
Review Articles and Meta-Analyses

Converging evidence of the impact of bilingualism on the brain's pragmatic language network

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Pragmatic language—the ability to understand and use language in social contexts—is a complex linguistic skill critical for effective social interactions. It involves interpreting indirect requests, figurative language, and relies on integrating linguistic, social, and contextual cues. While pragmatic language difficulties are common in neurodevelopmental disorders such as autism, emerging research suggests that bilingualism may enhance cognitive and social skills relevant to pragmatic competence. However, the neural mechanisms of bilingualism, and its influence on pragmatic language remain poorly understood. To address this, we conducted a multi-method investigation integrating a PRISMA-guided systematic review, meta-analyses using the open database Neurosynth, and an empirical analysis of the open neuroimaging data, OpenNeuro. The Neurosynth meta-analyses on the terms “communication,” “social cognition,” and “bilinguals”, identified consistent involvement of the bilateral insula, left inferior frontal gyrus (IFG), fusiform gyrus, and posterior cingulate cortex. An analysis of resting-state fMRI data from early bilinguals, late bilinguals, and monolinguals using OpenNeuro revealed early bilinguals showing decreased functional connectivity within core pragmatic language regions, including IFG, superior and middle temporal gyrus, and supramarginal gyrus, suggesting enhanced neural efficiency derived from dual-language management. These findings provide evidence that bilingualism may reshape the neural architecture underlying pragmatic language comprehension. By highlighting how language experience influences brain networks involved in social communication, this work has implications for both cognitive neuroscience and interventions targeting pragmatic deficits, particularly in clinical populations such as individuals with autism.

INTRODUCTION

Humans are social animals with a deep-seated need to form relationships and gain acceptance within social groups.¹ This need for connection drives the formation and maintenance of relationships, which is facilitated by language, especially pragmatic language, which serves as a powerful tool for communication.² Pragmatic language encompasses the use and comprehension of language within social contexts.³ It involves the use of speech acts and figurative language, such as metaphors, sarcasm, puns, idioms, and

irony.⁴ While neurotypical (NT) individuals may encounter difficulties in understanding pragmatic language, such challenges are especially pronounced in individuals with neurodevelopmental conditions, such as autism spectrum disorder,^{5,6} in which deficits in social communication are a hallmark feature.⁷

A growing body of behavioral research has investigated the potential impact of bilingualism on pragmatic language skills, resulting in mixed findings. While some studies report null effects,⁸⁻¹⁰ others suggest that early bilingual exposure, especially before the age of one, may facilitate so-

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cial-cognitive development and pragmatic competence.¹¹ Bilingualism may also confer broader cognitive advantages, such as enhanced working memory and inhibitory control.^{12,13} Furthermore, it has been found that bilinguals may outperform monolinguals on tasks that require high attention demands; they were also found to require less attentional effort.^{3,14} Although the evidence remains preliminary, these findings raise the possibility that bilingualism could positively influence pragmatic language competence through its impact on underlying cognitive processes.¹¹ Bilinguals who live in linguistically diverse geographical areas have been shown to rate ironic statements as more appropriate, suggesting the pragmatic comprehension of irony.¹⁵ There is also suggestion in the current literature that bilingualism may be a benefit to autistic children in the context of the syntax-pragmatics interface.¹⁶ Despite these behavioral insights, relatively little is known about the neural mechanisms through which bilingualism may influence pragmatic language. To date, only a few neuroimaging studies have addressed differences in brain activation patterns between monolingual and bilingual individuals.¹⁷⁻¹⁹

Traditional models of language lateralization emphasize the role of left-hemispheric perisylvian network (BA 44, 45, 47, 21, 22).²⁰ However, the comprehension of higher-order pragmatic content, such as figurative and context-dependent language, recruits a more distributed and bilateral network. This pragmatic network included key regions in both hemispheres, such as the inferior frontal gyrus (IFG), right temporoparietal junction (TPJ), and medial prefrontal cortex (MPFC).²¹⁻²⁴ The coarse coding semantic theory suggests that the right hemisphere supports the integration of distantly related concepts,²⁵ a process critical for interpreting figurative language. Frontal-parietal regions such as the supramarginal gyrus (SMG) further contribute to the integration of semantic and contextual cues during pragmatic comprehension.²⁴ Emerging evidence suggests that bilingualism may modulate the recruitment and functional connectivity of these areas,¹⁷⁻¹⁹ potentially via enhanced neural efficiency derived from managing multiple linguistic systems. However, the functional architecture of pragmatic language networks in bilinguals remains underexplored.

