion was controlled using elastic straps attached to the head-coil apparatus, and all children had access to a panic button if they felt distressed. We acquired a high-resolution T1-weighted, 3D anatomical scan lasting approximately five minutes for each child, followed by a 10-minute resting-state scan where the child was asked to look at a grey cross in the centre of a projector screen and avoid sleeping or closing their eyes, other than blinking.

MRI data analysis

Reconstructed functional MRI data were spatially preprocessed using the SPM8 software package (The FIL Methods Group, London, UK), including slice-timing correction, realignment for motion correction, coregistration to the mean aligned functional image, segmentation by tissue class, normalisation to the Montreal Neurological Institute space and spatial smoothing with an 8-mm Gaussian kernel. As connectivity analyses are incredibly sensitive to motion, this was corrected for using pyramid coregistration (38) in SPM8 as described in Appendix S1.

Functional connectivity analysis

Functional connectivity between the visual word form area seed and all Brodmann areas across the entire brain during the resting state was assessed using the CONN functional connectivity toolbox in SPM8 (39). This toolbox implements a component-based noise correction method for reducing physiological and other nuisance components that may affect the haemodynamic response signal, such as white matter and cerebrospinal fluid effects and motion effects. This enables group inferences to be made using random effects in a second-level analysis. A whole-brain functional connectivity analysis was performed, based on the average time series of the haemodynamic response in the voxels of the visual word form area and averaged time series of voxels in all other Brodmann areas across the entire brain, and pairwise bivariate correlation or connectivity scores were calculated. Each Brodmann area was a sphere of 10 mm. Only significant correlations, defined as uncorrected two-sided values of $p < 0.05$, were considered as edges within the resulting network. Regressors were then individually applied as predictor variables of interest for both the reported hours per week of independent reading time and the reported hours of screen time, based on previous studies using the approach of choosing seeds and exploring the correlation with functional connections with behavioural covariates of interest (40,41). To control for potential confounding factors, reading-ability scores using the letter-word scaled score were included as a covariate of no interest for each of these analyses. The difference between resting-state functional connectivity correlated with hours spent reading and for screen time was then calculated, controlling for reading ability. The level of functional connectivity between the visual word form area and each Brodmann area described in T and beta values, or effect sizes, was calculated for each pair of nodes and by analysis of variance for each analysis, that is the two conditions and the contrast between the two.

RESULTS

Behavioural measures

Verbal and nonverbal abilities and attention scores were within the average range (Table 1). Parents reported their children spent a mean of 3.89 hours per week on screen-time activities, with a standard deviation of 0.45, range of 3.00–5.00 and median of 4.00 hours. They also spent a mean of 4.00 hours per week on independent reading, with a standard deviation of 2.23, range of 0–8.00 and median of 4.00 hours. We comment on the relatively low weekly screen time found in this study in the Discussion section.

Correlation between resting-state connectivity and behavioural measures

The amount of time that the children spent reading was positively correlated with higher functional connectivity between the visual word form area and the regions related to language such as the left Brodmann areas 40, 42, 43 and 22. It was also positively correlated with visual association, such as the left and right Brodmann area 19, and cognitive control, such as the left Brodmann areas 7 and 44. Results were generated using an uncorrected threshold of $p < 0.05$, controlling for reading ability (F 3–14 = 4.88, $p < 0.001$

Table 1 Behavioural measures for children with reading difficulties and typical readers

Ability	Measure	Mean (SD)	Norms
Nonverbal ability	TONI-3 (Scaled score)	104.68 (7.31)	85 ± 15
Verbal ability	PPVT-4 (Scaled score)	106.42 (11.96)	85 ± 15
Attention	Conners (Per cent)	43.32 (22.83)	<59
Word reading	WJ-III letter-word and word-attack subtest (Scaled score)	103.26 (14.99)	85 ± 15

SD = Standard deviation; TONI-3 = Test of Nonverbal Intelligence 3rd edition; PPVT-4 = Peabody Picture Vocabulary test 4th edition; WJ-III = Woodcock–Johnson tests of cognitive abilities 3rd Edition.
Norms for each test are indicated in the right-hand column.

uncorrected). The regions involved and the connectivity strengths are shown in Figures 1A and 2, and the effect sizes are summarised in Figure 2B. Table S1 shows the node coordinates, T and beta values for the node pairs and the analysis of variance results.

