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Complementary hemispheric lateralization of language and social processing in the human brain

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Short title: Language versus social processing in brain

Abstract:

Humans have a unique ability to use language for social communication. The neural architecture for language comprehension and production may have emerged in the brain areas that were originally involved in social cognition. Here we directly tested the fundamental link between language and social processing using functional MRI data from over 1000 human subjects. Cortical activations in language and social tasks showed a striking similarity with a complementary hemispheric lateralization; within core language areas, the activations were left-lateralized in the language task and right-lateralized in the social task. Outside these areas, the activations were left-lateralized in both tasks, perhaps indicating multimodal integration of social and communicative information. Our findings could have important implications in understanding neurocognitive mechanisms of social disorders such as autism.

Keywords: language processing, social processing, cortical architecture, hemispheric lateralization, fMRI, human connectome project

Introduction:

Language is a distinctive component of human cognition. This cognitive process is mediated by a network of cortical areas in lateral temporal and lateral prefrontal cortex (1), which are collectively involved in language comprehension (2) and language production (3). A classic fact about the organization of language processing network is that the language areas are strongly lateralized to the left hemisphere (LH), in about 95% of right-handed individuals and about 75% of left-handed individuals (4). This hemispheric specialization for language raises some fundamental questions. Is there specialization for a certain cognitive faculty in the right-hemisphere (RH) areas corresponding (homotopic) to LH language areas? If there is such specialization, does it show an opposite lateralization (i.e. RH dominance)? Do the homotopic areas of the two hemispheres have complementary functions? Does the degree of hemispheric lateralization in these areas predict performance in specific tasks?

We hypothesized that the homotopic language areas in RH are prominently specialized for social processing. Social processing in the brain could be characterized as a set of cortical computations for (i) perceiving socially relevant stimuli such as biological motion, dynamic faces, and gaze direction (5), (ii) perceiving social interactions between people and between moving agents (6), (iii) recognizing intentions of other people's actions (7), and (iv) mental reasoning about beliefs and thoughts of other

people (theory of mind) (8). Understanding the social content of the environment is an evolutionarily old skill, seen in many forms across the animal kingdom. For instance, brain imaging in macaque monkeys has shown a dedicated network of bilateral cortical areas in temporal and prefrontal cortex for processing social interactions (9,10). One specific form of social communication is linguistic communication, and the cortical architecture for language processing may have emerged in LH within territories that were primarily involved in social processing. Thus, based on this scenario, it would be expected to find that the homotopic areas in RH contain an original selectivity for social processing.

Results:

To investigate the relationship between cortical networks of language and social processing, we used fMRI data of 1044 healthy young adults from the Human Connectome Project (HCP) database (<https://www.humanconnectome.org/study/hcp-young-adult>). In each subject, cortical activation maps were obtained for language (11) and social (12,13) tasks. The language task consisted of story blocks and math blocks. In the story blocks, subjects were presented with brief auditory stories and answered questions about the topic of stories. In the math blocks, subjects were auditorily presented with simple arithmetic questions. In the social task, subjects were presented with short video clips of objects (squares, circles, triangles) that either interacted in some way (approaching, chasing, etc.) or moved randomly on the screen. Subjects judged whether the objects had a social interaction or not. Functional maps from all subjects were multimodally transformed to a standard cortical surface where LH and RH were precisely registered to each other (i.e. there was a one-to-one correspondence between points/vertices of LH and RH) (14). Having such correspondence was crucial for an anatomically accurate evaluation of inter-hemispheric relations over the entire cortex.

