

The Impact of Television Viewing on Brain Structures: Cross-Sectional and Longitudinal Analyses

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Television (TV) viewing is known to affect children's verbal abilities and other physical, cognitive, and emotional development in psychological studies. However, the brain structural development associated with TV viewing has never been investigated. Here we examined cross-sectional correlations between the duration of TV viewing and regional gray/white matter volume (rGMV/rWMV) among 133 boys and 143 girls as well as correlations between the duration of TV viewing and longitudinal changes that occurred a few years later among 111 boys and 105 girls. After correcting for confounding factors, we found positive effects of TV viewing on rGMV of the frontopolar and medial prefrontal areas in cross-sectional and longitudinal analyses, positive effects of TV viewing on rGMV/rWMV of areas of the visual cortex in cross-sectional analyses, and positive effects of TV viewing on rGMV of the hypothalamus/septum and sensorimotor areas in longitudinal analyses. We also confirmed negative effects of TV viewing on verbal intelligence quotient (IQ) in cross-sectional and longitudinal analyses. These anatomical correlates may be linked to previously known effects of TV viewing on verbal competence, aggression, and physical activity. In particular, the present results showed effects of TV viewing on the frontopolar area of the brain, which has been associated with intellectual abilities.

Keywords: children, gray matter volume, television, verbal, white matter volume

Introduction

Many cross-sectional and longitudinal studies have reported deleterious effects of television (TV) viewing on the cognitive abilities, attention, behaviors, and academic performance of children (Johnson et al. 2002, 2007; Christakis et al. 2004). Longer TV viewing was associated with lower intelligence quotient (IQ) and reading grades in a cross-sectional study (Ridley-Johnson et al. 1983). However, the longitudinal effects of TV viewing on Full Scale IQ (FSIQ) are less clear (Gortmaker et al. 1990). In an intervention study, restricting children's TV viewing for a short period improved their cognitive abilities (Gadberry 1981) and another longitudinal study showed that TV viewing affected attention (Landhuis et al. 2007), which in turn is correlated with a wide range of cognitive performances (Sergeant et al. 2002). Finally, longitudinal studies have shown that TV viewing has detrimental effects on verbal abilities including verbal working memory (Zimmerman and Christakis 2005).

As described above, TV viewing during infancy and childhood is considered to be detrimental to the development of intellectual abilities, particularly verbal ones. Thus, revealing the effects of TV viewing on neural systems and revealing the mechanisms by which TV viewing affects children's intellectual abilities is socially and scientifically important. However, despite numerous related psychological and functional magnetic resonance imaging (fMRI) studies of brain activities in children watching certain content, the effects of TV viewing on brain structures in children are unknown.

The medial prefrontal cortex (mPFC), frontopolar areas, posterior parietal areas, and the left inferior frontal gyrus (IFG) are considered to be important for the development of intelligence and verbal intelligence in children. The frontopolar area, which is the most anterior part of the brain, is considered to be involved in the evaluation of internally generated information as well as with higher functioning associated with hierarchical organization of the prefrontal functions (for review, see Christoff and Gabrieli 2000). Regional gray matter structures in medial and lateral areas around the frontal pole have also been rather consistently correlated with intelligence in adults (Haier et al. 2004; Gong et al. 2005; Colom et al. 2006; Narr et al. 2007) and children (Wilke et al. 2003; Frangou et al. 2004; Karama et al. 2011; Menary et al. 2013). These areas show developmental cortical thinning during development, and children with superior IQs show the most vigorous cortical thinning in this area (Shaw et al. 2006). In addition, the posterior parietal areas have rather consistently been shown to be correlated with intelligence together with other less consistent findings across the brain (Jung and Haier 2007), which may suggest the importance of the fronto-parietal areas and the associated functional network in intelligence (Jung and Haier 2007). On the other hand, the left IFG has been shown to be critical in a wide range of verbal cognitions (phonological, semantic, and syntax-related) (Vigneau et al. 2006). Regional gray matter structures have also been correlated with the verbal intelligence quotient (VIQ) (Konrad et al. 2012). Furthermore, children whose verbal IQ improved in a longitudinal developmental study showed a greater increase in regional gray matter volume (rGMV) in the left IFG (Ramsden et al. 2011). Considering the association between the duration of TV viewing and IQ/VIQ that TV viewing is less associated with cognitions such as monitoring and the evaluation of internally generated information, which is covered by the frontopolar

area, we hypothesized that the duration of TV viewing would be apparent in the mPFC, posterior parietal areas, and left IFG areas.

The purpose of this study was to test these hypotheses and reveal the effects of TV viewing using cross-sectional and longitudinal analyses of brain structures in children. For this purpose, we employed cross-sectional analyses to identify associations between the duration of TV viewing and rGMV/regional white matter volume (rWMV) and then analyzed associations between the duration of TV viewing and rGMV/rWMV changes a few years later using a longitudinal design. We also investigated associations between the duration of TV viewing and VIQ/IQ using similar analyses to determine the nature of the associations between the duration of TV viewing and brain structural changes. We used voxel-based morphometry (VBM) to evaluate rGMV/rWMV (Good et al. 2001).

Methods

Subjects

All subjects were healthy Japanese children and the details related to their initial recruitment (preexperiment) were described elsewhere (Taki et al. 2010). In brief, we collected brain magnetic resonance (MR) images from 290 subjects (145 boys and 145 girls; age range, 5.6–18.4 years) who did not have any history of malignant tumors or head traumas involving loss of consciousness. We stipulated that only right-handed children could participate in the study in an advertisement used for subject recruitment and also confirmed that all subjects were right-handed using the self-report questionnaire, the “Edinburgh Handedness Inventory” (Oldfield 1971). As per the Declaration of Helsinki (1991), written informed consent was obtained from each subject and his/her parent prior to MR scanning after a full explanation of the purpose and procedures of the study was provided. Approval for these experiments was obtained from the Institutional Review Board of Tohoku University. A few years after the preexperiment, the postexperiment was conducted and 235 subjects participated.

Due to issues with the quality of the imaging data or lack of effective data of psychological variables, the cross-sectional imaging analyses were performed with 276 subjects (133 boys and 143 girls) and the longitudinal imaging analyses were performed with 216 subjects (111 boys and 105 girls). Ten of the cases of missing data were due to a lack of effective psychological data in the preexperiment and the remaining was due to the poor quality of imaging data.

