Associations Between Digital Media Use and Brain Surface Structural Measures in Preschool-Aged Children

John S. Hutton (John1.Hutton@cchmc.org)
Cincinnati Children's Hospital Medical Center
Jonathan Dudley
Cincinnati Children's Hospital Medical Center
Thomas DeWitt
Cincinnati Children's Hospital Medical Center
Tzipi Horowitz-Kraus
Technion – Israel Institute of Technology

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Abstract

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 in regression analyses, controlling for sex and age. Higher ScreenQ scores were correlated with lower CT in right-sided occipital, parietal and supramarginal areas ($p<0.10$, family-wise error/FWE-corrected) and also lower SD in inferior temporal/fusiform areas ($p<0.05$, FWE-corrected). These areas support primary visual and higher-order processing, notably social cognition. Results align with those of lower CT with higher media use recently described in adolescents. While differences in visual areas likely reflect maturation, those in higher-order areas expected to be in an accretive stage at this age suggest under-development, though further studies are needed.

Introduction

The American Academy of Pediatrics (AAP) recommends limits on digital media use ("screen time") for children at all ages.[1] Domains include access to screens, frequency of use, content and grownup-child co-viewing.[1] Cited risks of excessive and/or inappropriate use span developmental domains, including physical (e.g., obesity[2]), social-emotional (parent-child engagement[3]) and cognitive (e.g., language,[4] executive function[5,6]). Recent evidence suggests potential impacts on brain structure and function underlying these abilities.[7–11] Proposed mechanisms are direct (e.g. age-inappropriate content,[12–14] impaired sleep[15,16]) and indirect (e.g. displacement of parent-child interaction[17–19, 10,20]) 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.[21]

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.[22–24] 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[1] (ScreenQ measure[25]) was recently associated with lower microstructural integrity of major white matter tracts, and also with lower emergent literacy skills.[26] 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,[27,28,29] suggesting a potential displacement effect of screen use.

Early childhood (newborn through age 5) is a formative span of brain development.[30,31] 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.[30] 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 by late childhood.[32–34] 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.[35] 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.[36–42] 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.[43]

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.[7] 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 less 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 bran development. 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.

Material And Methods

Screen Time Measure (ScreenQ)

The ScreenQ is a 15-item parent-report measure of digital media use developed by the study team.[44] 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.[1] Internal consistency (Cronbach $\alpha = .74$), reliability and concurrent validity have been established in young children and more recently via wider age range using a Portuguese translation.[44,45]

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 documented history of head trauma with loss of consciousness or neurodevelopmental condition likely to confer cognitive delay, 4) native English-speaking custodial parent, and 5) 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. Measures of language, processing speed, and emergent literacy skills were administered to the child prior to MRI, reported in separate analyses.[26,27]

Magnetic Resonance Imaging (MRI) and Analyses

Details of play-based acclimatization techniques prior to MRI are described previously.[46] 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 msec; duration 5.25 minutes; FOV = 256 x 256 mm; matrix = 256 x 256; in-plane resolution = 1 x 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 (~ 2mm spacing) using age-matched a prior tissue probability maps generated from the TOM8 toolbox[47] for tissue segmentation. After this voxel-based spatial registration, the central surface and morphometric measures (CT, SD) were determined using the projection-based thickness method. The central surface was then spatially registered to the Freesurfer "FsAverage" template. Finally, measures of CT and SD were projected onto the template space and then smoothed along the surface with a 10mm and 15mm full-width half-maximum Gaussian kernel, respectively. Subjects with weighted image quality (calculated based on resolution, signal-to-noise ratio, and bias field strength) of 2 or more standard deviations below the group mean and/or subjects with a mean correlation coefficient of CT 2 standard deviations or more below the group mean were excluded as outliers.

Analyses involved multiple regression modeling with CT and SD as the respective dependent variable, applying ScreenQ score (continuous) as the predictor and controlling for covariates sex (categorical) and age (continuous). Smoothed thickness maps were fit to these models to estimate the effect of ScreenQ total scores on CT and SD across the cerebrum. Threshold-free cluster enhancement was used to circumvent arbitrary threshold dependence of cluster identification and 5,000 random permutations of the design matrix were used to control family-wise error (FWE) rate at $\alpha = 0.05$ or 0.10, with a two-sided test.