Group-average activation maps (effect size maps) for language and social tasks were obtained by statistically comparing the ‘story vs. baseline’ and ‘social vs. random’ conditions, respectively (**Figure 1a,b**). The stimuli and task instructions of the two tasks were drastically different. However, the activation maps showed a remarkable similarity in the topography of areas activated by story and social stimuli, especially in lateral temporal and lateral prefrontal cortex. It was also evident that the language-related activations were relatively stronger in LH, while the social-related activations were relatively stronger in RH. To perform a detailed analysis of hemispheric lateralization within core language areas, these areas were first localized based on the group-average language map in LH (**Figure 1c** and

Supplementary Figure 1). The localized areas, named based on a multi-modal parcellation of cerebral cortex (15), included PGI, PSL (perisylvian language area), STSp (superior temporal sulcus posterior), STSa (superior temporal sulcus anterior), STGa (superior temporal gyrus anterior), SFL (superior frontal language area), 55b, and Broca's area (areas 44, 45, and 47) (**Figure 1d**). PSL, which was located within the planum temporale, could be considered part of Wernicke's area. Most of these areas were also activated in the 'story vs. math' contrast – though the separation between language and default mode networks was more pronounced in the 'story vs. baseline' contrast (**Supplementary Figure 2**). Previous work confirms that the language network identified by the 'story vs. baseline' contrast includes neurobiologically relevant and functionally coupled areas (15).

Next, we examined the hemispheric lateralization within core language areas. For each task and each subject, the activation map in RH was subtracted from the activation map in LH, then the difference maps were averaged across subjects. The difference maps would allow evaluation of lateralization regardless of idiosyncratic differences in absolute activation levels. As expected, the language areas showed LH dominance in the language task (**Figure 1e**). Interestingly, the same areas in RH showed a relatively higher activation to social stimuli (**Figure 1f**). To quantify the effects, the functional asymmetry values (LH activation minus RH activation) were averaged across vertices in each area. All areas except PGI showed a significant double-dissociation effect: LH dominance in the language task and RH dominance in the social task (**Figure 2a**).

Based on data of individual subjects, we selected a minority group of atypical subjects ($n = 29$) who clearly had strong language activations in RH (**Figure 2b,c**), and tested whether the RH laterality effect in the social task is reduced (or perhaps eliminated) in these subjects. In the group-average maps of these subjects, most of the areas included subregions showing LH dominance in the social task (**Figure 2d**). Importantly at the areal level, none of the areas showed RH dominance in the social task (**Supplementary Figure 3**) – contrary to what we observed in the group-average map of all subjects.

At the areal level, the pattern of hemispheric biases was generally consistent across areas. However, a detailed look at the fine-scale spatial organization of language and social lateralization revealed an important difference between STSp and other areas (**Figure 3**). Within STSp, there was a considerable overlap between subregions showing laterality effects in language and social tasks, whereas in other areas especially within PGI, these subregions actually avoided each other (**Figure 3a,b**). In STSp, common

neural populations appear to be activated by language and social tasks (see also [16](#)), and therefore, the opposite hemispheric lateralization for language and social processing may be accentuated in this area through competition for shared neural resources. This prediction was confirmed in a subsequent analysis where we systematically tested the relationship between functional asymmetry values of language and social processing across subjects (**Figure 3c**). STSp showed a highly significant negative correlation between language and social lateralization, meaning that subjects with stronger language activation in left STSp tended to have stronger social activation in right STSp. This negative correlation in STSp was observed in both right-handed and left-handed subjects (**Supplementary Figure 4**). PSL also showed a weak but significant negative correlation, while PGI showed a significant positive correlation. In other areas, there was no association between language and social lateralization.

Do the individual differences in complementary hemispheric lateralization correlate with performance in language and social tasks? We addressed this question using behavioral data of all subjects in HCP. The behavioral measures of language processing were based on scores in vocabulary comprehension and reading recognition tests ([17](#)). The behavioral measure of social processing was based on accuracy in the social task during functional imaging. For two groups of subjects with high and low performance in these behavioral metrics, we estimated language and social lateralization effects in eight language areas (**Supplementary Figure 5**). In PGI and PSL, higher LH lateralization in the language task was linked to better performance in the language tests. In STSp and STSa, higher RH lateralization in the social task was linked to better accuracy in this task. Thus, at least in some areas, there was an association between hemispheric lateralization and behavioral outcome.

