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Review article

The language network as a natural kind within the broader landscape of the human brain

In the format provided by the authors and unedited

Supplementary Information for Fedorenko, Ivanova, and Regev

Supplementary Methods

SM1. Schematic representations of the anatomical locations of functional areas in Figures 1, 4, and 5.

All brain areas were drawn manually on the brain's lateral and/or medial surface and, as we specify in the captions, are meant to schematically represent the average anatomical locations. The precise locations of all of these functional areas vary across individuals (**Box 1**).

The functional areas/networks that we discuss include the following:

i) The language network (Figures 1, 4, 5)
ii) The speech perception area (Figures 1, 4)
iii) The articulatory motor planning area (Broca's area) (Figures 1, 4)
iv) The multiple demand network (Figures 1, 5)
v) The theory of mind network (Figures 1, 5)
vi) The default mode network (Figures 1, 5)
vii) The visual word-form area (VWFA) (Figure 4)
viii) The writing motor planning area (putative Exner's area) (Figure 4)
ix) The primary sensory areas (A1 and V1) (Figure 4)
x) The primary motor areas (different parts of M1) (Figure 4)

For i-vii, the areas were drawn based on visualizations of individual-level activation maps as well as group-level maps / probabilistic overlap maps for contrasts that robustly identify the relevant area/network (see **Figure 4C** for sample contrasts). In particular, to estimate the location for the ***language network***, we used visualizations in Lipkin et al. (2022); to estimate the location for the ***speech perception area***, we used visualizations in Norman-Haignere et al. (2015) and Overath et al. (2015); to estimate the location of ***Broca's area***, we used visualizations in Flinker et al. (2015) and Long et al. (2016); to estimate the location of the ***multiple demand network***, we used visualizations in Duncan (2013), Fedorenko et al. (2013) and Assem et al. (2020); to estimate the locations of the ***theory of mind network*** and the ***default mode network***, we used visualizations in Braga & Buckner (2017), Buckner & DiNicola (2019), and Braga et al. (2020). To estimate the location of the ***visual word-form area (VWFA)***, we used visualizations in Baker et al. (2007), Saygin et al. (2016), and Li et al. (2023). For viii, the ***putative Exner's area***, the location was estimated based on the anatomical description and figures in Roux et al. (2009, 2010). For ix, the ***primary sensory areas***, the locations were estimated using basic knowledge of functional anatomy. Finally, for x, the ***primary motor areas***, the locations were estimated based on Bouchard et al. (2013) for the oral-motor control areas and based on Gordon et al. (2023) for the finger/hand control area.

SM2. Extended caption for Figure 2.

Figure 2A. As described in Lipkin et al. (2022), to create the probabilistic activation overlap map, we selected for each individual the top 10% of language-responsive voxels across the brain; then, we binarized the individual maps and overlaid them averaging the value in each voxel such that the resulting values correspond to the proportion of the participant set for whom that voxel belongs to the top 10% most language-responsive voxels. We here show the activations restricted to the canonical frontal and temporal areas (see Lipkin et al., 2022 for the visualization of the full map, which can also be downloaded from: https://figshare.com/articles/dataset/LanADataset/20425209). The visualization was created with the Nilearn software (https://nilearn.github.io/stable/index.html) using the plot_img_on_surf function and the fsaverage template brain (graphing parameters: *threshold* (for the probability value) = 0.2 (only including voxels that belong to the Language network, as defined above (i.e., belong to the top 10% of most language-responsive voxels across the brain), in at least 20% of participants; *colormap upper bound* = 1).

Figure 2B. The activation t-maps for the four participants (and all other participants that comprise the probabilistic map shown in A) can be downloaded here: https://figshare.com/articles/dataset/LanADataset/20425209. (The EvLab unique IDs (UIDs) of the four participants are as follows: P1=048; P2=128; P3=172; P4=142.) The visualizations were created from the participants' t-maps with the Nilearn software (https://nilearn.github.io/stable/index.html) using the plot_img_on_surf function and the fsaverage template brain (graphing parameters: *threshold* (for the t-value) = 3.09 (which corresponds to a significance value of $p<0.001$; voxels with negative t values were not included); *colormap upper bound* = 10).