Assessments of Psychological Variables

In both the pre- and postexperiments, we measured the Full Scale intelligence quotient (IQ) using the Japanese version of the Wechsler Adult Intelligence Scale-Third Edition (WAIS-III) for subjects aged 16 years or older or the Wechsler Intelligence Scale for Children-Third Edition (WISC-III) for subjects younger than 16 years (Azuma et al. 1998). The tests were administered by trained examiners (Fujita et al. 2006). We calculated the Full Scale IQ, verbal IQ, and performance IQ (PIQ) for each subject from their WAIS/WISC scores. In the preexperiment, the duration of TV or video viewing during weekdays was collected using a self-report questionnaire with multiple choice questions. There were the following 8 options: 1, none; 2, a little; 3, ~30 min; 4, ~1 h; 5, ~2 h; 6, ~3 h; 7, ≥4 h; and 8, have no way of telling. These choices were transformed into hours of TV viewing (choice 1 = 0, choice 2 = 0.25, choice 3 = 0.5, choice 4 = 1, choice 5 = 2, choice 6 = 3, and choice 7 = 4) and hours of TV viewing were used in the statistical analyses described below. Data from subjects who chose option 8 were removed from the analyses involving hours of TV viewing. In the preexperiment, the measure of socioeconomic status consisted of 3 questions. One was an enquiry relating to family annual income as reported in our previous study (Takeuchi et al. forthcoming; Taki et al. 2010). Annual income data were collected using discrete variables: 1, annual income <US\$ 20 000 (the currency exchange rate was set at US\$ 1 = 100 yen); 2,

annual income US\$ 20 000–40 000; 3, annual income US\$ 40 000–60 000; 4, annual income US\$ 60 000–80 000; 5, annual income US\$ 80 000–100 000; 6, annual income US\$ 100 000–120 000; 7, annual income ≥US\$ 120 000. The values 1–7 were used in subsequent regression analyses. The other 2 questions related to the highest educational qualification of both parents. There were 8 options (1, elementary school graduate or below; 2, junior high school graduate; 3, normal high school graduate; 4, graduate of a short term school completed after high school (such as a junior college); 5, university graduate; 6, Master's degree; and 7, Doctorate) and each choice was converted into the number of years taken to complete the qualification in the normal manner in the Japanese education system (1, 6 years; 2, 9 years; 3, 12 years; 4, 14 years; 5, 16 years; 6, 18 years; 7, 21 years). The average of the converted values for each parent was used in the analyses. This protocol followed the standard approach used by the Japanese government for evaluating socioeconomic status.

Behavioral Data Analysis

The behavioral data were analyzed using Predictive Analysis Software release version 18.0.0 (PASW Statistics 18) (SPSS Inc., 2010). Multiple regression analyses were used to investigate the associations between hours of TV viewing and VIQ in the preexperiment as well as those between hours of TV viewing in the preexperiment and the pre- to posttest change in VIQ. Results with a threshold of $P < 0.05$ were considered statistically significant.

Image Acquisition

All images were collected using a 3-T Philips Intera Achieva scanner. Three-dimensional, high-resolution, T_1 -weighted images (T1WI) were collected using a magnetization-prepared rapid gradient-echo (MPRAGE) sequence. The parameters were as follows: 240×240 matrix, TR = 6.5 ms, TE = 3 ms, TI = 711 ms, FOV = 24 cm, 162 slices, 1.0-mm slice thickness, and scan duration of 8 min and 3 s.

Preprocessing and Analysis of Structural Data

Preprocessing of the structural data was performed using Statistical Parametric Mapping software (SPM8; Wellcome Department of Cognitive Neurology, London, UK) implemented in Matlab (Mathworks Inc., Natick, MA, USA). Using the new segmentation algorithm implemented in SPM8, T_1 -weighted structural images of each individual were segmented into 6 tissues. In this process, the gray matter tissue probability map (TPM) used in this procedure was manipulated from maps implemented in the software so that the signal intensities of the voxels with (gray matter tissue probability of the default tissue gray matter TPM + white matter tissue probability of the default TPM) > 0.25 became 0. When this manipulated gray matter TPM is used, the dura matter is less likely to be classified as gray matter (compared with when the default gray matter TPM is used) without other substantial segmentation problems. In this new segmentation process, default parameters were used, except affine regularization that was performed using the International Consortium for Brain Mapping (ICBM) template for East Asian brains. We then proceeded into the diffeomorphic anatomical registration through exponentiated lie algebra (DARTEL) registration process implemented in SPM8. In this process, we used DARTEL-imported images of the 6 TPM of gray matter created using the abovementioned new segmentation process. First, the template for the DARTEL procedures was created using the T1WI data from the prescan of all the subjects. Next, using this existing template, DARTEL procedures were performed using the pre- and postscan T1WI of all of the subjects included in this study and default parameter settings. The resulting images were then spatially normalized to the Montreal Neurological Institute (MNI) space to obtain images with $1.5 \times 1.5 \times 1.5 \text{ mm}^3$ voxels. In addition, we performed a volume change correction (modulation) by modulating each voxel with the Jacobian determinants derived from the spatial normalization allowing for the determination of regional differences in the absolute amount of brain tissue (Ashburner and Friston 2000). Subsequently, all images were smoothed by convolving them with an isotropic Gaussian kernel of 10-mm full-width at half-maximum (FWHM) for the reasons described below.

Finally, the signal change in rGMV/rWMV between pre- and postintervention images was computed at each voxel for each participant. In this computation, we included only voxels that showed GMV values >0.10 in both pre- and postscans to effectively limit the images to areas likely to be GM/WM. The resulting maps representing the rGMV or rWMV change between the pre- and postMRI experiments ($rGMV_{\text{post}} - rGMV_{\text{pre}}$) or ($rWMV_{\text{post}} - rWMV_{\text{pre}}$) were then forwarded to the longitudinal imaging analyses, as described in the following section.

Statistical Analysis

Statistical analyses of imaging data were performed with VBM5 software, an extension of SPM5, for the reasons described below.