Statistical Analyses

Descriptive statistics were computed for demographic and other variables featured here, specified in a statistical analysis plan. SES was defined as a binary variable using 2020 US poverty criteria, using the midpoint of income category relative to household size.[48] The criterion for statistical significance was $\alpha = 0.05$, unadjusted. Analyses were conducted using SAS v9.4 software.

Results

Sample Characteristics and ScreenQ Scores

A total of 58 children completed MRI, 52 of them with acceptable image quality for analyses, applying criteria described above (age 52.7 ± 7.7 months-old, range 37–63; 29 girls, 23 boys). The mean ScreenQ score for those included was 10.1 ± 4.5 (range 3–21). These data are summarized in Table 1.

Table 1

Demographics and ScreenQ Scores

	N (%)	Mean ±SD (Min, Max)
Total	52 (100)	
Child Age (months)		52.7 ± 7.7 (37, 63)
36+	15 (29)	
48+	23 (44)	
60+	14 (27)	
Child Gender		
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)

*2020 US Department of Health and Human Services Poverty Table (income to household size).

MRI Analyses

Higher ScreenQ scores were correlated with lower CT in five clusters located in right parietal and occipital regions, controlling for sex and age (two-tailed p-FWE < 0.10), shown in Fig. 1 and described in Table 2. Higher ScreenQ scores were also correlated with lower SD in two clusters located in the right inferior temporal/fusiform cortex, controlling for sex and age (two-tailed p-FWE < 0.05), shown in Fig. 2 and described in Table 3. Threshold-free maps showing more extensive associations are provided in Fig. 1s and Fig. 2s (online, supplemental).

Table 2
Details of significant clusters from Fig. 1.

Cluster #	Extent	p-FWE	MNI Coordinates	Regions	Major Function
1	305	0.089	55 -19 34	69% Postcentral 31% Supramarginal	Somatosensory, emotional processing Social cognition, proprioception
2	215	0.081	29 -51 43	77% Superior Parietal 23% Inferior Parietal	Focused attention Multisensory association, emotional processing, music, math operations
3	161	0.076	29 -85 4	98% Lateral Occipital 2% Inferior Parietal	Primary visual Multisensory association, emotional processing, music, math operations
4	86	0.097	25 -38 54	55% Postcentral 45% Superior Parietal	Somatosensory, emotional processing Focused attention
5	35	0.099	45 -37 42	100% Supramarginal	Social cognition, proprioception

Table 2: Extent, atlas labels and major function of clusters with lower thickness correlated with higher ScreenQ scores controlling for child sex and age, shown in Figure 2 (FWE-corrected two-sided p<0.10). Extent represents points on the cortical surface comprising each numbered cluster, all in the right hemisphere. 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 3
Details of significant clusters from Fig. 2

Cluster #	Extent	p-FWE	MNI Coordinates	Regions	Major Function
1	117	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	50	0.049	35 -39 -16	98% Fusiform 2% Parahippocampus	Visual processing (shapes, letter/word forms), imagery, semantic memory and retrieval Emotional learning, memory

Table 3: Extent, 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 Figure 2 (two-sided p-FWE<0.05). Extent represents points on the cortical surface comprising each numbered cluster, all in the right hemisphere. 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.

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 structure.[30] 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, higher use was related to decreased CT and SD in both primary visual and higher-order association areas.

Cortical thickness (CT) reflects synaptic density and supporting cellular architecture.[49] 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 adolescence.[35] Changes reflect cortical remodeling in response to environmental stimulation, which can be accretive (e.g., synaptogenesis) or reductive (e.g., pruning).[49] The current study involved 3-5-year old children, whose overall CT is expected to have largely peaked, though not in higher-order areas. While threshold-free maps suggest lower CT related to higher ScreenQ scores in diffuse, bilateral brain regions (Fig. 1s), these were lateralized to the right hemisphere, including all clusters reaching statistical significance. Significant clusters were in occipital and parietal areas (Fig. 1) that support both sensory (e.g., primary visual) and higher-order associative (e.g., supramarginal gyrus) processes, suggesting impacts on areas expected to be mature at this age and others that are still developing.

Synchronous thinning in functionally related areas has been linked to environmental factors (e.g., visual network, visual stimuli).[42] Thinning in visual cortices has also been attributed to higher maturation and efficiency.[7] Association between higher ScreenQ scores and lower CT in occipital areas in the current study is consistent with these models, likely 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 stimuli.[50]

Association between higher ScreenQ scores and lower CT in the postcentral gyrus, whose major role is somatosensory processing, is more counter-intuitive. A reasonable mechanism involves the stimulation of mirror neurons during the processing of imagined sensations in video scenes.[51,52] Indeed, these clusters with lower CT were in the more posterior Brodmann Area 2, where mirror neurons are well-documented[53] and which supports higher-order somatosensory processing.[54] 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 situations.

