Associations between digital media use and brain surface structural measures in preschool-aged children

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The American Academy of Pediatrics recommends limits on digital media use ("screen time"), citing cognitive-behavioral risks. Media use in early childhood is ubiquitous, though few imaging-based studies have been conducted to quantify impacts on brain development. Cortical morphology changes dynamically from infancy through adulthood and is associated with cognitive-behavioral abilities. The current study involved 52 children who completed MRI and cognitive testing at a single visit. The MRI protocol included a high-resolution T1-weighted anatomical scan. The child’s parent completed the ScreenQ composite measure of media use. MRI measures included cortical thickness (CT) and sulcal depth (SD) across the cerebrum. ScreenQ was applied as a predictor of CT and SD first in whole-brain regression analyses and then for regions of interest (ROIs) identified in a prior study of screen time involving adolescents, controlling for sex, age and maternal education. Higher ScreenQ scores were correlated with lower CT in right-lateralized occipital, parietal, temporal and fusiform areas, and also lower SD in right-lateralized inferior temporal/fusiform areas, with substantially greater statistical significance in ROI-based analyses. These areas support primary visual and higher-order processing and align with prior findings in adolescents. While differences in visual areas likely reflect maturation, those in higher-order areas may suggest under-development, though further studies are needed.

Abbreviations
AAP American academy of pediatrics
FWE Family-wise error
MNI Montreal neurological institute
MRI Magnetic resonance imaging
SES Socioeconomic status

The American Academy of Pediatrics (AAP) recommends limits on digital media use ("screen time") for children at all ages. Domains include access to screens, frequency of use, content and grownup-child co-viewing. Cited risks of excessive and/or inappropriate use span developmental domains, including physical (e.g., obesity), social-emotional (parent–child engagement) and cognitive (e.g., language, executive function). Recent evidence suggests potential impacts on brain structure and function underlying these abilities. Proposed mechanisms are direct (e.g. age-inappropriate content, impaired sleep) and indirect (e.g. displacement of parent–child interaction) in nature. Despite these risks and recommendations, use has been increasing beginning in infancy, fueled by portable devices and amplified during the COVID-19 pandemic.

Magnetic Resonance Imaging (MRI) is a powerful tool that can provide insights into relationships between environmental factors and brain structure and function. Several studies have explored neurobiological impacts of adverse childhood experiences, such as neglect and poverty. However, few have explored relationships.
between digital media use and brain development, particularly during early childhood when plasticity is high. Higher media use referenced to AAP guidelines (ScreenQ measure) was recently associated with lower microstructural integrity of major white matter tracts, and also with lower emergent literacy skills. By contrast, other studies have found positive associations between shared reading at home and these white matter measures (and also functional MRI measures) at this age, suggesting a potential displacement effect of screen use.

Early childhood (newborn through age 5) is a formative span of brain development. Essential structural and functional networks are established by age two and then shaped by genetic and environmental factors, manifest via shifts in grey matter density (e.g., pruning, synaptogenesis) and myelination of white-matter tracts. Cerebral surface morphology evolves across childhood, reflected by features such as cortical thickness (CT) and sulcal depth (SD). While developmental changes are non-linear and non-uniform, early childhood is an accretive stage of gray matter growth (i.e., thickening, deepening) with CT in most areas maximal by age 3 and SD maximal by late childhood. However, maturation in limbic and sensory areas precedes that in higher-order areas (e.g., association, executive), which do not reach local maxima until adolescence. Further, while thinning in sensory areas is thought to reflect maturation, greater CT and SD in higher-order areas have been linked to a range of cognitive abilities in children, adolescents and young adults. While there have been few such studies involving preschool-age children, higher CT in occipital-parietal-temporal areas known to support reading were recently associated with higher language and emergent literacy skills.

A recent analysis from the large, ongoing Adolescent Brain Cognitive Development (ABCD) study found associations between higher digital media use (reported minutes/day) and lower CT and SD in areas involved with visual processing, executive functions, memory and attention. The authors attributed findings to accelerated maturation of the visual system, yet noted thinning in areas that are not functionally homologous, suggesting non-uniform impacts of media use that are not clear. Potential correlates included higher externalizing behaviors for children with higher use.

The objective of the current study was to explore relationships between reported digital media use and measures of CT and SD in a sample of healthy preschool-age children during a rapid span of brain development. While relatively little is known at this age, the hypotheses were that higher use would be associated with lower CT and SD in (1) occipital areas, reflecting accelerated maturation of the visual system expected to be in a reductive phase at this age, and (2) frontal-parietal-temporal areas, reflecting relative under-development of higher-order areas expected to be in an accretive phase at this age. To address concerns about limited statistical power for this moderate sample size and to account for demographic covariates, analyses included a regions of interest (ROIs) approach limited to areas where differences in CT and SD were most strongly associated with digital media use in the ABCD study.

Material and methods

Overview/design. The current study is a secondary analysis of data collected for an MRI-based study involving impacts of home reading practices and digital media use on brain structure and function supporting emergent literacy skills in preschool-age children.

Screen time measure (ScreenQ). The ScreenQ is a 15-item parent-report measure of digital media use developed by the study team. Its conceptual model involves four domains featured in AAP recommendations for young children: access to screens, frequency of use, content and parent–child co-viewing. Internal consistency (Cronbach α = 0.74), reliability and concurrent validity have been established in young children and more recently via wider age range using a Portuguese translation. A recent analysis from the large, ongoing Adolescent Brain Cognitive Development (ABCD) study found associations between higher digital media use (reported minutes/day) and lower CT and SD in areas involved with visual processing, executive functions, memory and attention. The authors attributed findings to accelerated maturation of the visual system, yet noted thinning in areas that are not functionally homologous, suggesting non-uniform impacts of media use that are not clear. Potential correlates included higher externalizing behaviors for children with higher use.

Participants/setting. Healthy children between 3- and 5-years old were recruited at a pediatric academic center and primary care clinics in a large Midwestern city. Eligibility criteria were: (1) gestation ≥ 36 weeks, (2) age 36–52 months, (3) no prior or current kindergarten attendance, (4) no documented history of head trauma with loss of consciousness or neurodevelopmental condition likely to confer cognitive delay, (5) native English-speaking custodial parent, and (6) no contraindications for MRI such as metal implants, orthodontic braces or claustrophobia. Written informed consent was obtained from a parent and families were provided with financial compensation for time and travel.