The asymmetry maps shown in **Figure 1e,f** also revealed lateralization effects outside the language network. To quantitatively evaluate the effects in all parts of cortex, we first computed functional asymmetries in the language task for all 180 cortical areas from multi-modal parcellation ([15](#)). In this parcellation, each parcel in LH had a corresponding parcel in RH. 25 parcels with the highest absolute values of asymmetry were then selected as regions-of-interest (ROIs) (**Supplementary Figure 6**) and visualized on the cortical surface (**Figure 4a**). We identified eight ROIs outside language-auditory network. When comparing with resting-state networks ([18](#)), these ROIs were predominantly located within default and frontoparietal networks (**Supplementary Figure 7a**). Although responses in these ROIs were generally negative, they could differentiate story and math stimuli (**Supplementary Figure 7b**). Interestingly, four frontal ROIs located immediately anterior to 55b and Broca's area showed LH

dominance in both language and social tasks (**Figure 4b,c**). Furthermore, in the majority of non-language ROIs, degree of lateralization in the language task was positively correlated with degree of lateralization in the social task (**Figure 4d** and **Supplementary Figure 8**). A possible interpretation is that some LH regions outside the language network might be involved in integrating linguistic and social information.

Discussion:

The two cerebral hemispheres sometimes show complementarity of function. While LH is more specialized in fine-grained processing of visual stimuli, RH is more specialized in holistic processing of global form (**19**). In the case of category-selective areas of visual cortex, the fusiform face area (FFA) is generally right-lateralized (**20,21**), whereas the visual word form area (VWFA) is better localized in LH (**22,23**). The brain networks of language and attention also show opposite hemispheric lateralization (**24**). While the language areas are typically located in LH, RH appears to be specifically involved in the control of visuospatial attention. In all cases described above, the lateralization of a certain area/processing in one hemisphere is often accompanied with the lateralization of another area/processing in the other hemisphere. Complementary lateralization of language and social processing reported in our study is unique in the sense that the homologous areas of the two hemispheres showed such lateralization effects.

Previous studies have shown that the homologues of language areas in RH are involved in the processing of prosody (**25**). Affective-prosodic components of speech play an important role in social communications, and they may tightly linked to other elements of social processing in RH. It has also been reported that the homologue of Broca's area (Brodmann areas 44/45) in RH is active during the observation of hand/mouth actions performed by other individuals (**26**). Thus, this area along with other areas of the 'mirror-neuron' system could encode information necessary for gestural communication (**27**). Another possibility is that this area represents social contents of actions rather than actions *per se*. Overall, the previously proposed functions for the RH homologues of language areas could be characterized as various forms of social processing.

It has been suggested that hemispheric lateralization has computational benefits (**28**). Unilateral systems could be efficient for coordinating rapid sequences of precise, ordered operations. In fact, the degree of functional asymmetry across the two hemispheres predicts behavioral measures of verbal and

visuospatial ability (29). Such systems would also contribute to compact wiring of the brain by minimizing the aggregate length of cortico-cortical connections. Complementary hemispheric lateralization of language and social processing might be essential for a normal behavior in these domains, and it may be disrupted in autistic patients who have difficulty in both linguistic and social communications. A recent study has reported reduced language lateralization in autism (30). Further studies are needed to comprehensively explore complementary lateralization of language and social processing in autistic patients. Such tests could provide new insights about the possible neurobiological causes of autism spectrum disorder. •

Authors' contributions:

R.R. conceived the idea and designed the analyses; A.F. performed data analysis and prepared figures; H.R. and N.A. provided analysis tools; R.R. wrote the manuscript; J.D. critically revised the manuscript. All authors approved final version of the manuscript.

The authors declare no competing interests.

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Figure Captions:

Figure 1: Hemispheric lateralization effects in the language and social tasks.