Reported screen-time hours were negatively correlated with functional connectivity between the visual word form area and the regions related to cognitive control such as the right Brodmann areas 24 and 13 and the left Brodmann areas 25 and 47. It was also negatively correlated with

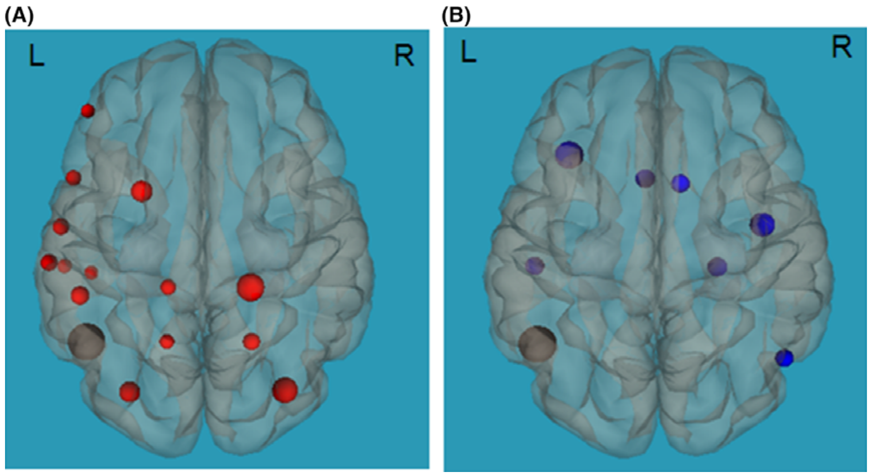

Figure 1 Correlations of time spent either reading or on screen and the visual word form area (BA 37) with other Brodmann areas in the entire brain. Positive and negative correlations between functional connectivity of the visual word form area (black circle) and reading, language and cognitive control regions (red circles in A, blue circles in B) during (A) hours spent on reading and (B) hours spent on screen, respectively. Panels are shown in neurological orientation: L = Left, R = Right.