This study was approved by the Cincinnati Children's Hospital Institutional Review Board. All research was performed in accordance with human subjects protections guidelines in accordance with the Declaration of Helsinki principles.

Screening and assessments. Clinical research coordinators collected demographic information and administered the ScreenQ to the child's parent in a private room before the MRI scan. Standard measures of expressive language (Expressive Vocabulary Test, 2nd Edition; EVT-2), processing speed (Comprehensive Test of Phonological Processing, rapid object naming subscale; CTOPP-2), rhyming abilities (Pre-reading Inventory of Phonological Awareness, rhyming subscale; PIPA) and emergent literacy composite (Get Ready to Read; GRTR) skills were administered to the child prior to MRI, and have been reported previously.

Descriptive analyses. Descriptive statistics were computed for demographic and other variables featured here, specified in a statistical analysis plan. Poverty status was defined using 2020 US Department of Health and Human Services criteria, using the midpoint of income category relative to household size. Analyses were conducted using SAS v9.4 software.
Magnetic resonance imaging (MRI). Details of play-based acclimatization techniques prior to MRI have been described previously. The protocol involved structural and functional MRI, but only the T1-weighted structural scan was used for the current study. Children were awake and non-sedated during MRI, which was conducted using a 3-Tesla Philips Ingenia scanner with a 32-channel head coil. High-resolution, 3D T1-weighted anatomical images were acquired (TR/TE = 8.1/3.7 ms; duration 5.25 min; FOV = 256 × 256 mm; matrix = 256 × 256; in-plane resolution = 1 × 1 mm; slice thickness = 1 mm; number of slices = 180, sagittal plane). Processing utilized the Computational Anatomy Toolbox (CAT12, Structural Brain Mapping Group, Jena, Germany), which performs non-linear transformations for voxel-based preprocessing, then computes surface-based morphometric (cortical thickness) measures. Individual subjects were mapped to a standard template space using age-matched a priori tissue probability maps generated from the TOM8 toolbox. Many), which performs non-linear transformations for voxel-based preprocessing, then computes surface-based morphometric (cortical thickness) measures. Individual subjects were mapped to a standard template space (~2 mm spacing) using age-matched a priori tissue probability maps generated from the TOM8 toolbox. Many), which performs non-linear transformations for voxel-based preprocessing, then computes surface-based morphometric (cortical thickness) measures. Individual subjects were mapped to a standard template space (~2 mm spacing) using age-matched a priori tissue probability maps generated from the TOM8 toolbox. Many), which performs non-linear transformations for voxel-based preprocessing, then computes surface-based morphometric (cortical thickness) measures. Individual subjects were mapped to a standard template space (~2 mm spacing) using age-matched a priori tissue probability maps generated from the TOM8 toolbox. Many), which performs non-linear transformations for voxel-based preprocessing, then computes surface-based morphometric (cortical thickness) measures. Individual subjects were mapped to a standard template space (~2 mm spacing) using age-matched a priori tissue probability maps generated from the TOM8 toolbox.
As an additional covariate, the extent of associations was nearly identical and remained statistically significant at p-FDR < 0.05 for the cuneus and fusiform areas, shown in Fig. 4B and detailed in Table 5.

**Discussion**

Brain development is a dynamic, non-linear process influenced by genetic and environmental factors. Environmental influences include relationships and experiences and can be nurturing, adverse or neutral. Given the prominent and increasing role of digital media for families beginning in infancy, it is critical to understand the direct and indirect impacts of various aspects of use on emerging skills and underlying neurobiology. These are likely to be greatest during early childhood when brain networks develop rapidly and plasticity is high, manifest via differences in gray and white matter structure30. However, currently, very little is known about these potential impacts. The purpose of this study was to examine associations between digital media use and established measures of cortical morphology (CT, SD) at this formative age. In line with our hypotheses, in both whole-brain and ROI-based analyses, higher media use was related to differences in CT (all lesser) and SD (primary visual greater, higher-order lesser) in both primary visual and higher-order association areas.

Cortical thickness (CT) reflects synaptic density and supporting cellular architecture53. While overall CT reaches maximal levels by age 2, that of limbic and sensory areas precedes higher-order (e.g. association, executive) areas, which do not achieve local maxima until adolescence35. It has been suggested that thickness may even be a marker for “lower” sensory processes (thinning occurs earlier) versus “higher” associative and integrative processes (thinning occurs later)54. Changes reflect cortical remodeling in response to environmental stimulation, which can be accretive (e.g., synaptogenesis) or reductive (e.g., pruning)53. The current study involved 3–5-year old children, whose overall CT is expected to have largely peaked, though not yet in higher-order areas. Despite limited statistical power, particularly when controlling for maternal education, significant (ROI-based) and/or marginally significant (whole-brain) associations were identified between higher screen-based media use and lesser CT involving both primary and higher-order areas. The most extensive and significant clusters were in right-lateralized occipital and superior parietal regions (Figs. 1 and 3) that support both sensory (e.g., cuneus) and multi-modal associative (e.g., supramarginal gyrus) processes, suggesting impacts in areas expected to be mature at this age and in others that are expected to still be developing.