(a,b) Group-average activation maps for the contrasts of ‘story vs. baseline’ in the language task and ‘social vs. random’ in the social task. The maps represent Cohen’s d effect size, and they are displayed on lateral and medial views of the inflated cortical surface (fs_Lr surface). In each panel, LH is shown on the left, and RH is shown on the right. (c) The group-average activation map for the language task is displayed on a 2-D flat patch of LH, so that the activation pattern of the entire cortex could be seen in a single view. The most active areas (black and green borders) were defined by thresholding the map (**Supplementary Figure 1**). Black and green borders correspond to auditory cortex and language areas, respectively. The activations in the superior temporal region showed three distinct ‘hot spots’ (indicated by white arrows) along the posterior-anterior direction, and therefore, this region was divided into three areas. (d) Eight language areas localized in panel c were named based on an atlas of cortical areas (**15**). (e,f) Functional asymmetry maps for each task were obtained by subtracting RH activations from LH activations.

Figure 2: Hemispheric lateralization for language and social processing within language areas.

(a) The lateralization effects in language areas were quantified based on data of all subjects. For each subject and each task, functional asymmetry values were averaged across vertices in each area. Data were then averaged across subjects. Error bars indicate one standard error of the mean across subjects. Mean asymmetry values were significantly different from zero in all areas (FDR-adjusted $p < 0.0005$; t -test). (b) For each subject and each task, a lateralization index was calculated by averaging functional asymmetry values across vertices of all areas except PGi (i.e. seven areas which showed a double-dissociation effect). The scatter plot demonstrates distribution of these indices across all subjects. A

group of subjects, marked with red dots, showed strong language activations in RH. As one would expect, the prevalence of left-handedness was higher in these subjects compared to the general population. (c,d) For this group of subjects, functional asymmetry maps were obtained by subtracting RH activations from LH activations.

Figure 3: Fine-grained organization of language and social lateralization within the language areas.

(a) Functional asymmetry maps within the language areas. The areal patches were selected from the maps shown in **Figure 1e,f**, and they were magnified to show fine-grained spatial organization of language and social lateralization. Note that the maximum threshold of the maps here was set at a slightly higher value (99th percentile of data instead of 98th percentile used in other figures) to allow for a better visualization of variations in the maps. (b) Spatial overlap between language and social asymmetry maps was quantified using the Jaccard index. In each area, we selected just vertices with positive values in the language asymmetry map, and took the x% most positive. Similarly we selected just vertices with negative values in the social asymmetry map, and took the x% most negative. Then, spatial overlap between these two sets of vertices was calculated. Given the varying degree of functional asymmetries in the maps, spatial overlap was systematically measured at different values of x. The black borders in panel a show subregions at the threshold of 30%. (c) The scatter plots demonstrate the functional asymmetry values of all subjects in eight language areas. Positive values indicate stronger activation in LH, and negative values indicate stronger activation in RH. *: $p < 0.05$, **: $p < 0.005$, ***: $p < 0.0005$.

Figure 4: Relationship between hemispheric lateralization of language and social processing in areas outside language-auditory network.

(a) The flat patch shows ROIs with strong lateralization in the language task. The language-auditory ROIs are marked with white color. The colors in the remaining ROIs indicate sign and magnitude of functional asymmetry. (b) For the same non-language ROIs, functional asymmetries were calculated in the social task. (c) Functional asymmetry values were obtained for eight non-language ROIs. Error bars indicate one standard error of the mean across subjects. Mean asymmetry values were positive in most ROIs, and they were significantly different from zero in all ROIs except 31pd, 9a, and 8BL in the social task (FDR-adjusted $p < 0.05$; t-test). (d) For each subject, functional asymmetry values were calculated for an aggregate ROI comprising eight non-language ROIs. Data of all subjects were then visualized in the scatter plot.

Methods:

Subjects:

In this study, we used the “HCP1200” dataset (March 2017 data release) of healthy adults aged 22-35 (<https://www.humanconnectome.org/study/hcp-young-adult/document/1200-subjects-data-release>).

The dataset included 1045 subjects. One subject (subject ID: 765864) had a large MR artifact, and this subject was excluded after consulting with the HCP team. The remaining 1044 subjects (559 females, 485 males) had complete functional data for both language and social tasks. Subjects were recruited from Washington University (St. Louis, MO) and the surrounding area. The HCP data were acquired using protocols approved by the Washington University institutional review board, and written informed consent was obtained from all subjects.