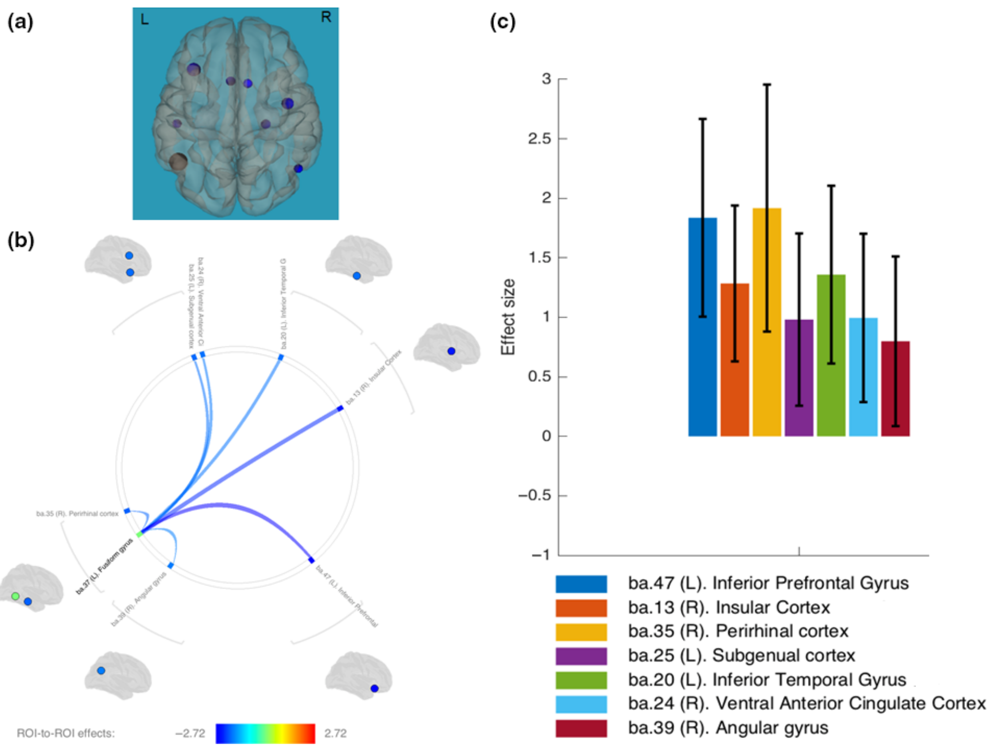

Figure 2 Correlations of time spent reading and functional connectivity between the visual word form area (BA 37) and other Brodmann areas in the entire brain. (A) presents a sagittal view of functional connectivity between the visual word form area (green circle) and other Brodmann areas (orange and red circles) over a glass brain. Line thickness represents the strength of functional connections between each pair of regions (T values for the functional connectivity range between −3.27 and +3.27). (B) presents effect sizes for the correlation between reading time and functional connectivity (Y axis) between the visual word form area and the entire brain.

language regions such as the left and right Brodmann areas 39 and 20. Results were generated using an uncorrected threshold of $p < 0.05$, controlling for reading ability (F 4–3 = 1.99, $p < 0.001$, uncorrected). The regions involved and the connectivity strengths are shown in Figures 1B and 3, and the effect sizes are summarised in Figure 3B. Table S1 shows the node coordinates, the T and beta values for the node pairs and the analysis of variance results.

Contrasting functional connectivity between the visual word form area and the regions independently correlated with the reports of the hours spent on reading and screen time revealed greater functional connectivity between the visual word form area and the regions related to cognitive control. These included the left Brodmann areas 47, 9, 3, 24 and 6 and right Brodmann areas 13, 5 and 6, and language, such as the right Brodmann areas 39 and 7 and the left Brodmann area 20. The regions involved and described above, the connectivity strengths and the effect sizes are summarised in Figure S1 and Table S1.

DISCUSSION

The purpose of this study was to explore neurobiological correlates of reported reading and screen time in school-age children during a formative stage of their development, in order to provide insights into the mechanics of potential beneficial and deleterious effects. The results of the study suggest that reading time was positively correlated and screen time was negatively correlated with functional connectivity between the visual word form area and the regions related to language, visual processing and cognitive control.

Consistent with our hypothesis, greater reported reading time was positively correlated with increased functional connectivity between the visual word form area and regions supporting higher-order visual processing, language, and executive functions and cognitive control. The relationships between language, executive functions and reading abilities have been well established in behavioural and imaging-based studies (42), and our results were consistent with this evidence. Intriguingly, visual-association brain regions play an important role in narrative comprehension (2) and reading (2), via the use of visual imagery. Our findings therefore suggest that greater connectivity between the visual word form area and visual-association regions, which were correlated with time spent reading, reflected the neurobiological benefits of practising seeing and imagining what was happening in stories. The involvement of regions related to language, visual processing and executive functions in the right hemisphere in our results was also notable, highlighting a previously described role of the right hemisphere in reading comprehension (43,44). These results