Synchronous thinning in functionally related areas has been linked to environmental factors (e.g., visual network via visual stimuli)42. Thinning in visual cortices has also been attributed to higher maturation and efficiency7. Association between higher ScreenQ scores and lower CT in bilateral, right-lateralized occipital areas (cuneus) in the current study is consistent with these models, possibly via greater exposure to screen-based media during early childhood. Higher ScreenQ scores were also associated with lower CT in the right superior parietal lobe, which is a major node in the "top-down" dorsal attention network, particularly involving visual-spatial

| Demographics and ScreenQ scores | N (%) | Mean ± SD (Min, Max) |
|---------------------------------|-------|----------------------|
| Total                           | 52 (100) | 52.7 ± 7.7 (37, 63) |
| Child Age (months)              |       |                      |
| 36+                             | 15 (29)  |                      |
| 48+                             | 23 (44)  |                      |
| 60+                             | 14 (27)  |                      |
| Male                            | 23 (44)  |                      |
| Female                          | 29 (56)  |                      |
| Annual household income ($)     |       |                      |
| ≤ 25,000                        | 7 (13)   |                      |
| 25,001–50,000                   | 9 (17)   |                      |
| 50,001–100,000                  | 15 (29)  |                      |
| 100,001–150,000                 | 11 (21)  |                      |
| Above 150,000                   | 10 (19)  |                      |
| *Income Relative to Needs       |       |                      |
| At or under poverty threshold   | 9 (17)   |                      |
| Above poverty threshold         | 43 (83)  |                      |
| Maternal Education              |       |                      |
| High School or Less             | 4 (8)    |                      |
| Some College                    | 9 (17)   |                      |
| College graduate                | 22 (42)  |                      |
| More than college               | 17 (33)  |                      |
| ScreenQ total score             | 52 (100) | 10.1 ± 4.5 (3, 21)  |

Table 1. Demographics and ScreenQ Scores. *2020 US Department of Health and Human Services Poverty Table (income to household size).
stimuli55. Whether this finding reflects accelerated maturation via more frequent and/or stimulating screen-based media use, or under-development via less exposure to non-screen stimuli (e.g., shared reading) is unclear and in need of further study.

By contrast to primary visual areas, lower CT in the lingual gyrus, which is considered to be a higher-order visual-association area, was left-lateralized (especially ROI-based, Fig. 3), suggesting asynchronous thinning that tends to occur in these specialized brain areas. Adjacent to the parahippocampus, the lingual gyrus is involved with complex visual memory encoding, including facial and emotional expressions, core social-cognitive processes56. Lower CT in the lingual gyrus has been linked to lower episodic memory and social cognition in adults57. The lingual gyrus has also been found to support printed letter recognition, a pre-reading skill that

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**Figure 1.** 3-D Maps Showing Correlation Between ScreenQ Scores and Cortical Thickness for the Whole Brain. Three-dimensional maps showing correlations between ScreenQ total scores and cortical thickness for the whole cerebrum, controlling for age and sex (A) and also for maternal education (B). These are displayed on an inflated brain for better visibility of clusters, with blue representing thinner cortex. Upper views are lateral and superior, lower views are medial and inferior, with the frontal lobe facing upward. Cortical regions surviving p-FDR < 0.10 and shown in (A) are detailed in Table 2.
cognition and emergent literacy skills36–38,64,65. Thus, akin to findings involving the lingual gyrus, it is less clear whether associations between higher ScreenQ scores and lower CT in the right inferior parietal lobe, which supports somatosensory processing, is more counter-intuitive. A reasonable potential mechanism involves the stimulation of mirror neurons during the processing of imagined sensations in video scenes60,61. Indeed, these clusters with lower sulcal depth (SD) correlated with higher ScreenQ scores controlling for child sex and age, shown in Fig. 1A (thresholds: two-sided p-FDR < 0.10 and p-FDR < 0.05). Montreal Neurological Institute (MNI) coordinates are left–right, posterior-anterior and inferior-superior relative to the anterior commissure. Regions indicates the percentage of each cluster residing in the respective Desikan-Killiany DK40 atlas-defined area.

### Table 2. Details of significant clusters from Fig. 1. Corrected p-value, location, atlas labels and major function of clusters with lower cortical thickness (CT) correlated with higher ScreenQ scores controlling for child sex and age, shown in Fig. 1A (thresholds: two-sided p-FDR < 0.10 and p-FDR < 0.05). Montreal Neurological Institute (MNI) coordinates are left–right, posterior-anterior and inferior-superior relative to the anterior commissure. Regions indicates the percentage of each cluster residing in the respective Desikan-Killiany DK40 atlas-defined area.

| Cluster # | p-FDR | MNI coordinates | Regions | Major function |
|-----------|-------|----------------|---------|----------------|
| 1         | 0.089 | 55 – 19 – 34    | 69% Postcentral 31% Supramarginal | Somatosensory; emotional processing Social cognition, proprioception |
| 2         | 0.081 | 29 – 51 – 43    | 77% Superior Parietal 23% Inferior Parietal | Focused attention Multisensory association, emotional processing, music, math operations |
| 3         | 0.076 | 29 – 85 – 4     | 98% Lateral Occipital 4% Inferior Parietal | Primary visual Multisensory association, emotional processing, music, math operations |
| 4         | 0.097 | 25 – 38 – 54    | 55% Postcentral 45% Superior Parietal | Somatosensory; emotional processing Focused attention |
| 5         | 0.099 | 45 – 37 – 42    | 100% Supramarginal | Social cognition, proprioception |

typically develops in the preschool-age range, with greater left-lateralization linked to higher skill18,59. As both social cognition and emergent literacy skills are typically in early stages of development in the formative preschool age range, lower CT found here may reflect under-development rather than efficiency, though this is speculative and in need of further study.

Association between higher ScreenQ scores and lower CT in the postcentral gyrus, whose major role is somatosensory processing, is more counter-intuitive. A reasonable potential mechanism involves the stimulation of mirror neurons during the processing of imagined sensations in video scenes60,61. Indeed, these clusters with lower CT were in the more posterior Brodmann Area 2, where mirror neurons are well-documented62 and which supports higher-order somatosensory processing and social cognition83. Thus, if this mechanism is accurate, a major question is whether somatosensory cortical remodeling via digitally presented scenes is of functional relevance compared to thinning that may manifest via real-world human-interactive situations.