In the cross-sectional analyses of rGMV/rWMV, we included only voxels that showed rGMV/rWMV values of >0.10 in all subjects. The primary purpose for using this type of threshold is to cut the periphery of the GM/WM area and to effectively limit the area for analysis to areas likely to be GM/WM.

In the whole-brain analyses, we used voxel-wise analysis of covariance (ANCOVA), with sex difference as a grouping factor (using the full factorial option of SPM5). In this analysis, age (days after birth), family annual income, average number of years of parents' highest educational qualification, total intracranial volume and hours of TV viewing were used as covariates. Age (days after birth), family annual income, average number of years of parents' highest educational qualification, and hours of TV viewing were modeled so that each covariate had a unique relationship with rGMV/rWMV for each sex (using the interactions option in SPM5), which enabled investigation of the effects of interaction between sex and each covariate. On the other hand, total intracranial volume was not modeled in this manner, and a common effect of total brain volume on rGMV/rWMV was assumed for both sexes. In these analyses, the centering option was used for centering the interactions. The main effects of hours of TV viewing (contrasts of [the effects of hours of TV viewing for males, that for females] were $[0.5 \ 0.5]$ or $[-0.5 \ -0.5]$) and the interaction between sex and hours of TV viewing (contrasts of [the effect of TV viewing for males, that for females] were $[-0.5 \ 0.5]$ or $[0.5 \ -0.5]$) were assessed using *t*-contrasts.

In the longitudinal analyses of rGMV/rWMV, the maps representing signal changes in rGMV/rWMV between the pre- and postintervention images ($rGMV_{\text{post}} - rGMV_{\text{pre}}$ or $rWMV_{\text{post}} - rWMV_{\text{pre}}$), which were calculated in the Preprocessing and analysis of structural data subsection, were analyzed. In the whole-brain analyses, we used voxel-wise ANCOVA, with sex difference as a grouping factor (using the full factorial option of SPM5). In this longitudinal analysis of rGMV, the dependent variable was the abovementioned maps representing signal changes in rGMV ($rGMV_{\text{post}} - rGMV_{\text{pre}}$) and in the longitudinal analysis of rWMV, the dependent variable was the abovementioned maps representing signal changes in rWMV ($rWMV_{\text{post}} - rWMV_{\text{pre}}$). In these analyses, age (days after birth) in the preexperiment, family annual income in the preexperiment, average number of years of parents' highest educational qualification in the preexperiment, the duration of time between the pre- and postscan and hours of TV viewing were covariates. All of these covariates were modeled so that each had a unique relationship with rGMV for each sex (using the interactions option in SPM5), which enabled investigation of the effects of any interaction between sex and each covariate. The main effects of hours of TV viewing and the interaction between sex and hours of TV viewing were assessed using the same *t*-contrasts as those used in the cross-sectional imaging analyses.

The statistical significance level was set at $P < 0.05$, corrected at the nonisotropic adjusted cluster level (Hayasaka et al. 2004) with an underlying voxel level of $P < 0.0025$. Nonisotropic adjusted cluster-size tests can and should be applied when cluster-size tests are applied to data known to be nonstationary (in another words, not uniformly smooth), such as VBM data (Hayasaka et al. 2004). In this nonisotropic cluster-size test of random field theory, a relatively higher cluster-determining threshold combined with high smoothing values of more than 6 voxels leads to appropriate conservativeness in real data. With high smoothing values, an uncorrected threshold of $P < 0.01$ seems to lead to anticonservativeness, whereas that of $P < 0.001$ seems to lead to slight conservativeness (Silver et al. 2010), and thus the

abovementioned threshold was used. We used the VBM5/SPM5 version of this test and a smoothing value of 10 mm. This is because a previous validation study of this test using a real dataset (Silver et al. 2010) showed that the conditions of this cluster-size test are very limited and are dependent on the smoothness of the data as described above. However, SPM8 and SPM5 estimate actual FWHM substantially differently in the areas analyzed and this directly affects the cluster test threshold. Therefore, regardless of which (SPM5 or SPM8) is appropriate, our view is that the conditions shown in the previous study (Silver et al. 2010) are no longer guaranteed in SPM8 because different analyses are performed and these return different results. We used a 10-mm FWHM instead of a 12-mm FWHM, which was recommended in the previous study (Silver et al. 2010) because the normalized volume image that resulted from the DARTEL procedure appeared to have greater smoothness. In addition, a 10-mm FWHM appears to be sufficient to achieve actual smoothness in analyses of data acquired when the recommended smoothing value is used with the segmented VBM images from previous versions.

In these analyses, for areas with a strong a priori hypothesis, namely the mPFC, posterior parietal areas, and left IFG, the statistical significance level was set at $P < 0.05$, with a small volume correction for multiple comparisons [family wise error (FWE)] in regions of interest (ROIs). Detailed reasons for these regions being chosen were described in the Introduction. All ROIs were constructed using the WFU PickAtlas Tool (<http://www.fmri.wfubmc.edu/cms/software#PickAtlas>) (Maldjian et al. 2003, 2004) and were based on the Talairach Daemon (Lancaster et al. 2000) option of the PickAtlas. ROIs in the posterior parietal areas were constructed by adding the bilateral masks of the inferior and posterior parietal lobule, angular gyrus, and supramarginal gyrus. Further, to confirm that the effects observed in the cross-sectional analyses were also seen in the same areas in the longitudinal analyses (or vice versa) within areas identified as significant clusters, small volume corrections were applied as described above.

Interaction Effects Between Age and Hours of TV Viewing and Their Impact on Significant Correlates of TV Viewing

To investigate whether psychological and anatomical correlates of the length of TV viewing were driven by a particular age group, we performed 2 types of analyses. Both were performed using ANCOVAs in PASW Statistics 18. The dependent variables in both analyses were the significant correlates of TV viewing identified in the present study (namely, one of the following: VIQ in the cross-sectional and longitudinal analyses and the mean rGMV or rWMV value for significant clusters identified in the cross-sectional and/or longitudinal analyses). In the first analysis, the subjects were divided into 2 groups based on whether they are aged <11 years (which is close to the mean age) and we added this group factor analysis as well as the interaction of hours of TV viewing and this group factor in the models of each analysis as covariates in addition to all other covariates that were used in each of abovementioned analysis of correlates of hours of TV viewing. In the second analysis, we added the interaction between age and hours of TV viewing as an additional covariate in the models of each analysis the interaction between age and hours of TV viewing as an additional covariate in addition to all other covariates that were used in each analysis of correlates of hours of TV viewing.