In contrast to 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 and emergent literacy skills.[36–38] Thus, 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) processing[55] and also learned and creative skills such as music[56] and math,[57] 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),[58,59] and lower CT in this area has been linked to conduct disorder in adolescents.[60] While not assessed here, excessive and inappropriate digital media use has been linked to lower empathy,[61] and a “video-deficit” in social cognition described in preschool-age children.[62] Thus, while speculative, findings in the current study may reflect SMG under-development at this age, a 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 linked to these domains.[54] Further studies involving measures of social cognition and other skills would be helpful to better characterize these potential impacts.

The current findings align with those from the large, ongoing ABCD study involving pre-adolescent children, where higher media use was associated with lower CT in both sensory (including primary visual, postcentral) and higher-order (including SMG) areas.[7] 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 highly consistent, suggesting that relationships between higher media use and brain structure begin to manifest in early childhood and become more extensive over time. They are also consistent with a recent functional MRI study involving preschool-age children, where functional connectivity involving primary visual networks was maximal during animated relative to traditional story formats, a potential mechanism for accelerated thinning.[63]

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.[35,49,64] The current study found significantly lower SD in two clusters in the right inferior temporal/fusiform gyrus, which supports processing specific categories of visual stimuli (e.g., places, shapes).[65,66] One interpretation of this finding, akin to that for lower CT in occipital areas, is accelerated maturation of visual areas via higher media use. However, the fusiform cortex includes the putative Visual Word Form Area (VWFA), which develops to rapidly process letters and words during reading.[67] Thicker fusiform cortex has been associated with higher reading abilities in children,[41] including at young ages before formal reading instruction.[68] The current findings complement those of thicker fusiform cortex in preschool-age children with higher emergent literacy skills.[43] They also align with associations between higher media use (ScreenQ) and both lower emergent literacy skills and measures of white matter microstructure supporting these skills found in a related study involving preschool-age children.[26] Thus, while speculative, the current findings may be a biomarker of impacts of higher digital 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. 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. Findings of lower CT did not survive at FWE-$p < 0.05$ yet did for FWE-$p < 0.10$, yet stringent correction greatly reduces the likelihood of false positives and findings for SD survived both cutoffs. The cross-sectional nature prohibits comment on causality, which requires a longitudinal design. It is also impossible to discern whether associations between higher use and lower 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 development.[69] Finally, while there were structural differences in areas known to support higher-order skills (notably social cognition), measures of these were not administered, rendering brain-behavior relationships speculative.

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 of these to our knowledge involving cortical structure. Analyses controlled for age and sex, which may reflect general maturation rather than environment.[34,70,71] Findings align with the ABCD study involving adolescents,[7] and complement previous studies at this age involving differences in cognitive skills, functional connectivity and white matter microstructure.[26,43,63] Findings involved both CT and SD, complimentary measures with non-uniform developmental trajectories, reflecting synapse-level changes and brain growth.[35] Altogether, while several findings are unclear, attributable to the complex nature of cortical development, this study provides novel evidence that changes related to digital media use are evident in early childhood. Longitudinal studies, ideally beginning in infancy given trends in digital media use, are needed to characterize longer-term impacts on cognitive, social-emotional and overall health outcomes.

Conclusions

This study found associations between higher digital media use and lower cortical thickness and sulcal depth in right-sided areas supporting visual processing, attention and higher-order functions such as social cognition. These findings are consistent with a large ongoing study involving adolescents, suggesting that differences in cortical structure related to screen use begin to manifest in early childhood. They also compliment associations between higher media use and lower skills and white matter structure documented at this age. Further studies are needed to determine the longer-term evolution and relevance of these structural differences in terms of cognitive, social-emotional and overall development.

Abbreviations

AAP: American Academy of Pediatrics; FWE: Family-Wise Error; MNI: Montreal Neurological Institute; MRI: Magnetic Resonance Imaging; SES: socioeconomic status

Declarations

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For more information about the ScreenQ measure, contact John1.Hutton@cchmc.org.