In contrast to primary sensory areas where thinning is generally adaptive, CT in higher-order areas (e.g., executive, association) has been positively associated with cognitive performance, including IQ, language, social cognition and emergent literacy skills36–38,64,65, Thus, akin to findings involving the lingual gyrus, it is less clear whether associations between higher ScreenQ scores and lower CT in the right inferior parietal lobe, which supports multi-modal (e.g., visual, somatosensory, emotional) processing66 and also learned and creative skills such as music67 and math68, are benign or maladaptive in nature. Similarly, higher media use was associated with lower CT in the right supramarginal gyrus (SMG), a higher-order area not expected to have peaked at preschool age. The right SMG supports empathy (in children, overcoming egocentricity bias)69,70, and lower CT in this area has been linked to conduct disorder in adolescents71. While not assessed here, excessive and inappropriate digital media use has been linked to lower empathy72, and a “video-deficit” in social cognition described in preschool-age children3. Thus, while speculative, findings in the current study may reflect SMG under-development at this age, an additional potential early biomarker of impacts of higher media use on social cognition. Interestingly, the postcentral gyrus is also involved with emotional processing and empathy (largely via the mirror neuron system), with lower CT possibly suggesting maladaptive neurodevelopment in these domains63. Further studies involving measures of social cognition are needed to better characterize these potential impacts.

### Table 3. Details of significant clusters from Fig. 2 Corrected p-value, location, atlas labels and major function of clusters with lower sulcal depth (SD) correlated with higher ScreenQ scores controlling for child sex and age, shown in Fig. 2A and also controlling for maternal education shown in Fig. 2B (thresholds: two-sided p-FDR < 0.05 for 2A and p-FDR < 0.10 for 2B). Montreal Neurological Institute (MNI) coordinates are left–right, posterior-anterior and inferior-superior relative to the anterior commissure. Regions indicates the percentage of each cluster residing in the respective Desikan-Killiany DK40 atlas-defined area.

| Cluster # | p-FDR | MNI coordinates | Regions | Major function |
|-----------|-------|----------------|---------|----------------|
| 1 (2A)    | 0.046 | 42 – 19 – 23    | 66% Fusiform 34% Inferior Temporal | Visual processing (shapes, letter/word forms), imagery, semantic memory and retrieval Visual processing, emotional regulation |
| 2 (2A)    | 0.049 | 35 – 39 – 16    | 98% Fusiform 2% Parahippocampus | Visual processing (shapes, letter/word forms), imagery, semantic memory and retrieval Emotional learning, memory |
| 3 (2B)    | 0.071 | 42 – 19 – 23    | 74% Fusiform 21% Inferior Temporal 5% Parahippocampus | Visual processing (shapes, letter/word forms), imagery, semantic memory and retrieval Visual processing, emotional regulation Emotional learning, memory |
The current findings align with those from the large, ongoing "ABCD" study involving early-adolescent children, where higher media use was associated with lower CT in both sensory (e.g., primary visual, postcentral) and higher-order (e.g., fusiform, SMG) areas. The authors attributed these findings to accelerated maturation of the visual system, with impacts on other, non-functionally homologous areas less clear. At a minimum, findings in the current study involving visual areas are consistent with those in the ABCD study, suggesting that relationships between higher media use and brain structure begin to manifest in early childhood and may become more extensive over time. They are also consistent with recent functional MRI studies involving preschool-age children presented with stories in illustrated and animated formats, where functional connectivity involving

Figure 2. 3-D Maps Showing Correlation Between ScreenQ Scores and Sulcal Depth for the Whole Brain. Three-dimensional maps showing correlations between ScreenQ total scores and sulcal depth for the whole cerebrum, controlling for age and sex (A) and also for maternal education (B). These are displayed on an inflated brain for better visibility of clusters, with blue representing shallower depth. Upper views are lateral and superior, lower views are medial and inferior, with the frontal lobe facing upward. Numbered cortical regions surviving p-FDR < 0.05 and p-FDR < 0.10 and shown in (A) and (B) are detailed in Table 3.
primary visual networks was substantially higher during the animated story, a potential mechanism for accelerated thinning\textsuperscript{74,75}.

Sulcal depth (SD) is an established measure of cortical surface area, which exhibits more gradual maturational changes with age, reaching overall maxima in late childhood\textsuperscript{35,53,76}. The current study found significant association between higher ScreenQ scores and significantly greater SD in primary visual cortex (right cuneus), which may reflect accelerated maturation in concert with lower CT. By contrast, higher ScreenQ scores were associated with significantly lesser SD in the right fusiform gyrus, which supports higher-order processing of complex visual stimuli (e.g., faces, places, shapes)\textsuperscript{77,78}. The fusiform cortex also includes the putative Visual Word Form Area (VWFA), which gradually develops to rapidly process letters and words during reading\textsuperscript{79}. Greater SD (and also

Figure 3. 3-D Maps Showing Correlation Between ScreenQ Scores and Cortical Thickness for Defined Regions of Interest. Three-dimensional maps showing correlations between ScreenQ total scores and cortical thickness for defined regions of interest (ROIs), controlling for age and sex (A) and also for maternal education (B). These are displayed on an inflated brain for better visibility of clusters, with blue representing thinner cortex. Upper views are lateral and superior, lower views are medial and inferior, with the frontal lobe facing upward. Effect sizes and FDR-corrected p-values for these ROIs in (A) and (B) are detailed in Table 4.
CT) in the fusiform cortex has been associated with higher reading abilities41,80, including at young ages before formal reading instruction81 and with higher emergent literacy skills43. They also align with associations between higher media use (ScreenQ) and both lower emergent literacy skills and white matter microstructural integrity supporting these skills found in a related study involving preschool-age children76. Thus, while speculative, the current findings may be a biomarker of impacts of higher screen-based media use on cortical surface area (SD) supporting reading at this age, though further studies are needed.

This study has limitations that should be noted. While 17% of participants met poverty criteria, the sample was largely of higher income and maternal education, and results might be different with greater socioeconomic diversity. There were few significant findings applying maternal education level as a covariate alongside child age and sex, attributable to limited statistical power and moderate correlation between this covariate and ScreenQ scores, which is consistent with prior studies linking media use to numerous aspects of SES82. However, these analyses still generated significant and/or marginally significant results aligned with previous studies involving early adolescents7, to inform more expansive research. Analyses were limited to children completing MRI and meeting necessary motion criteria, which may bias results towards those with higher self-regulation and other behavioral characteristics. The cross-sectional nature prohibits comment on causality, which requires a longitudinal design. It is also impossible to discern whether associations between higher media use and differences in CT and SD stemmed from direct (e.g., visual stimulation) or indirect (e.g., displacement of reading) mechanisms. While differences in cortical morphology related to higher use were found at a single time point, rates of change may be more relevant to cognitive development83. Finally, while there were structural differences in areas known to support higher-order skills (e.g., social cognition, emergent literacy), only measures related to emergent literacy were administered (all negatively correlated, reported previously)76,44, rendering brain-behavior relationships speculative. Future studies incorporating a range of cognitive-behavioral measures at this formative age are needed.