Results

Basic Data

The characteristics of the subjects are shown in Table 1. The duration of TV viewing during weekdays was collected by

self-report questionnaire, and the distribution of this duration for all subjects is shown in Figure 1. The average postexperiment FSIQ of all subjects analyzed in the longitudinal analyses tended to be larger than the average FSIQ of all subjects analyzed using the preexperiment data ($P=0.065$, 2-tailed t -test); FSIQ of the subjects who were analyzed in the longitudinal analyses was significantly increased between the pre- and postexperiments ($P=0.01$, 2-tailed paired t -test). This slight increase in the average FSIQ may be due to persisting practice effects, which can increase IQ by 10 points in a re-test performed after 2-month separation (Wechsler 1997).

Cross-Sectional Behavioral Analysis

A multiple regression analysis that used preexperiment data revealed (after correcting for the effects of age, sex, family annual income, and the average number of years of parents' highest educational qualification) that hours of TV viewing in the preexperiment was significantly and negatively correlated with VIQ in the preexperiment ($P=0.003$, standardized partial regression coefficient (β) = -0.180 , Fig. 2a) and with FSIQ in the preexperiment ($P=0.019$, $\beta = -0.140$), but not with PIQ in the preexperiment ($P=0.314$, $\beta = -0.061$). Analysis of covariances, in which each test score in the preexperiment was the dependent variable, sex was the fixed factor, hours of TV

viewing was the random factor, and age, family annual income, and the average number of years of parents' highest educational qualification in the preexperiment were covariates, revealed that there were no significant interaction effects between sex and hours of TV viewing on each test score in the preexperiment ($P>0.1$).

Longitudinal Behavioral Analysis

A multiple regression analysis performed using the longitudinal data revealed (after correcting for the effects of age, sex, family annual income, average number of years of parents' highest educational qualification in the preexperiment, the duration of time between the postexperiment and preexperiment, and the score for each test in the preexperiment) that hours of TV viewing in the preexperiment were significantly and negatively correlated with the VIQ change between the pre- and postexperiment data ($P=0.032$, $\beta = -0.140$, Fig. 2b), but not with the FSIQ change between the pre- and

Table 1

Psychological variables of the study participants (mean \pm SD, range) in the cross-sectional analyses (133 boys and 143 girls, upper lines) and their change in the longitudinal analyses (111 boys and 105 girls, lower lines when there are 2 lines)

Measure	Boys	Girls
Age (years) (mean \pm SD, range)	10.8 \pm 2.8, 5.7–16.6 3.0 \pm 0.3, 1.7–4.0	11.5 \pm 3.8, 5.8–18.4 3.0 \pm 0.3, 1.8–4.1
FSIQ (mean \pm SD, range)	103.8 \pm 12.6, 77–133 0.9 \pm 8.9, –18–24	101.1 \pm 11.4, 71–128 2.4 \pm 9.8, –44–26
VIQ (mean \pm SD, range)	105.2 \pm 13.3, 67–152 0.0 \pm 10.4, –27–27	102.2 \pm 13.3, 67–134 1.5 \pm 10.9, –41–24
PIQ (mean \pm SD, range)	101.4 \pm 13.7, 62–135 1.5 \pm 10.4, –27–27	99.7 \pm 11.0, 73–129 2.8 \pm 10.9, –50–32
Family annual income ^a	4.03 \pm 1.52, 1–7	3.88 \pm 1.48, 1–7
Average number of years of parents' highest educational qualification	14.3 \pm 1.77, 9–18.5	14.1 \pm 1.55, 10.5–18.5
Hours of viewing TV ^b	2.02 \pm 1.02, 0.25–4	1.82 \pm 1.08, 0–4

^aFamily annual income was classified as follows: annual income below 2 million yen, 1; 2–4 million yen, 2; 4–6 million yen, 3; 6–8 million yen, 4; 8–10 million yen, 5; 10–12 million yen, 6; >12 million yen, 7.

^bThe answer "none" was scored as 0, "a little" was scored as 0.25, and "4 h or more" was scored as 4.

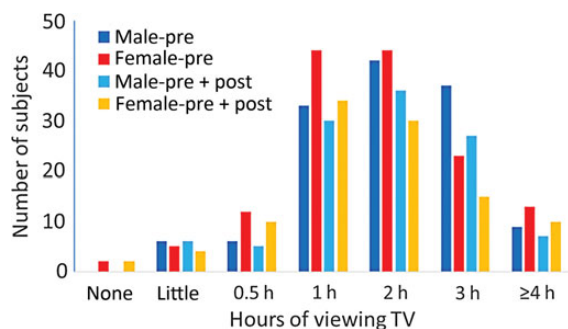


Figure 1. Histograms showing hours of TV viewing (on weekdays) of boys and girls in the cross-sectional analyses (pre) and in the longitudinal analyses (pre + post).