Data acquisition:

The HCP MRI data acquisition has previously been described in detail (Glasser et al., 2013; Smith et al., 2013; Uğurbil et al., 2013). Images were acquired using a customized 3T Siemens ‘Connectom’ Skyra scanner having a 100 mT/m SC72 gradient insert and a standard Siemens 32-channel RF-receive head coil. At least one 3D T1w MPRAGE image and one 3D T2w SPACE image were acquired at 0.7 mm isotropic resolution. Whole-brain resting-state fMRI and task fMRI data were acquired using multi-band EPI sequence with parameters of TR=720 ms, 2 mm isotropic voxels, and multi-band acceleration factor of 8. Spin echo field maps were acquired during both structural and fMRI scanning sessions to enable accurate cross-modal registration of structural and functional images in each subject.

Task paradigm:

Functional data in this study were based on the HCP language processing and the HCP social cognition (theory of mind) tasks (Barch et al., 2013).

The language task consisted of two runs (run duration = 3:57 min:sec). In each run, 4 blocks of a story task were interleaved with 4 blocks of a math task. The lengths of blocks varied, and the average

duration of blocks was approximately 30 s. In the story blocks, participants were presented with brief auditory stories (5–9 sentences) adapted from Aesop’s fables, followed by a 2-alternative forced-choice question that asked participants about the topic of the story. For example, after a story about an eagle that saves a man who had done him a favor, participants were asked “That was about *revenge* or *reciprocity*?” Participants pressed a button to select either the first or the second choice. The math task also included trials that were presented auditorily. In these trials, participants completed a series of simple arithmetic (addition and subtraction) operations (e.g., “Fourteen plus twelve”), followed by “equals” and then two choices (e.g., “twenty-nine or twenty-six”). Participants pressed a button to select either the first or the second answer. The math task was adaptive to maintain a similar level of difficulty across participants.

In the social task, participants were presented with short video clips (20 s) of objects (squares, circles, triangles) either interacting in some way or moving randomly. After each video clip, participants were required to choose between 3 possibilities: a social/mental interaction (an interaction that appears as if the shapes are taking into account each other’s feelings and thoughts), not sure, or no interaction (i.e., there is no obvious interaction between the shapes, and the movement appears to be random). The social task consisted of two runs (run duration = 3:27 min:sec). Each run contained 5 video blocks (2 Social and 3 Random in one run, 3 Social and 2 Random in the other run) and 5 fixation blocks (15 s each).

The stimuli used in the social task had some low-level retinotopic differences, which could result in differential activations in early visual cortex. To test this possibility, we examined the root mean square (RMS) contrast of images in four quadrants of visual field. We found differences between quadrants (**Supplementary Figure 9**), which could potentially explain the apparent asymmetry patterns seen in early visual cortex of the social asymmetry map (**Figure 1f**). Thus, these patterns do not appear to be related to a genuine functional asymmetry for social processing.

Data analysis software:

Data were preprocessed and analyzed using the publicly released HCP pipelines ([Glasser et al., 2013](#)). The software packages used for analysis included Connectome Workbench commandline tools, FreeSurfer, and FSL ([Fischl, 2012](#); [Jenkinson et al., 2012](#)). Connectome Workbench ‘wb_view’ GUI

(<http://www.humanconnectome.org/software/connectome-workbench.html>) was used for visualization of maps. The analyzed data were imported to Matlab for further computations.

Analysis of structural data:

Structural images (T1w and T2w) were used for extracting subcortical gray matter structures and reconstructing cortical surfaces in each subject. Volume data were transformed from native space into MNI space using a nonlinear volume-based registration. For accurate cross-subject registration of cortical surfaces, a multimodal surface matching (MSM) algorithm (Robinson et al., 2014) was used. The MSM algorithm had two versions: ‘MSMSulc’ (non-rigid surface alignment based on folding patterns) and ‘MSMAll’ (optimized alignment of cortical areas using sulcal depth maps plus features from other modalities including myelin maps, resting-state network maps, and visuotopic connectivity maps). Data in our work were based on MSMAll registration. After surface and volume registration, cortical vertices were combined with subcortical gray matter voxels to form the standard ‘CIFTI grayordinates’ space (91,282 vertices/voxels with ~ 2 mm cortical vertex spacing and 2 mm isotropic subcortical voxels) (Glasser et al., 2016).