This study also has important strengths. It involves a reasonably large sample of very young children, where there have been few MRI-based studies involving media use, and none to our knowledge involving cortical structure. Rather than a single aspect of use, it applies ScreenQ as its predictor variable, which is a validated, composite measure25,46 capturing evidence-based facets of use cited in AAP recommendations1. Analyses involved CT and SD, complimentary measures with non-uniform developmental trajectories, reflecting synapse-level changes and brain growth46. All controlled for age and sex, minimizing the influence of general maturation rather than environment46,64,65. While impacting statistical power, significant and/or marginally significant results were found controlling for maternal education, which has been cited as a major SES-related predictor of child cognitive and social-emotional development26. All analyses applied conservative false-discovery rate (FDR) correction, reducing the likelihood of false positive results. Perhaps most importantly, the current findings align with those involving CD and SD in the large ABCD study involving older children7, and complement previous studies at this age involving differences in cognitive skills, functional connectivity and white matter microstructure26,74,75.

Altogether, while several findings are unclear and/or speculative, attributable to the complex nature of cortical development, this study provides novel evidence that differences in brain structure related to screen-based media use are evident during early childhood. Longitudinal studies, ideally beginning in infancy given trends in digital media use and prevalence of portable devices46,87, are needed to characterize longer-term impacts on cognitive, social-emotional and overall health outcomes.

Table 4. Cohen’s d effect sizes and false-discovery rate (FDR) corrected p-values for associations between ScreenQ and cortical thickness for selected regions of interest (ROIs) defined by the Desikan-Killiany cortical atlas and shown in Fig. 3. Negative signs added to effect sizes indicate a negative association between ScreenQ score and cortical thickness, p-FDR false-discovery rate corrected p-value controlling for age and sex, p-FDRSES false-discovery rate corrected p-value controlling for age, sex and socioeconomic status (maternal education), C cortex, G gyrus. *Signifies that p-FDR is less than 0.05, defined as statistically significant (p-FDR < 0.10 is defined as marginally statistically significant).

| ROI               | Left hemisphere | Right hemisphere |
|-------------------|-----------------|------------------|
|                   | Effect size     | p-FDR            | p-FDRSES | Effect size | p-FDR | p-FDRSES |
| Cuneus C          | −0.65           | 0.042*            | 0.085    | −0.68       | 0.042* | 0.085    |
| Fusiform G        | −0.33           | 0.131             | 0.175    | −0.31       | 0.131  | 0.175    |
| Inferior Temporal G | 0.04      | 0.433             | 0.449    | −0.048      | 0.107  | 0.123    |
| Lateral Occipital C | −0.44         | 0.062             | 0.131    | −0.045      | 0.075  | 0.131    |
| Lingual G         | −0.72           | 0.040*            | 0.085    | −0.07       | 0.304  | 0.434    |
| Percalcarine C    | −0.32           | 0.122             | 0.175    | −0.19       | 0.220  | 0.288    |
| Postcentral G     | −0.31           | 0.131             | 0.175    | −0.32       | 0.122  | 0.175    |
| Precuneus C       | −0.36           | 0.122             | 0.175    | −0.58       | 0.042* | 0.085    |
| Superior Parietal C | −0.55         | 0.056             | 0.090    | −0.59       | 0.042* | 0.085    |
| Supramarginal G   | −0.01           | 0.374             | 0.483    | −0.58       | 0.042* | 0.085    |
Conclusions

This study found associations between higher digital media use and lower cortical thickness and sulcal depth in brain areas supporting primary visual processing and higher-order functions such as top-down attention, complex memory encoding, letter recognition and social cognition. These findings are consistent with those from a large study involving adolescents, suggesting that differences in cortical structure related to screen use may begin to manifest in early childhood. They also compliment associations between higher media use and lower cognitive skills and related white matter microstructure previously found at this age. Further studies are

Figure 4. 3-D Maps Showing Correlation Between ScreenQ Scores and Sulcal Depth for Defined Regions of Interest. Three-dimensional maps showing correlations between ScreenQ total scores and sulcal depth for defined regions of interest (ROIs), controlling for age and sex (A) and also for maternal education (B). These are displayed on an inflated brain for better visibility of clusters, with blue representing shallower and red representing deeper. Upper views are lateral and superior, lower views are medial and inferior, with the frontal lobe facing upward. Effect sizes and FDR-corrected p-values for these ROIs in (A) and (B) are detailed in Table 5.
Table 5. Cohen’s d effect sizes and false-discovery rate (FDR) corrected p-values for associations between ScreenQ and sulcal depth for selected regions of interest (ROIs) defined by the Desikan-Killiany cortical atlas and shown in Fig. 4. Negative signs added to effect sizes indicate a negative association between ScreenQ score and sulcal depth. p-FDR: false-discovery rate corrected p-value controlling for age and sex, p-FDRSES: false-discovery rate corrected p-value controlling for age, sex and socioeconomic status, C cortex, G gyrus.

*Signifies that p-FDR is less than 0.05, defined as statistically significant (p-FDR < 0.10 is defined as marginally statistically significant).

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necessary to determine the longer-term evolution and relevance of these structural differences in terms of cognitive, social-emotional and overall development.

**Data and code availability**

All survey and MRI data for this study were newly acquired via methods described. These data will be made available to the scientific community in a deidentified manner upon notice of publication via written request to the corresponding author (JH). Requests must include description of the project (e.g., project outline) and also acknowledgment of the data source in any grant submissions, presentations or publications. The rationale for written request is that no repository currently exists and creation would exceed the scope and current funding resources of the study team. Any costs associated with data transfer will be the responsibility of the requesting parties. Software utilized in the current analyses is freely available and described in the methods section.