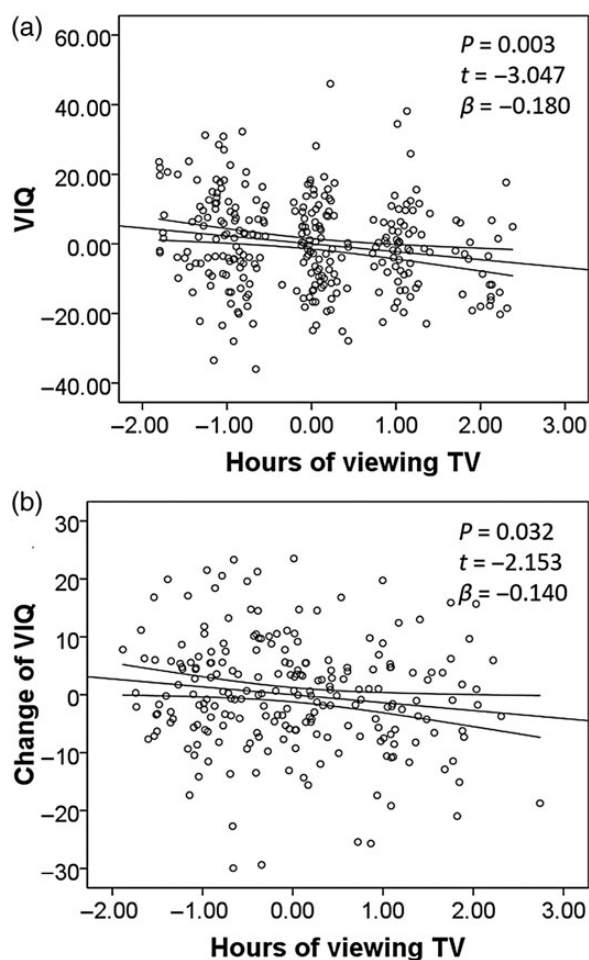


Figure 2. Associations between hours of TV viewing and VIQ as well as changes across time. (a) Residual plots with trend lines depicting the correlations between residuals in the multiple regression analyses with VIQ in the preexperiment as a dependent variable and hours of TV viewing in the preexperiment and other confounding factors as independent variables; 95% confidence intervals for the trend lines are shown. (b) Residual plots with trend lines depicting the correlations between residuals in the multiple regression analyses with longitudinal changes in VIQ as the dependent variable and hours of TV viewing in the preexperiment and other confounding factors as independent variables; 95% confidence intervals for the trend lines are shown.

postexperiment data ($P=0.141$, $\beta=-0.096$) or the PIQ change between the pre- and postexperiment data ($P=0.734$, $\beta=-0.021$). Analysis of covariances, in which the change in the results for each test before and after the experiment were the dependent variables and sex was the fixed factor with hours of TV viewing as the random factor, and age, family annual income, average number of years of parents' highest educational qualification in the preexperiment, the duration of time between the pre- and postexperiment data, and the score for each test in the preexperiment were covariates, revealed no significant interaction between sex and hours of TV viewing on the changes between the pre- and postexperiment data for each test ($P>0.1$).

Cross-Sectional rGMV/rWMV Analysis

Analysis of covariances that used the preexperiment data and took confounding factors into account revealed an overall positive main effect (regardless of sex) of hours of TV viewing on rGMV in an anatomical cluster that spread from the left middle, inferior, and superior occipital lobe to the calcarine cortex and the cuneus (MNI coordinates $x, y, z = -18, -100.5, -3$, t -value of the peak = 4.01, $P < 0.001$, corrected for multiple comparisons at the nonisotropic adjusted cluster level, Fig. 3a). There were no other significant results in the whole-brain analysis of rGMV. Among areas with a strong a priori hypothesis, a small volume correction was employed and significantly positive main effects of TV viewing were found in the ventral part of the frontopolar area (MNI coordinates $x, y, z = -10.5, 66, -18$, t -value of the peak = 4.40, small volume correction for areas with a strong a priori hypothesis: $P = 0.010$ corrected for FWE at the voxel level within the bilateral medial frontal gyrus; Fig. 3a). No significant effects of interactions between hours of TV viewing and sex were observed on rGMV.

Analysis of covariances that used the preexperiment data and took confounding factors into account also revealed an overall positive main effect (regardless of sex) of hours of TV viewing on rWMV in an anatomical cluster of white matter areas that spread across the right calcarine cortex (MNI coordinates $x, y, z = 19.5, -64.5, 21$, t -value of the peak = 4.82, $P = 0.029$, corrected for multiple comparisons at the nonisotropic adjusted cluster level, Fig. 3b) and in an anatomical cluster of white matter areas that spread across the left calcarine cortex (MNI coordinates $x, y, z = -10.5, -52.5, 6$, t -value of the peak = 4.24, $P = 0.024$, corrected for multiple comparisons at the nonisotropic adjusted cluster level, Fig. 3b).

To reveal the nature of each significant cluster in terms of their association with VIQ, we employed voxel-by-voxel ANCOVAs to investigate the association between rGMV and VIQ within these clusters; small volume corrections were applied and corrections for multiple comparisons were performed only within each cluster. Analysis of covariances that used the preexperiment data and took confounding factors into account revealed an overall negative main effect of VIQ on rGMV in the frontopolar area (MNI coordinates $x, y, z = -12, 66, -18$, t -value of the peak = 2.13, small volume correction, $P = 0.043$ corrected for FWE at the voxel level within the significant cluster that showed the positive main effects of hours of TV viewing). There were no other significant findings.

Longitudinal rGMV/rWMV Analysis

Analysis of covariances that used the longitudinal data and took confounding factors into account revealed an overall positive main effect (regardless of sex) of hours of TV viewing on rGMV in an anatomical cluster that spread from the left precentral gyrus to the left postcentral gyrus and paracentral lobule (MNI coordinates $x, y, z = -10.5, -34.5, 75$, t -value of the peak