Analysis of fMRI data:

Functional images were minimally preprocessed using the HCP pipeline (Glasser et al., 2013). Preprocessing included correction for spatial distortions due to gradient nonlinearity and b0 field inhomogeneity, fieldmap-based unwarping of EPI images, motion correction, brain-boundary-based registration of EPI to structural T1w scans, non-linear registration to MNI space, and grand-mean intensity normalization. Data from the cortical gray matter ribbon were projected onto the surface and then onto the standard grayordinates space. Data were minimally smoothed by a 2mm FWHM Gaussian kernel in the grayordinates space. Thus, smoothing was constrained to the cortical surface mesh in each hemisphere. Data were cleaned up for artifacts and structured noise using ICA+FIX.

The preprocessed functional time-series were entered into a general linear model (GLM) to estimate functional activities in each vertex/voxel in each run (Barch et al., 2013). Two regressors/predictors were included in the GLM design of the language task – Story and Math. Each predictor covered the duration of a block (~ 30 s). Two regressors/predictors were included in the GLM design of the social

task – Social and Random. Each predictor covered the duration of a single video clip (20 s). All regressors were convolved with a canonical hemodynamic response function and its temporal derivatives. The time-series were temporally filtered with a Gaussian-weighted linear highpass filter with a cutoff of 200 s, to remove low-frequency drifts/fluctuations presumably unrelated to the task design. The time-series were also prewhitened to remove temporal autocorrelations in the fMRI signal. For three comparisons ('story vs. baseline', 'story vs. math', and 'social vs. random'), the contrast of parameter estimate (COPE) was computed based on beta values of the GLM. The language task did not have typical fixation blocks (there was only an 8-second 'get ready' countdown at the beginning of the run), and the baseline condition in this task represented the mean activity across all time-points in each run. Fixed-effects analyses were conducted to estimate the average effects across runs within each subject, then mixed-effects analyses treating subjects as random effects were conducted to obtain group-average maps. The group-average maps were Cohen's d effect size maps. Cohen's d in each vertex/voxel was computed as the mean COPE (across subjects) divided by the standard deviation.

Data/Code availability:

All data used in this manuscript are part of publicly available and anonymized HCP database (<https://www.humanconnectome.org>). All analysis codes are available for sharing upon request.

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Supplementary Figure Captions:

Supplementary Figure 1: Thresholded activation map in the language task.

For thresholding, vertices with positive Cohen's d values were first selected, then the mean value across these vertices was used as the threshold. After binarizing, a multi-modal parcellation of cerebral cortex (15) was overlaid on the thresholded map to identify the auditory cortex (low-level and high-level auditory regions), divide the superior temporal region, and name activated language areas. The multi-modal parcellation contained 180 parcels/areas in each hemisphere.

Supplementary Figure 2: The language network localized based on 'story vs. baseline' and 'story vs. math' contrasts.

The group-average activation maps are displayed on a 2-D flat patch of LH. Black and green borders correspond to auditory cortex and language areas, respectively.

Supplementary Figure 3: Quantification of lateralization effects in subjects with strong language activations in RH.

For each subject and each task, functional asymmetry values were averaged across vertices in each area. Data were then averaged across subjects. Error bars indicate one standard error of the mean across subjects. Mean asymmetry values were not significantly different from zero in all areas for the social task, and in PSL for the language task (FDR-adjusted $p > 0.05$; t-test).

Supplementary Figure 4: Relationship between hemispheric lateralization of language and social processing in right-handed and left-handed subjects.

The scatter plots demonstrate the functional asymmetry values of right-handed and left-handed subjects in eight language areas. Handedness was defined based on the Edinburgh Handedness Inventory (EHI). 947 subjects were right-handers ($EHI > 0$), 94 subjects were left-handers ($EHI < 0$), and 3 subjects were ambidexters ($EHI = 0$; excluded from plots).