Author Contributions

JH developed the ScreenQ measure used in this study, designed all aspects of the study including the MRI protocol, collaborated in analyses, drafted the initial manuscript and subsequent revisions, and approved the final manuscript as submitted.

JD collaborated in and oversaw the MRI acquisition protocol, conducted all MRI data analyses and interpretation, created all derivative tables and figures, assisted with manuscript preparation and revisions, and approved the final manuscript as submitted.

TD provided guidance on study design and analyses, reviewed and revised the manuscript, and approved the final manuscript as submitted.

THK collaborated in study design, MRI protocol, analyses and interpretation, reviewed and revised the manuscript and subsequent revisions, and approved the final manuscript as submitted.

Data and Code Availability Statement

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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The authors have no financial relationships relevant to this article to disclose.

Potential Conflicts of Interest

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Figures

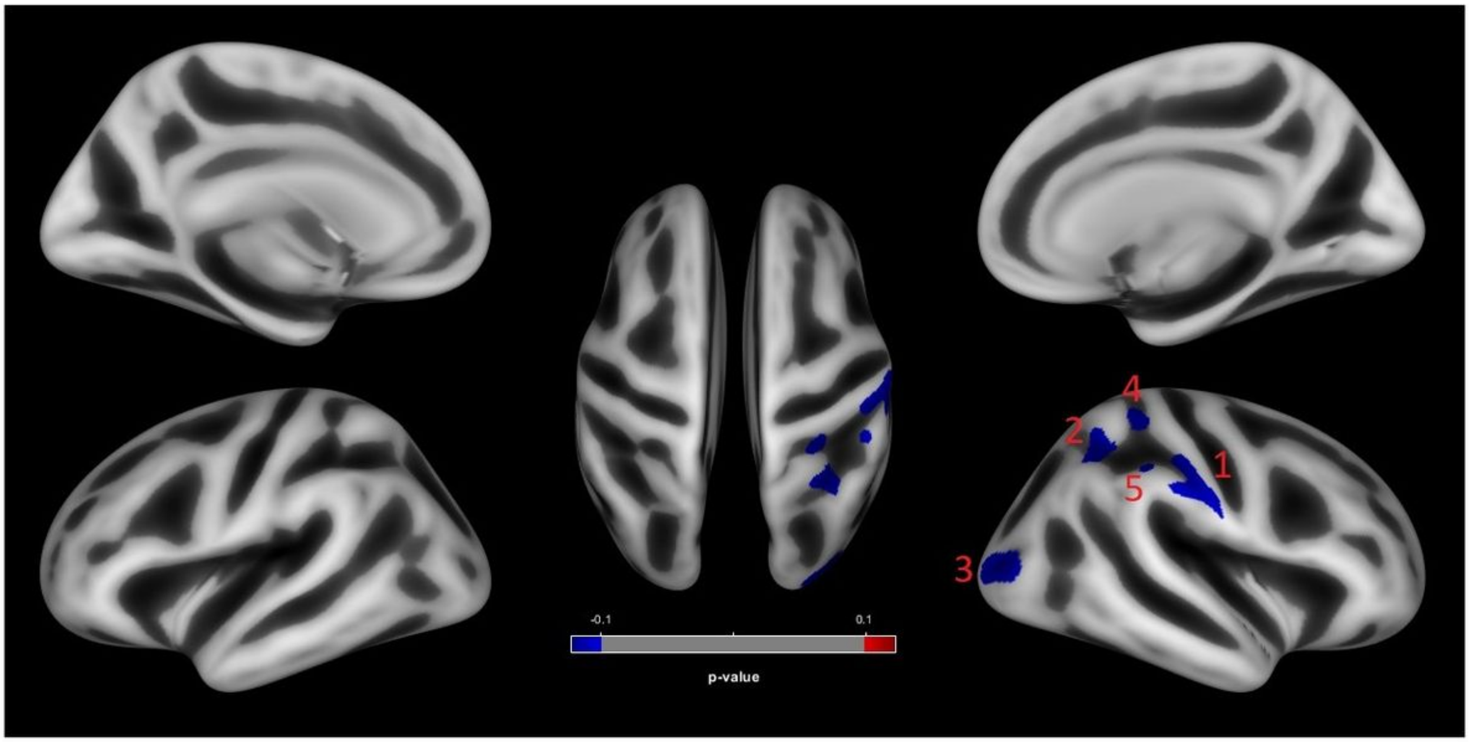

Figure 1

3-D Maps Showing Correlation Between *ScreenQ* Scores and Cortical Thickness

Three-dimensional maps showing correlations between *ScreenQ* total scores and cortical thickness (*p*-FWE<0.10). These are displayed on an inflated brain for better visibility of clusters in sulcal regions, with blue representing thinner cortex. Upper views are medial, lower views are lateral and central view is superior with frontal lobe facing upward. Numbered cortical regions are detailed in Table 2.