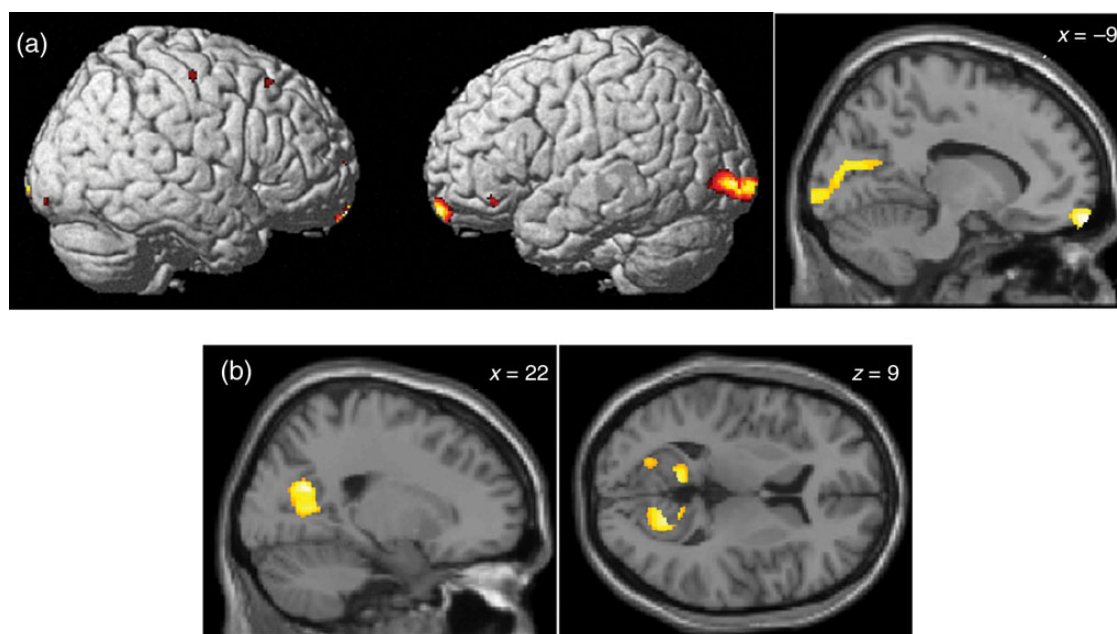


Figure 3. Anatomical correlates of duration (hours) of TV viewing in the cross-sectional analyses. (a) Positive rGMV correlates of correlations with duration of TV viewing. Results are shown with $P < 0.0025$ uncorrected for visualization purposes. In the right figure, the regions of correlation are overlaid on an SPM5 "single subject" T1 image. Significant positive correlations in the frontopolar area and the visual cortex were seen together with other nonsignificant correlations. (b) Positive rWMV correlates of correlations with duration of TV viewing. Results are shown with $P < 0.0025$ uncorrected for visualization purposes. The regions of correlation are overlaid on a SPM5 "single subject" T1 image. Significant correlations in the bilateral calcarine cortices are seen.

=4.40, $P=0.023$, corrected for multiple comparisons at the nonisotropic adjusted cluster level, Fig. 4) and in an anatomical cluster that spread from the hypothalamus to the septum, caudate, and contingent areas (MNI coordinates $x, y, z = -1.5, 10.5, 9$, t -value of the peak = 4.25, $P=0.016$, corrected for multiple comparisons at the nonisotropic adjusted cluster level, Fig. 4). A similar tendency was also observed in an anatomical cluster that spread from the right precentral gyrus to the post-central gyrus (Fig. 4). There were no other significant findings in the whole-brain analyses of rGMV/rWMV changes. No significant effects of interaction between hours of TV viewing and sex were observed on rGMV/rWMV changes.

Among areas with significant clusters identified in the cross-sectional analyses, small volume corrections within each cluster were employed and significant positive correlations were found in the ventral part of the frontopolar area (MNI coordinates $x, y, z = -12, 66, -18$, t -value of the peak = 2.42, small volume correction, $P=0.020$ corrected for FWE at the voxel level within a significant cluster that showed the positive main effects of hours of TV viewing; Fig. 4). There were no other significant findings.

Interaction Effects Between Age and Hours of TV Viewing on Significant Correlates of TV Viewing

We also investigated interaction effects between age and hours of TV viewing and determined their impact on the significant correlates of TV viewing identified in the present study using 2 different types of analyses. In both types of analyses, across the analyses for all psychological and imaging correlates of the length of TV viewing, the interaction effects between age and hours of TV viewing on psychological and imaging correlates of the length of TV viewing were insignificant ($P>0.05$, uncorrected).

Discussion

Previous cross-sectional and longitudinal studies have reported negative effects of TV viewing on verbal functions (Ridley-Johnson et al. 1983; Zimmerman and Christakis 2005). In this study, we newly revealed the effects of TV viewing on brain structures of children in a study that included both cross-sectional and longitudinal analyses. Our hypotheses were partly confirmed and our cross-sectional studies newly revealed that the duration of TV viewing was positively correlated with rGMV in an anatomical cluster around the mPFC and the frontopolar area as well as a further increase in rGMV in

the same area a few years later. Congruent with the abovementioned previous studies, the duration of TV viewing was found to be negatively correlated with VIQ in the cross-sectional studies and also predicted a further decrease in VIQ a few years later. Considering that VIQ was found to be negatively correlated with rGMV in the mPFC/frontopolar area in cross-sectional studies, this area's structure may partly mediate the link between the duration of TV viewing and lower VIQ. These types of relationships were not observed in the IFG and posterior parietal areas at the applied threshold at least and the associations between rGMV and duration of TV viewing were not confirmed in the IFG and posterior parietal areas in this study. Further, the duration of TV viewing was positively correlated with rGMV/rWMV of areas of the visual cortex in the cross-sectional studies and a longitudinal increase in rGMV in the hypothalamus/septum and sensorimotor areas. Previous studies have shown that the visual cortex is functionally or structurally involved in visual perception, the hypothalamus/septum areas in aggression, and the sensorimotor area in motor functioning. These studies have reported a number of effects of TV viewing on these functions as discussed below. However, we did not use any relevant measures for these variables and did not observe any such associations in the cross-sectional or longitudinal analyses. Thus, the functional relevance of these areas remains inconclusive.

The present findings indicate that TV viewing affects rGMV of the frontopolar area and that this effect is associated with the negative effect of children's TV viewing on their verbal abilities. The duration of TV viewing was positively correlated with rGMV in the frontopolar area and negatively correlated with VIQ in the cross-sectional studies. Further, the duration of TV viewing was positively correlated with developmental changes in this area a few years later and negatively correlated with such changes in VIQ. On the other hand, this area's rGMV was negatively correlated with VIQ. This area shows cortical thinning after adolescence (Sowell et al. 2003) and children with superior IQ show the most vigorous cortical thinning (Shaw et al. 2006). Further, contingent regions show a negative correlation between rGMV and cognitive functions associated with that area in young adults (Takeuchi et al. 2011a, Takeuchi, Taki, Nouchi, et al. 2013; Banissy et al. 2012). The present findings and those of the studies described above suggest a negative association between verbal abilities and rGMV in this area during development. They also indicate that TV viewing affects this area and that any resultant changes may underlie or be associated with the effects of TV viewing on verbal abilities.