Supplementary Figure 5: Relationship between hemispheric lateralization and behavior.

Two language tests were used for assessing the linguistic abilities of subjects. In the vocabulary comprehension test, subjects were presented with an audio recording of a word and they had to select the picture that best matched the meaning of the word. In the reading recognition test, subjects were

asked to read and pronounce words as accurately as possible. For each subject, the age-adjusted scores in the two tests were z-normalized and averaged. Based on average scores, we selected two groups of subjects who either had high score (one SD above mean, $n = 152$) or low score (one SD below mean, $n = 174$). Similarly, two groups of subjects were selected based on accuracy in the social task (high-accuracy group: $n = 430$, low-accuracy group: $n = 259$). Since accuracy did not have a normal distribution ($p < 0.05$, Kolmogorov-Smirnov normality test), we used median $\pm$ median absolute deviation as cutoff points. The bar plots in panels a-b demonstrate the functional asymmetry values for two groups of subjects in eight language areas. In each area, the statistical comparison was based on two-sample t-test (*: uncorrected $p < 0.05$ in panel a, FDR-adjusted $p < 0.05$ in panel b). Error bars indicate one standard error of the mean across subjects.

Supplementary Figure 6: Lateralization effects in 180 cortical areas/parcels of multi-modal parcellation. Parcels were sorted based on the magnitude of laterality effect (the absolute value of LH - RH activation) in the language task. 25 parcels with the highest values were selected based on the elbow point in the plot. The elbow point was determined by the procedure of fitting two regression lines. The selected parcels were used as ROIs in the subsequent analyses. Error bars indicate one standard error of the mean across subjects.

Supplementary Figure 7: Location and response profile of non-language ROIs which showed strong lateralization effects.

(a) The location of ROIs (black borders) with respect to twelve resting-state networks (Ji et al., 2019). The language network largely overlapped with our functionally defined language areas (green borders).
(b) Responses of LH ROIs in the 'story vs. baseline' and 'math vs. baseline' contrasts of the language task. Error bars indicate one standard error of the mean across subjects. In p47r and IFSa, responses were significantly higher in the math condition compared to the story condition (FDR-adjusted $p < 0.0005$; paired t-test). In other ROIs, responses were significantly higher in the story condition compared to the math condition (FDR-adjusted $p < 0.0005$; paired t-test).

Supplementary Figure 8: Relationship between hemispheric lateralization of language and social processing in individual ROIs outside language-auditory network.

The scatter plots demonstrate the functional asymmetry values in eight ROIs. ROIs are ordered based on Pearson r correlation coefficient values. In 7 (out of 8) ROIs, there was a significant positive correlation between lateralization effects in language and social tasks.

Supplementary Figure 9: Image-based analysis of social and random stimuli, and their estimated activation patterns in early visual cortex.

(a) Example frames of social and random movies used in the social task. The stimulus set included two versions of movie stimuli. (b) For each frame, the RMS contrast was calculated in four quadrants of the visual field, then the values were averaged across all frames and all movies. Since we used the 'social-vs-random' comparison in the fMRI experiment, here we also computed the difference between the contrast values of social and random movies. Each quadrant of visual field was color-coded based on the difference values (LVF: left visual field, RVF: right visual field). (c) Schematic maps demonstrating the cortical representation of the resulting image in early visual cortex (V1/V2/V3/V4) (LVF -> RH, RVF -> LH, upper visual field -> ventral occipital cortex, lower visual field -> dorsal occipital cortex). (d) The RH map was subtracted from the LH map to obtain an asymmetry map. This estimated asymmetry map resembled the actual asymmetry map from the fMRI experiment.

Figure 1

Figure 2

Figure 3

Figure 4

Supplementary Figure 2

Story vs. Baseline

Story vs. Math

Supplementary Figure 3

Supplementary Figure 4

Right-handed subjects

Left-handed subjects

Supplementary Figure 5

a

b

Supplementary Figure 6

Supplementary Figure 7

a ROIs outside language-auditory network

b

Supplementary Figure 8

Supplementary Figure 9