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**References**

1. AAP Council on Communications and Media. *Media and Young Minds* (American Academy of Pediatrics, 2016).
2. Robinson, T. N. *et al.* Screen media exposure and obesity in children and adolescents. *Pediatrics* **140**(Suppl 2), S97–S101 (2017).
3. McDaniel, B. T. & Radesky, J. S. Technoference: Parent distraction with technology and associations with child behavior problems. *Child Dev.** **89**(1), 100–109 (2018).
4. Anderson, D. R. & Subrahmanyam, K. Digital screen media and cognitive development. *Pediatrics* **140**(Suppl 2), S57–S61 (2017).
5. Lillard, A. S., Li, H. & Boguszewski, K. Television and children’s executive function. *Adv. Child Dev. Behav.** **48**, 219–248 (2015).
6. Walsh, J. J. *et al.* Associations between 24 hour movement behaviours and global cognition in US children: A cross-sectional observational study. *Lancet Child Adolesc. Health** **2**(11), 783–791 (2018).
7. Paulus, M. P. *et al.* Screen media activity and brain structure in youth: Evidence for diverse structural correlation networks from the ABCD study. *Neuroimage** **185**, 140–153 (2019).
8. Hutton, J. S., Dudley, J., Horowitz-Kraus, T., DeWitt, T. & Holland, S. K. Differences in functional brain network connectivity during stories presented in audio, illustrated, and animated format in preschool-age children. *Brain Imaging Behav.* https://doi.org/10.1007/s11868-018-9985-y (2018).
9. Horowitz-Kraus, T. & Hutton, J. S. Brain connectivity in children is increased by the time they spend reading books and decreased by the length of exposure to screen-based media. *Acta Paediatr.* (Oslo, Norway: 1992)** 107**(4), 685–693 (2018).
10. Horowitz-Kraus, T. *et al.* Longer screen vs. reading time is related to greater functional connections between the salience network and executive functions regions in children with reading difficulties vs. typical readers. *Child Psychiatry Hum. Dev.* **52**(4), 681–692 (2021).
11. Zivian, M. *et al.* Screen-exposure and altered brain activation related to attention in preschool children: An EEG study. *Trends Neurosci. Educ.* **17**, 100117 (2019).
12. Lillard, A. S. & Peterson, J. The immediate impact of different types of television on young children’s executive function. *Pediatrics** **128**(4), 644–649 (2011).
13. Zimmerman, F. J. & Christakis, D. A. Associations between content types of early media exposure and subsequent attentional problems. *Pediatrics** **120**(5), 896–922 (2007).
14. Christakis, D. A. & Zimmerman, F. J. Violent television viewing during preschool is associated with antisocial behavior during school age. *Pediatrics** **120**(5), 993–999 (2007).
15. Carter, B., Rees, P., Hale, L., Bhattacharjee, D. & Paradkar, M. S. Association between portable screen-based media device access or use and sleep outcomes: A systematic review and meta-analysis. *JAMA Pediatr.* https://doi.org/10.1001/jamapediatrics.2016.2341 (2016).
16. Garrison, M. M., Liekgew, K. & Christakis, D. A. Media use and child sleep: The impact of content, timing, and environment. *Pediatrics** **128**(1), 29–35 (2011).
17. Choi, J. H. *et al.* Real-world usage of educational media does not promote parent-child cognitive stimulation activities. *Acad. Pediatr.** **18**(2), 172–178 (2018).
18. Tomopoulos, S. *et al.* Is exposure to media intended for preschool children associated with less parent-child shared reading aloud and teaching activities? *Ambul. Pediatr.* **7**(1), 18–24 (2007).
19. Mendelsohn, A. L. et al. Infant television and video exposure associated with limited parent-child verbal interactions in low socioeconomic status households. *Arch. Pediatr. Adolesc. Med.* **162**(5), 411–417 (2008).
20. Horowitz-Kraus, T. & Hutton, J. S. From emergent literacy to reading: How learning to read changes a child’s brain. *Acta Paediatr.* **104**(7), 648–656 (2015).
21. Rideout, V. *The Common Sense Census: Media Use by Kids Age Zero to Eight* (Common Sense Media, 2020).
22. Chad-Friedman, E., Botdorf, M., Riggins, T. & Dougherty, L. R. Early childhood cumulative risk is associated with decreased global brain measures, cortical thickness, and cognitive functioning in school-age children. *Dev. Psychobiol.* **63**(2), 192–205 (2021).
23. Turesky, T. K. et al. Brain morphometry and diminished physical growth in Bangladeshi children growing up in extreme poverty: A longitudinal study. *Dev. Cogn. Neurosci.* **52**, 101029 (2021).
24. Piccolo, L. R., Mez, E. C., He, X., Sowell, E. R. & Noble, K. G. Age-related differences in cortical thickness vary by socioeconomic status. *PLoS ONE* **11**(9), e0162511 (2016).
25. Hutton, J. S., Huang, G., Sahay, R. D., DeWitt, T. & Ittenbach, R. F. A novel, composite measure of screen-based media use in young children (ScreenQ) and associations with parenting practices and cognitive abilities. *Pediatr. Res.* https://doi.org/10.1038/s41390-020-0765-1 (2020).
26. Hutton, J. S., Dudley, J., Horowitz-Kraus, T., DeWitt, T. & Holland, S. K. Associations between screen-based media use and brain white matter integrity in preschool-aged children. *JAMA Pediatr.* **174**(1), e193869 (2020).
27. Hutton, J. S., Dudley, J., Horowitz-Kraus, T., DeWitt, T. & Holland, S. K. Associations between home literacy environment, brain white matter integrity and cognitive abilities in preschool-age children. *Acta Paediatr.* (Oslo, Norway: 1992) https://doi.org/10.1111/apa.15124 (2019).
28. Hutton, J. S., Horowitz-Kraus, T., Mendelsohn, A. L., DeWitt, T. & Holland, S. K. Home reading environment and brain activation in preschool children listening to stories. *Pediatrics* **136**(3), 466–478 (2015).