Figure 2C. The activation t-maps can be downloaded here: https://doi.org/10.6084/m9.figshare.22183564 (as part of the nii.zip file; this FigShare resource is an online supplement to Mahowald & Fedorenko, 2016, created to release the data published in the 2016 article, along with additional data). (The EvLab unique IDs (UIDs) of the participants are 007 and 163, and the data for both were included in Mahowald & Fedorenko, 2016.) The visualizations were created from the participants' t-maps with the Nilearn software (https://nilearn.github.io/stable/index.html) using the same parameters as in Figure 2B.

For Figures 2A-C, the black outlines correspond to 'parcels', which are derived from a probabilistic overlap map (as described in Fedorenko et al., 2010) for 220 participants and which have been used in many prior studies (e.g., Shain, Blank et al., 2020; Diachek, Blank, Siegelman et al., 2020; Fedorenko et al., 2020; Ivanova et al., 2020; Jouravlev et al., 2020; Malik-Moraleda, Ayyash et al., 2022 *inter alia*). These parcels denote brain areas within which the majority of individuals show responses to language, and they are used to constrain the selection of language ROIs in individual participants. In particular, each individual activation map for the language localizer contrast (like those shown in Figure 2B) is intersected with these parcels, and voxels that respond to the localizer contrast within each parcel are selected. The parcels are available at https://osf.io/4tdcx/. To create the parcel boundaries (shown in Figures 2A-C), the parcel binary mask file was projected onto the surface of the fsaverage template brain and the outline of each parcel was manually traced.

Figure 2D. The data come from 14 fMRI experiments (between 1 and 4 conditions are included from each experiment) that were conducted in the Fedorenko lab and whose results have been published. All the data were preprocessed and modeled in the same Fedorenko lab pipeline (see e.g., Shain, Paunov, Chen et al., 2022). The language fROIs were defined in each individual participant by selecting the top 10% of localizer-responsive voxels within each of the five parcels (a reading-based localizer was used for these experiments), and the responses to the critical condition were extracted from these localizer-defined voxels and averaged within each of the five parcels, and then averaged across the five parcels to derive a single value per participant per condition. To estimate the response to the visual sentence comprehension condition, which is used in the language localizer, the data were divided in half, and the fROIs were defined using one half of the data and the responses were estimated in the other half of the data, ensuring independence. A table that contains both the meta data (brief description of each condition, number of participants, reference to the study from which the condition(s) came, etc.) and the values for the means and standard errors of the mean, which were used for plotting, are available at https://osf.io/4tdcx/ (see file FedIvReg_SuppTable1_forFig2D.xlsx; the data for the individual participants and fROIs and, in some cases, the activation maps are available on the OSF, or similar, pages that are linked from each paper). Similarly, a full set of references for the studies from which the data came is available at https://osf.io/4tdcx/ (see file FedIvReg_SuppTables1and2_References.docx).

For completeness, we also include below Supplementary Figure 1, which shows an extended set of non-linguistic conditions and complements Figure 2D.

The data for Supp. Figure 1 come from 25 fMRI experiments (between 1 and 7 conditions are included from each experiment) that were conducted in the Fedorenko lab (between 2007 and 2022) and whose results have been published. All the data were preprocessed and modeled in the same Fedorenko lab pipeline (see e.g., Shain, Paunov, Chen et al., 2022). As in Figure 2D, the language fROIs were defined in each individual participant by selecting the top 10% of localizer-responsive voxels within each of the five parcels (a reading-based localizer was used for these experiments), and the responses to the critical condition were extracted from these localizer-defined voxels and averaged within each of the five parcels, and then averaged across the five parcels to derive a single value per participant per condition. A table that contains both the meta data (brief description of each condition, number of participants, reference to the study from which the condition(s) came, etc.) and the values for the means and standard errors of the mean, which were used for plotting, are available at https://osf.io/4tdcx/ (see file FedIvReg_SuppFig1_metadata.xlsx; the data for the individual participants and fROIs and, in some cases, the activation maps are available on the OSF, or similar, pages that are linked from each paper).

SM3. Extended caption for Figure 3.