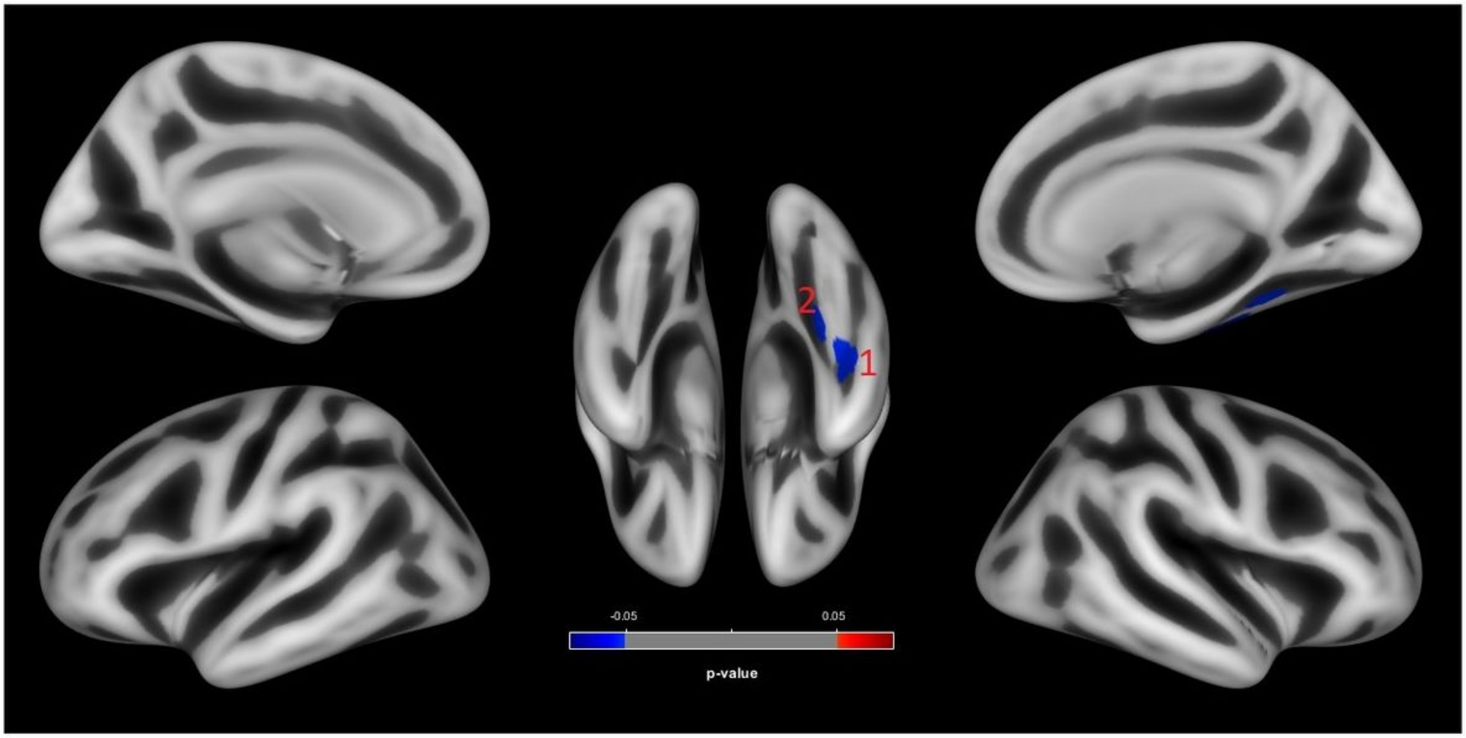

Figure 2

3-D Maps Showing Correlation Between *ScreenQ* Scores and Sulcal Depth

Clusters with p-FWE<0.05 displayed on an inflated brain for better visibility of clusters in sulcal regions, with blue representing shallower sulcal depth (SD). Upper views are medial, lower views are lateral and central view is inferior with occipital lobe facing upward.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ScreenQMorphSupplementalFigs1and2.docx