29. Hutton, J. S. et al. Story time turbocharger? Child engagement during shared reading and cerebellar activation and connectivity in preschool-age children listening to stories. *PLoS ONE* **12**(5), e0177398 (2017).
30. Gilmore, J. H., Knickmeyer, R. C. & Gao, W. Imaging structural and functional brain development in early childhood. *Nat. Rev. Neurosci.* **19**(3), 123–137 (2018).
31. Knudsen, E. I. Sensitive periods in the development of the brain and behavior. *J. Cogn. Neurosci.* **16**(8), 1412–1425 (2004).
32. Knickmeyer, R. C. et al. A structural MRI study of human brain development from birth to 2 years. *J. Neurosci.* **28**(47), 12176–12182 (2008).
33. Matsuzawa, J. et al. Age-related volumetric changes of brain gray and white matter in healthy infants and children. *Cereb. Cortex* **11**(4), 335–342 (2001).
34. Frangou, S. et al. Cortical thickness across the lifespan: Data from 17,075 healthy individuals aged 3–90 years. *Hum. Brain Mapp.* **43**(1), 431–451 (2021).
35. Shaw, P. et al. Neurodevelopmental trajectories of the human cerebral cortex. *J. Neurosci.* **28**(14), 3586–3594 (2008).
36. Burgaleta, M., Johnson, W., Weber, D. P., Colom, R. & Karama, S. Cognitive ability changes and dynamics of cortical thickness development in healthy children and adolescents. *Neuroimage* **84**, 810–819 (2014).
37. Williams, V. J., Juranek, J., Cirino, P. & Fletcher, J. M. Cortical thickness and local gyriﬁcation in children with developmental dyslexia. *Cereb. Cortex* **28**(3), 963–973 (2018).
38. Qi, T., Schaadt, G. & Friederici, A. D. Cortical thickness lateralization and its relation to language abilities in children. *Dev. Cogn. Neurosci.* **39**, 100704 (2019).
39. Karma, S. et al. Positive association between cognitive ability and cortical thickness in a representative US sample of healthy 6 to 18 year-olds. *Intelligence* **37**(2), 145–155 (2009).
40. Schnack, H. G. et al. Changes in thickness and surface area of the human cortex and their relationship with intelligence. *Cereb. Cortex* **25**(6), 1608–1617 (2015).
41. Torre, G. A., Matejko, A. A. & Eden, G. F. The relationship between brain structure and proficiency in reading and mathematics in children, adolescents, and emerging adults. *Dev. Cogn. Neurosci.* **45**, 100856 (2020).
42. Sotiras, A. et al. Patterns of coordinated cortical remodeling during adolescence and their associations with functional specialization and evolutionary expansion. *Proc. Natl. Acad. Sci. U. S. A.* **114**(3), 3527–3532 (2017).
43. Hutton, J. S. et al. Validation of the reading house and association with cortical thickness. *Pediatrics* https://doi.org/10.1542/peds. 2020-1641 (2021).
44. Hutton, J. S., Dudley, J., Horowitz-Kraus, T., DeWitt, T. & Holland, S. K. Associations between home literacy environment, brain white matter integrity and cognitive abilities in preschool-age children. *Acta Paediatr.* (Oslo, Norway: 1992) **1992**(7), 1376–1386 (2020).
45. Hutton, J. S., Huang, G., Sahay, R. D., DeWitt, T. & Ittenbach, R. F. A novel, composite measure of screen-based media use in young children (ScreenQ) and associations with parenting practices and cognitive abilities. *Pediatr. Res.* **87**(7), 1211–1218 (2020).
46. Monteiro, R. et al. Psychometric properties of the ScreenQ for measuring digital media use in Portuguese young children. *Acta Paediatr.* (Oslo, Norway: 1992) https://doi.org/10.1111/apai.16439 (2022).
47. Phillips, B. M., Lonigan, C. J. & Wyatt, M. A. Predictive validity of the get ready to read! Screener: Concurrent and long-term relations with reading-related skills. *J. Learn. Disabil.* **42**(2), 133–147 (2009).
48. US Department of Health and Human Services. 2020 Poverty Guidelines for the 48 Contiguous States and the District of Columbia. 2020; https://aspe.hhs.gov/2020-poverty-guidelines. Accessed July, 2020 (2020).
49. Hutton, J., Horowitz-Kraus, T., Mendelsohn, A., DeWitt, T. & Holland, S. Home reading environment and brain activation in preschool children listening to stories. *Pediatrics* **136**(3), 466–478 (2015).
50. Wilke, M., Holland, S. K., Altay, M. & Gaser, C. Template-O-Matic: A toolbox for creating customized pediatric templates. *Neuroimage* **41**(3), 903–913 (2008).
51. Desikan, R. S. et al. An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *Neuroimage* **31**(1), 968–980 (2006).
52. Jackson, M., Kierman, K. & McLanahan, S. Maternal education, changing family circumstances, and children’s skill development in the United States and UK. *Am. Acad. Polit. Soc. Sci.* **67**(11), 84–87 (2014).
53. Lyall, A. E. et al. Dynamic development of regional cortical thickness and surface area in early childhood. *Cereb. Cortex* **25**(8), 2204–2212 (2015).
54. Alvarez, I., Parker, A. J. & Bridge, H. Normative cerebral cortical thickness for human visual areas. *Neuroimage* **201**, 116057 (2019).
55. Bertucci, G. & Vallar, G. The history of the neurophysiology and neurology of the parietal lobe. *Handb. Clin. Neurol.* **151**, 1–30 (2018).
56. Loh, D. & Murphy, A. Radiopaedia.org: Lingual Gyrus (Reference Article). 2022; https://radiopaedia.org/articles/lingual-gyrus-lang=us. Accessed August, (2022).
57. Swierkot, A. & Rajah, M. N. Cortical thickness in right frontal and left lingual gyrri differentially mediate episodic memory for spatial contextual details across the adult lifespan. *bioRxiv* https://doi.org/10.1101/289447 (2018).
58. Polk, T. A. et al. Neural specialization for letter recognition. *J. Cogn. Neurosci.* **14**(2), 145–159 (2002).
59. Centanni, T. M. et al. Early development of letter specialization in left fusiform is associated with better word reading and smaller fusiform face area. *Dev. Sci.* **21**(5), e12658 (2018).
60. Keysers, C., Kaas, J. H. & Gazzola, V. Somatosensation in social perception. *Nat. Rev. Neurosci.* **11**(6), 417–428 (2010).