Figure 3A-B. The data come from 3 fMRI experiments (2, 6, and 3 conditions are included from each experiment) that were conducted in the Fedorenko lab and whose results have been published or preprinted. The data for conditions 3 through 11) were preprocessed and modeled in the same Fedorenko lab pipeline (see e.g., Shain, Paunov, Chen et al., 2022); the data for conditions 1 and 2 were preprocessed and modeled in a slightly different pipeline (as described in Jacoby & Fedorenko, 2020). (This difference means that the magnitudes are not directly comparable between conditions 1-2 and conditions 3-11, but this comparison is not relevant to the points we are making, which focus on within-experiment between-condition comparisons.) The language fROIs were defined in each individual participant by selecting the top 10% of localizer-responsive voxels within each of the five parcels (a reading-based localizer was used for these experiments), and the responses to the critical condition were extracted from these localizer-defined voxels and averaged within each of the five parcels (results in 3A), and then averaged across the five parcels to derive a single value per participant per condition (results in 3B). A table that contains both the meta data (brief description of each condition, number of participants, reference to the study from which the condition(s) came, etc.) and the values for the means and standard errors of the mean, which were used for plotting, are available at https://osf.io/4tdcx/ (see file FedIvReg_SuppTable2_forFig3AB.xlsx; the data for the individual participants and fROIs and, in some cases, the activation maps are available on the OSF, or similar, pages that are linked from each paper/preprint). Similarly, a full set of references for the studies from which the data came is available at https://osf.io/4tdcx/ (see file FedIvReg_SuppTables1and2_References.docx).

Figure 3C. The figure comes directly from Tuckute et al. (2024), where it appears as Figure 4B.

SM4. Extended caption for Figure 4.

Figure 4B. As noted in the main caption, all profiles are schematic but based on data in published studies (importantly, as noted in the text, we are drawing on studies where the relevant areas were functionally localized; cf. using anatomical definitions). Here we provide details on papers that support these profiles. This is not meant to be a comprehensive list of relevant papers, only examples.

The ***language network***:

i) The *Sentences* > *Word-lists* > *Nonword-lists* profile has been reported in Fedorenko et al. (2010), in Blank et al. (2016), and in an intracranial investigation (Fedorenko et al., 2016). The *Sentences* > *Word-lists/Words* effect has additionally been reported (across many experiments) in a meta-analysis by Diachek, Blank, Siegelman et al. (2020) (see also Snijders et al., 2009 and Pallier et al., 2011 for data from other labs). The *Sentences* > *Nonword-lists* effect has additionally been reported across dozens of papers from the Fedorenko lab, including a large-scale investigation with several hundred participants (Lipkin et al., 2022).

ii) Selectivity for language relative to non-linguistic conditions has been reported in multiple studies in the Fedorenko lab and several other labs (see main text for references and discussion).

The ***speech perception area***: Both i) similar responses to auditorily-presented structured and meaningful stimuli (Sentences) and unstructured and/or meaningless stimuli (similar to Nonword-lists, but specifically, speech in an unfamiliar foreign language was used) and ii) selectivity for speech relative to other auditory stimuli (e.g., animal vocalizations, mechanical noises, music, etc.) have been reported in Norman-Haignere et al. (2015) and Boebinger et al. (2021) (see also Deen et al., 2015 for related data, although the speech perception area is defined with a slightly different contrast, which includes not only speech, but non-speech vocalizations, like laughter).

The ***visual word-form area (VWFA)***:

i) Similar responses to visually-presented meaningful stimuli (Words) and meaningless stimuli (similar to Nonwords, but specifically, consonant strings were used) have been reported in Baker et al. (2007) and Hamame et al. (2013).

ii) Selectivity for visual words relative to other visual stimuli (e.g., faces, objects, etc.) has been reported in Baker et al. (2007), Hamame et al. (2013), and Li et al. (2023).

Broca's area: Both i) strong responses during the planning of meaningless speech (Nonwords and similar stimuli, like syllable sequences), and ii) selectivity for speech vs. non-speech oral-motor (and hand-motor) movements have been reported in Fedorenko et al. (2015) and Basilakos et al. (2018) (see Wolna et al., 2023 for a profile with a wider range of conditions).

Putative Exner's area: No data for this region (functionally defined) is available, so this region's profile is speculative, motivated by the profiles of Broca's area and the specialized perceptual areas.

Primary sensory and motor areas: Primary sensory regions are well-established to respond to diverse visual (V1) and auditory (A1) stimuli. Different parts of the primary motor cortex are well-established to respond during the production of diverse motor movements for the relevant effector.

SM5. Extended caption for Figure 5.

As noted in the main caption, all profiles are schematic but based on data in published studies (importantly, as noted in the text, we are mostly drawing on studies where the relevant areas were functionally localized; cf. using anatomical definitions). Here we provide details on papers that support these profiles. This is not meant to be a comprehensive list of relevant papers, only examples.