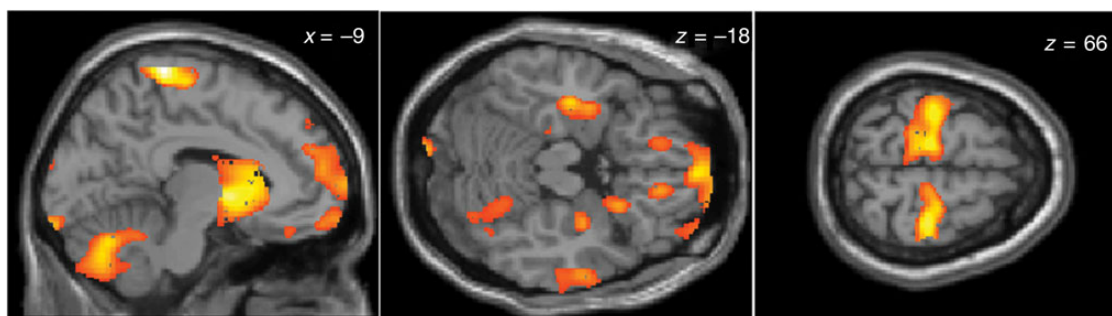


Figure 4. Anatomical correlates of duration (h) of TV viewing in the longitudinal analyses. Positive correlations between rGMV changes and duration of TV viewing. Results are shown with $P < 0.025$ uncorrected for visualization purposes. The regions of correlation are overlaid on a SPM5 "single subject" T1 image. Significant positive correlations in the frontopolar area, a cluster that included the hypothalamus, septum, and contingent areas, and the left sensorimotor area are seen together with other nonsignificant correlations.

However, this interpretation may require caution. While the association between psychometric intelligence and medial and lateral areas around the frontal pole has been repeatedly shown (as described in the Introduction), the gray matter structure is likely to be widely distributed across the brain, and the areas around the frontal pole can be lobotomized without substantially compromising psychometric intelligence (Jung and Haier 2007). Further, it is becoming increasingly clear that associations between structure and cognition are not that strong (Takeuchi, Taki, Nouchi, et al. 2013, Takeuchi, Taki, Thyreau, et al. 2013), and thus, any analysis of that should reveal overall effects of structural correlates of certain cognitions requires substantial statistical power. Thus, other areas that could not be detected in the present study may underlie the observed association between TV viewing and reduced VIQ. Further, Shaw et al.'s (2006) finding of vigorous cortical thinning in subjects with higher intelligence involves superior intelligence with IQ > 120 and so far have not been replicated. On one hand, evidence from studies of normal young adults is increasingly indicating a negative association between the structure of medial prefrontal and contingent areas and associated cognitions (Modinos et al. 2010; Hu et al. 2011; Takeuchi et al. 2011a, 2013, Takeuchi et al., unpublished; Banissy et al. 2012; Takeuchi et al. forthcoming), and the importance of cortical thinning for cognition has been highlighted (for review, see Kanai and Rees 2011). On the other hand, cross-sectional studies have generally shown a positive association between psychometric general intelligence and regional gray matter structures in areas around the frontal pole (Haier et al. 2004; Gong et al. 2005; Colom et al. 2006; Narr et al. 2007). Whether cognition is positively or negatively associated with these structures may depend on a number of factors, such as age and the areas of the brain involved (i.e., whether the areas show cortical thinning during the age of the sample and whether thinned cortices reflect advanced development), as well as normality of the samples (clinical samples or not) (while development must lead to adaptive cortical thinning, diseases can reduce gray matter structures and associated cognitive competence)

(Takeuchi et al. 2011a). The Japanese are known to exhibit earlier maturation in terms of body development; therefore, the rate of brain development may also differ, too and this may be another factor to consider (Okada 1971). Thus, future studies need to ascertain whether populations of subjects with other characteristics show greater rGMV in the frontopolar area instead of reduced rGMV.

The duration of TV viewing in the preexperiment was positively correlated with rGMV of areas of the visual cortex and rWMV of white matter areas adjacent to the calcarine cortex (primary visual cortex), but only in the cross-sectional studies. We speculate that these changes may have been caused by use-dependent structural change. While watching TV, one may receive frequent visual stimuli or novel stimuli that we are not exposed to in everyday life. These experiences may lead to use-dependent rGMV/rWMV increases (Draganski et al. 2004; Jäncke et al. 2009; Takeuchi, Taki, Nouchi, et al. 2013). However, we did not observe any associations between the duration of TV viewing in the preexperiment and further rGMV/rWMV increases a few years later. The reasons for this observation are not clear. However, we speculate that it may be because structural changes caused by TV viewing may already be largely saturated (because of the direct effects of TV

viewing on the visual cortices). Further, we do not have any particular reason to believe that, unlike in the case of some forms of training, such as playing music, in which the amount of accumulated experience and structural change is correlated in some cases (Sluming et al. 2002), after viewing TV for a long period of time the programs we watch on TV do not necessarily advance to a higher level, speed up, or vary. When this type of increase in level of experience does not occur with increasing experience, there is less of an effect on cognitive functioning and brain structures (Takeuchi, et al. 2011b). Alternatively, subjects with more rGMV/rWMV in the visual cortices may view TV more often or other common factors may simultaneously increase rGMV/rWMV and hours of TV viewing. However, we are not aware of any previous studies that have suggested any such mechanism, whereas experience-dependent structural changes in brain areas relevant to the experience (Draganski et al. 2004; Jäncke et al. 2009; Takeuchi, Taki, Nouchi, et al. 2013) are well known. Thus, we believe that a causal effect of TV viewing on rGMV/rWMV is most likely. However, these are purely speculations and future studies need to investigate this issue.

The duration of TV viewing in the preexperiment was associated with a tendency toward increased rGMV in an anatomical cluster that spread around the precentral gyrus and postcentral gyrus as well as in an anatomical cluster that spread around the septum and hypothalamus a few years later. Although the functional relevance of these findings is not clear from our study, there are certain comparable previous studies regarding these areas. As for the findings around the hypothalamus and the septum, a wide range of neuroscientific studies have associated aggression and functioning of the hypothalamus and septum (Greenstein and Greenstein 2000). Further, rGMV of the hypothalamus is enlarged in patients with borderline personality disorders (Kuhlmann et al. 2013), which are characterized by aggressiveness (Látalová and Praško 2010). However, an association between the structure of the hypothalamus and mood disorders has also been shown (Turner and Schönknecht 2012). As for the findings regarding the precentral gyrus and postcentral gyrus, longitudinal neuroimaging pediatric studies have shown that developmental increases in motor skills are negatively correlated with changes in cortical thickness in the left precentral gyrus (children with a greater improvement in motor skills showed greater thinning of gray matter structures in the precentral gyrus) (Lu et al. 2007).