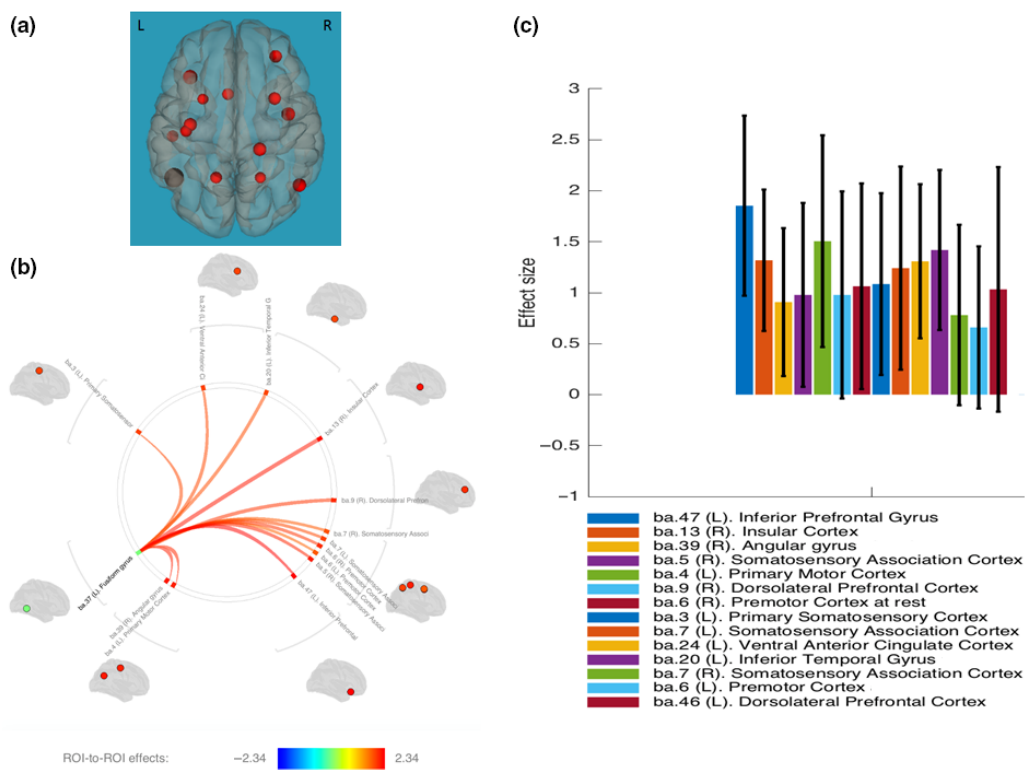

Figure 3 Correlations of screen time and functional connectivity between the visual word form area (BA 37) and other Brodmann areas in the entire brain. (A) presents a sagittal view of functional connectivity between the visual word form area (green circle) and other Brodmann areas (orange and red circles) over a glass brain. Line thickness represents the strength of functional connections between each pair of regions (T values for the functional connectivity range between −3.27 and +3.27). (B) presents effect sizes for the correlation between reading time and functional connectivity (Y axis) between the visual word form area and the entire brain.

indicate the role of the right hemisphere in comprehension (45,46) and understanding metaphors and humour (47,48) during language processing. However, while it is reasonable to speculate such a role, the current study did not examine the effect of reading time on comprehension skills, which would be useful to investigate in future studies.

Also consistent with our hypothesis, higher reported screen time was correlated with decreased functional connectivity between the visual word form area and the regions related to language and cognitive control. This finding was consistent with behavioural evidence of ill-effects of screen-based media use, including language delays (20) and academic difficulties (23,49), and provides novel neurobiological support for these effects. Potential catalysts include decreased verbal interaction with grown-up caregivers (50) and passive media occupying potential reading time. While screen-based media, such as apps and television programmes, are often advertised as educational and interactive (26), there is little evidence of such benefits (51). It is intriguing to speculate whether the well-cited benefits of both shared and independent reading practices are influenced by traditional versus screen-based formats and this would be worth considering for future research. The answer is surely quite subtle, as, for example, there is evidence that screen-based curricula can be positively used for at-risk kindergarten children (52,53) and specially designed video games can help children with reading difficulties (54).

The fact that time spent on traditional reading and screen-based media exposure exerts different effects on functionally related brain regions may suggest that they have distinct influences on the developing brain. This finding raises important questions about current behavioural trends in children (16), while reinforcing the screen time and literacy recommendations (15). Potential trade-offs between screen-based activities and traditional reading on neural development supporting foundational cognitive abilities such as imagery, executive, language and other emergent literacy skills warrant further study. However, as the results of the current study were uncorrected for multiple comparisons, the findings should be treated as exploratory.