The ***language network*** (top-row profiles): Selectivity for language relative to non-linguistic conditions has been reported in multiple studies in the Fedorenko lab and several other labs (see main text for references and discussion).

The profiles in the bottom row come from three high-level cognitive networks:

The ***multiple demand network***:

i) The lack of response during language processing (unaccompanied by external task demands) has been reported in Diachek, Blank, Siegelman et al. (2020) and Malik-Moraleda, Ayyash et al. (2022).

ii) A similarly strong response to demanding problems presented linguistically vs. non-linguistically has been reported in Fedorenko et al. (2013) (verbal vs. non-verbal working memory) and Amalric et al. (2019) (math problems presented in words vs. using math notation).

The ***theory of mind network***:

i) The lack of response during language processing where the content does not have to do with mental states has been reported in Saxe & Kanwisher (2003), Saxe & Powell (2006), and Deen et al. (2015).

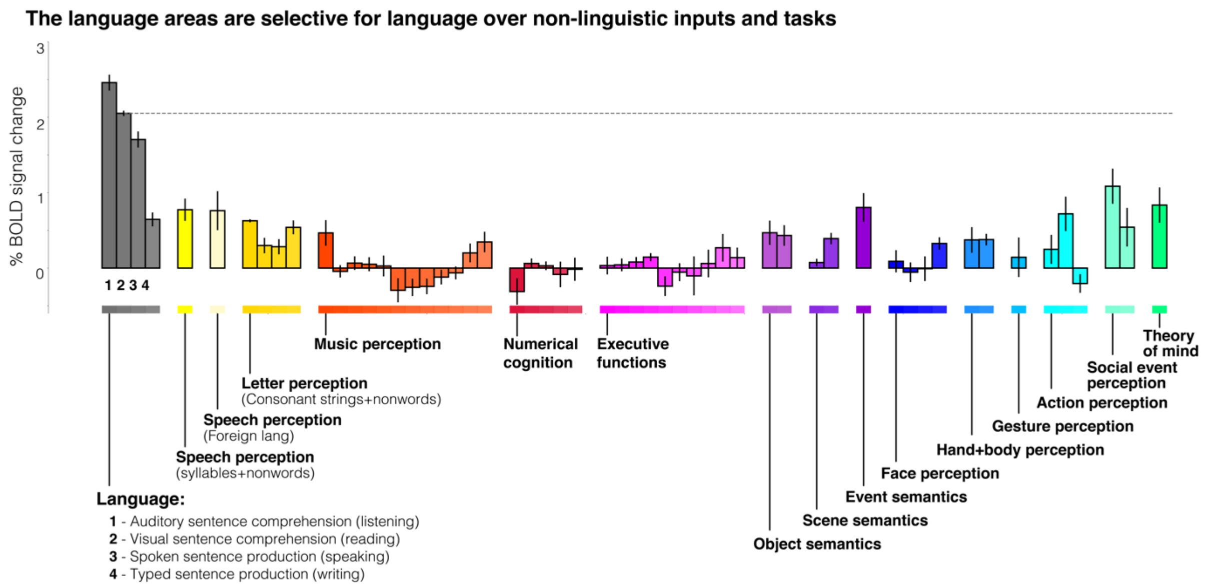
ii) A similarly strong response to mental state content presented linguistically vs. non-linguistically has been reported in Jacoby et al. (2016), Paunov et al. (2022), and Shain, Paunov, Chen et al. (2022).

The ***default mode network***:

i) The lack of response during the processing of isolated sentences has been reported in Mineroff, Blank et al. (2018).

ii) A strong response to extended narratives presented linguistically vs. non-linguistically has been reported in Baldassano et al. (2017, 2018).

Supplementary Figures



Supplementary Figure 1 - The selectivity of the language network for language over non-linguistic inputs and tasks for an extended set of non-linguistic conditions. Responses, as measured with fMRI, in the language network during language processing (grey bars) and diverse non-linguistic inputs and tasks (color bars). Error bars represent standard error of the mean by participants. The dashed horizontal line is drawn from the reading-based language localizer, for which we have the most data (among the language conditions), to facilitate the comparisons with non-linguistic conditions. As can be seen, the Language network is strongly selective for language processing over diverse non-linguistic stimuli and tasks.

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