On the other hand, other than intellectual abilities, TV viewing is known to affect psychological properties. It is known that the duration of TV viewing or the viewing of violent TV predicts an increase in aggression longitudinally (Anderson and Bushman 2002). Moreover, TV viewing has been suggested to aggravate depressive mood (Potts and Sanchez 1994). On the other hand, the duration of TV viewing is associated with less physical activity and the 2 independently have the same effects on the body (Andersen et al. 1998). Further, more physical activity is associated with higher motor skills (Houwen et al. 2009). Thus, if we are forced to speculate as to the specific functional relevance of the observed findings in and around the precentral gyrus and postcentral gyrus as well as around the septum and hypothalamus, we speculate one possibility is these psychological effects of TV may have something to do with TV viewing's effects on these areas. However, we did not perform any assessments of

motor function, emotion, or aggression because those were not the areas of interest in this study, and because one brain area usually has multiple functions and TV viewing is known to affect a wide range of psychological variables, as described above. Thus, we wish to avoid making any conclusions regarding functional relevance from these findings and suggest that they be addressed in future studies. Further, other than the neuroscientific findings relating to the precentral gyrus described above, the neuroimaging studies of adolescent girls has shown that playing TV games (visuospatial games; tetris) increases the cortical thickness of the adjacent premotor area (Haier et al. 2009). This may suggest a possible positive implication of the increase in rGMV of the precentral gyrus observed in the present study. However, training-related gray matter structural changes are complex (Takeuchi, Taki, Hashizume, et al. 2011, 2011b; Takeuchi, Taki, Nouchi, et al. 2013), and our results were not affected by including the time spent playing videogames on a daily basis, as is noted below, and this implication is not clear, either. Future studies need to investigate this issue further.

We speculate that one possible reason why we could not observe any associations between brain structures in the sensorimotor areas and hours of TV viewing in the cross-sectional studies was because the effect of TV viewing on structures in the sensorimotor areas may not be direct (more frequent TV viewing is associated with less physical activity, which in turn causes rGMV changes in sensorimotor areas) and thus the effects of TV viewing may not have been accumulated in the cross-sectional studies. On the other hand, we speculate that one possible reason why we could not observe any associations between the subcortical structures and hours of TV viewing in the cross-sectional studies was because the effect of TV viewing on these areas may not be strong (because only some parts of TV programs include violence and violent TV in itself may affect rGMV changes in this area) and thus there may not have been enough effects of TV viewing to accumulate in the cross-sectional study. Nevertheless, the fact that associations between TV viewing and rGMV were not found in the cross-sectional analysis is a weak point, and future studies may need to replicate these findings for a more robust conclusion.

We also speculated that the lack of any effects of TV viewing on PIQ and the posterior parietal areas may have some relevance. In the present study, TV viewing was not significantly associated with the PIQ cross-sectionally or longitudinally and neither were the posterior parietal gray matter structures. Thus, the effects of TV viewing on intellectual abilities seemed to be rather specific despite the cross-sectional association between VIQ and PIQ (Wechsler 1997). This may have something to do with the lack of any findings of effects of TV viewing on the posterior parietal gray matter structures, which was in contrast to our original hypothesis. This is because although the posterior parietal areas have many distinct functional roles, structurally, an association between gray matter structures in these areas and visuospatial cognition has been shown, independent of general intelligence (Hänggi et al. 2010), and PIQ as well as TV viewing involves visuospatial cognition. However, evidence of a specific structural association between the posterior parietal areas and PIQ (or visuospatial cognition) is not as common as that of an association between intelligence and the fronto-parietal areas. Further, negative findings from voxel-based structural analyses are not that robust, even with SVCs, given the relatively weak

association between structures and cognition (Takeuchi, Taki, Sassa, et al. 2013, Takeuchi, Taki, Thyreau, et al. 2013). Thus, all these speculations should be viewed with caution.

The present study had some limitations. First, this was not an intervention study. Thus, although we have shown a relationship between hours of TV viewing and brain structures and verbal IQ using both cross-sectional and longitudinal analyses, we cannot clarify whether TV viewing directly affects these measures. It is possible that a reduction in the number of activities performed (such as studying, reading, playing videogames, interacting with friends, interacting with family members, exercise, and so on) due to the increased time spent viewing TV may directly affect these measures. In fact, it has been suggested that whether TV viewing has good or bad effects is dependent on what activity replaces TV viewing (Gentzkow and Shapiro 2008). Some of the subjects responded that they viewed TV for 4 h or more. Assuming that they sleep for 8 h a day and go to school for 8 h, they spend more than half of the rest of their free time viewing TV. In this case, activities (such as exercise or reading) replaced by TV viewing may well affect cognitive functions and neural mechanisms. Even when this was the case, we do not think the purpose of this study was not fulfilled, that is, even when our results showed that viewing TV “instead of studying or reading” disturbs the development of cognitive functions and brain structures, we do not think the purpose of the study was not fulfilled. In different cultures or groups, viewing TV “instead of being neglected or relaxed doing nothing” may favorably affect the development of cognitive functions and brain structures. Future studies in different cultures can investigate this issue. However, when we corrected for the effects of number of brothers and sisters, birth order, reading habit, hours of studying, and time spent talking with parents, and time spent playing games by including these as independent variables in addition to original independent analyses, with the same dependent variables in the psychological analyses and with the mean value within the significant clusters as dependent variables in the imaging analyses, all significant results remained significant except for those related to the cross-sectional analysis hours of TV viewing and VIQ ($P = 0.057$ in the case of this analysis, suggesting a tradeoff between hours of TV viewing and other variables). Alternatively, individual tendencies to indulge in TV viewing may affect these measures directly or indirectly. Future intervention studies can more precisely describe these issues. Second, some studies have that shown that the content of the TV shows viewed by children (such as violence) affects related psychological variables (children’s violent behaviors) (Paik and Comstock 1994). Because our study’s purpose was not associated with these issues, we did not gather the data required for such analyses, but these could be studied further in the future.

In conclusion, TV viewing is directly or indirectly associated with the neurocognitive development of children. At least some of the observed associations are not beneficial and guardians of children should consider these effects when children view TV for long periods of time.

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