Historically, reading research has mainly focused on the cognitive circuits involved with processing written words, including phonological decoding (55) and comprehension (56). Each of these is predictors of reading ability (1) and influenced by the home reading environment (12). Executive functions have been found to support successful reading development (57,58) at a younger age than previously thought (59), suggesting novel aetiologies for reading disabilities and interventions. The visual word form area has been suggested to be functionally connected to the dorsal attention executive functions network, which tunes visual attention to the reading process (6,58). Functional connectivity has also been described between the visual word form area and cognitive control networks correlated with reading ability (60). Thus, it is not surprising and is consistent with our hypothesis that hours spent reading were positively correlated with functional connectivity between the visual word form area and executive functions areas in our analysis. The same was true when we contrasted reading and screen time (Table S1 and Figure S1). By contrast, screen time was correlated with decreased connectivity between the visual word form area and executive functions areas. This suggests a different functional relationship that potentially reflects decreased cognitive loading during more active behaviours, such as reading, compared to passive, screen-based behaviours. Further research is needed to identify the importance of activities that foster greater cognitive practices and engagement of the executive and attentional networks, as these, in turn, support reading abilities during child development.

Our study has important strengths. It involved a well-defined, diverse sample of children during a formative developmental stage, namely early reading acquisition, that was adequate for imaging-based analyses (61). It also controlled for reading ability using standardised test scores, which minimised the influence of this potentially confounding factor. The study was novel in that it was the first study to our knowledge to detect a correlational signal between reported screen and reading time and neural connectivity in school-age children. Applying a well-described functional brain area as a seed, the visual word form area, meant that our connectivity findings were consistent with evidence-based models of reading (3), language (62,63) and cognitive control (64) networks and that guided our analyses. Finally, our study addressed the increasingly urgent public health issues of screen-based media use and reading in children and their influence on cognitive and brain development, which inform the recommendations produced by the American Academy of Pediatrics and other organisations and will help to guide future, imaging-based research.

Our study also had limitations. Due to the relatively low number of participants and the need to correct for multiple comparisons across the brain—approximately 100 000 voxel comparisons—our connectivity results did not survive the false discovery rate correction. However, the visual word form area seed and functionally connected areas that we identified were consistent with our *a priori* hypotheses which involved current, brain-based models of reading, adding credence to our findings. A future study employing a larger number of children and focusing on functional connectivity within, and between, the specific networks related to language, visual and executive functions, which were all identified in this study as potentially related to reading or screen time, is warranted. Our parental survey did not subdivide screen time into specific components, such as watching television or playing video games, alone or with a caregiver, despite behavioural evidence of the differential effects of these platforms (65,66). Similarly, the survey did not elaborate on reading content, such as whether the children were reading narratives, nonfiction, popular book, whether they were reading for pleasure or for school and whether their reading was slow or fast paced. Nor did it elaborate on screen-based content, such as whether children read texts on their screens. These factors could have potentially influenced our outcomes (67,68) and should be elaborated on in future work. Our analyses did not stratify children according to excessive screen-based media use as defined by the American Academy of Pediatrics, which may have identified disproportionate effects in the highest users. Another important point is that the children participating in the current study were all Caucasian, from average socio-economic background, and attending a private school, which may be related to the low screen time noted in the current study. Including additional children with a low socio-economic status might have strengthened the current study's results. Finally, although there is evidence that children who use more screen-based media read less, it is important to note that our results did not identify such a relationship. However, our findings do suggest that even the relatively crude screen and reading time measures used were adequate to elicit an important neurobiological signal to guide future work. Longitudinal studies with the potential to explore causality seem particularly imperative, given the rising debate regarding the role of screen-based media in a child's life across development and the increasing emphasis and investment in technology in schools (16).

CONCLUSION

Reading is a relatively recent cultural invention that is becoming eclipsed by a far newer one, screen-based media. The processing of each activity requires brain circuits that have evolved for other functions to focus on new purposes and integrate into functional networks. Our study is novel in that it describes correlations between time spent reading and exposure to screen-based media, based on parental reports, and the connectivity between a key component of the reading network and brain areas supporting important, reading-related visual, language and executive cognitive processes in eight- to 12-year-old children. Our findings suggest that screen-based media use and exposure was negatively correlated with connectivity between the visual word form area and these reading-supporting circuits, while reading time was positively correlated with such connectivity. While it is unclear whether these represent truly antagonistic influences, our findings were consistent with behavioural evidence of the consequences of excessive screen time and benefits of reading practice on language, executive functions and academic performance. They also suggest novel neurobiological mechanisms for such effects. Further studies on the effects of screen time and reading environments, and their interrelationships with the neurodevelopment of children, are warranted.

FINANCE

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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