61. Bolognini, N., Rossetti, A., Maravita, A. & Minnissi, C. Seeing touch in the somatosensory cortex: A TMS study of the visual perception of touch. Hum. Brain Mapp. 32(12), 2104–2114 (2011).
62. Molenberghs, P., Cunnington, R. & Mattingley, J. B. Brain regions with mirror properties: A meta-analysis of 125 human fMRI studies. Neurosci. Biobehav. Rev. 36(1), 341–349 (2012).
63. Kroef, E., Syan, S. K., Minuzzi, L. & Frey, B. N. From anatomy to function: The role of the somatosensory cortex in emotional regulation. Braz. J. Psychiatry 41(3), 261–269 (2019).
64. Serra, L. et al. Abnormal cortical thickness is associated with deficits in social cognition in patients with myotonic dystrophy type 1. Front. Neurol. 11, 113 (2020).
65. Brito, N. H., Piccolo, L. R. & Noble, K. G. Associations between cortical thickness and neurocognitive skills during childhood vary by family socioeconomic factors. Brain Cogn. 116, 54–62 (2017).
66. Iglesiström, K. M. & Graziano, M. S. A. The inferior parietal lobule and temporoparietal junction: A network perspective. Neropsychologia 105, 70–83 (2017).
67. Royal, I. et al. Activation in the right inferior parietal lobule reflects the representation of musical structure beyond simple pitch discrimination. PLoS ONE 11(5), e0155291 (2016).
68. Wang, L., Li, M., Yang, T., Wang, L. & Zhou, X. Mathematics meets science in the brain. Cereb. Cortex 32(1), 123–136 (2021).
69. Silani, G., Lamm, C., Ruff, C. C. & Singer, T. Right supramarginal gyrus is crucial to overcome emotional egocentricity bias in social judgments. J. Neurosci. 33(39), 15466–15476 (2013).
70. Steinbeis, N., Bernhardt, B. C. & Singer, T. Age-related differences in function and structure of rSMG and reduced functional connectivity with DLPFC explains heightened emotional egocentricity bias in childhood. Soc. Cognit. Affect. Neurosci. 10(2), 302–310 (2015).
71. Hyatt, C. J., Haney-Caron, E. & Stevens, M. C. Cortical thickness and folding deficits in conduct-disordered adolescents. Biol. Psychiatry 72(3), 207–214 (2012).
72. James, C. et al. Digital life and youth well-being, social connectedness, empathy, and narcissism. Pediatrics 140(Suppl 2), S71–S75 (2017).
73. Reis, M., Kruger, M. & Krist, H. Theory of mind and the video deficit effect: Video presentation impairs children's encoding and understanding of false belief. Media Psychol. 22(1), 23–38 (2017).
74. Hutton, J. S., Dudley, J., Horowitz-Kraus, T., DeWitt, T. & Holland, S. K. Functional connectivity of attention, visual, and language networks during audio, illustrated, and animated stories in preschool-age children. Brain Connect. https://doi.org/10.1089/brain.2019.0679 (2019).
75. Hutton, J. S., Dudley, J., Horowitz-Kraus, T., DeWitt, T. & Holland, S. K. Differences in functional brain network connectivity during stories presented in audio, illustrated, and animated format in preschool-age children. Brain Imaging Behav. 14(1), 130–141 (2020).
76. Raznahan, A. et al. How does your cortex grow? J. Neurosci. 31(19), 7174–7177 (2011).
77. Jackson, R. L., Bajada, C. J., Rice, G. E., Cloutman, L. L. & Lambon Ralph, M. A. An emergent functional parcellation of the temporal cortex. Neuroimage 170, 385–399 (2018).
78. Lin, Y. H. et al. Anatomy and white matter connections of the inferior temporal gyrus. World Neurosurg. 143, e656–e666 (2020).
79. Saygin, Z. M. et al. Connectivity precedes function in the development of the visual word form area. Nat. Neurosci. 19(9), 1250–1255 (2016).
80. Kristanto, D., Liu, M., Liu, X., Sommer, W. & Zhou, C. Predicting reading ability from brain anatomy and function: From areas to connections. Neuroimage 218, 116966 (2020).
81. Beelen, C., Vanderauwera, J., Wouters, J., Vandermosten, M. & Ghesquière, P. Atypical gray matter in children with dyslexia before the onset of reading instruction. Cortex 121, 399–413 (2019).
82. Trinh, M. H. et al. Association of trajectory and covariates of children’s screen media time. JAMA Pediatr. 174(1), 71–78 (2020).
83. Shaw, P. et al. Intellectual ability and cortical development in children and adolescents. Nature 440(7084), 676–679 (2006).
84. Wu, K. et al. Topological organization of functional brain networks in healthy children: Differences in relation to age, sex, and intelligence. PLoS ONE 8(2), e55347 (2013).
85. Girault, J. B. et al. Cortical structure and cognition in infants and toddlers. Cereb. Cortex 30(2), 786–800 (2020).
86. Radesky, J. S. et al. Young children’s use of smartphones and tablets. Pediatrics https://doi.org/10.1542/peds.2019-3518 (2020).
87. Kılıç, A. O. et al. Exposure to and use of mobile devices in children aged 1–60 months. Eur. J. Pediatr. 178(2), 221–227 (2019).

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Author contributions
J.H. developed the ScreenQ measure used in this study, designed all aspects of the study including the MRI protocol, analysed in collaborations, drafted the initial manuscript and subsequent revisions, and approved the final manuscript as submitted. J.D. collaborated in and oversaw the MRI acquisition protocol, conducted all MRI data analyses and interpretations, created all derivative tables and figures, assisted with manuscript preparation and revisions, and approved the final manuscript as submitted. T.D. provided guidance on study design and analyses, reviewed and revised the manuscript, and approved the final manuscript as submitted. T.H. collaborated in study design, MRI protocol, analyses and interpretation, reviewed and revised the manuscript and subsequent revisions, and approved the final manuscript as submitted.

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Competing interests
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Additional information
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