The present study aims to examine how bilingualism affects the neural organization of pragmatic language using fMRI data. We adopt a multipronged approach that combines a systematic review of literature, large-scale meta-analyses via the platform Neurosynth, and resting-state functional connectivity analyses of publicly available datasets. We hypothesize that bilingual experience modulates the neural architecture supporting pragmatic comprehension. Specifically, we predict that bilingual individuals will exhibit reduced functional connectivity within core pragmatic neural regions, compared to monolinguals, reflecting greater neural efficiency. This neural efficiency may arise from bilinguals' lifelong experience in managing multiple linguistic systems, which could facilitate more efficient selection and integration of contextually appropriate meanings during pragmatic tasks.

Given that over half of the global population uses more than one language regularly,²⁵ clarifying how the bilingual experience shapes pragmatic processing is of broader scientific and societal interest. Furthermore, given the critical role of pragmatic competence in social communication, and the particular challenges faced by autistic individuals, understanding how bilingualism shapes pragmatic language networks have important implications not only for cognitive neuroscience but also translational science. By elucidating the neurocognitive mechanisms through which bilingualism influences pragmatic language, this study seeks to bridge current gaps in the literature and provide new insights into the dynamic interplay between language experience, brain function, and social communication.

METHODS

This study is organized into three main sections: 1) a systematic review of task-based fMRI studies investigating the effects of bilingualism on pragmatic language processing; 2) meta-analyses using Neurosynth (a platform for large scale, automated synthesis of functional neuroimaging data) to further explore the neural correlates of pragmatic processing; and 3) an empirical analysis of resting-state fMRI data to assess functional connectivity within the pragmatic language network in bilingual individuals using open-access data from the OpenNeuro repository (National Institute of Health's BRAIN initiative designated data archive).

SYSTEMATIC REVIEW: TASK-FMRI

The literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.²⁶ On May 6th, 2025, a comprehensive search was conducted across three databases: Web of Science, PubMed, and PsycINFO. The search strategy combined three thematic keyword sets: (1) terms related to pragmatic language, (2) terms referring to fMRI, and (3) terms identifying the target population. To identify relevant literature on the topic of pragmatics, a total of 17 keywords were selected. The following keywords were used in the search: "speech acts," "indirect request," "direct request," "indirect reply," "direct reply," metaphor, idiomatic, idioms, irony, sarcasm, puns, jokes, lies, metonymy, pragmatics, deceit, and prosody. Two keywords were employed for fMRI studies: "fMRI" and "functional magnetic." Regarding the group: "biling*" were utilized. The aforementioned topics of keywords were combined using the "AND" operator and searched in the section "keywords and abstract." The search term was constructed as follows: ((TS=("speech acts")) AND TS=("fMRI")) AND TS=(biling*). A total of 51 combinations of keywords were searched in each database (153 searches). The following criteria were used to select articles for inclusion in the study: the articles were required to examine pragmatic language, utilize task-fMRI, and include a group of bilingual participants. Articles were excluded if they did not report results from the effect of bilingualism on the brain.

Table 1. Demographic information from the OpenNeuro data.

	Early Bilingual (n = 27)	Late Bilingual (n = 32)	Monolingual (n = 33)	p-value
Sex	18 F, 9 M	14 F, 18 M	19 F, 14 M	0.20
Age	22.59 (19-29)	22.00 (21-28)	20.70 (18-26)	0.009
Ethnicity				< 0.0001
Hispanic/Latino	68%	3%	0%	
Hispanic/Latino and White	26%	0%	0%	
White	6%	94%	100%	
Asian	0%	3%	0%	

Group differences were assessed using ANOVA for age, and chi-squared tests for sex and ethnicity.

This systematic review revealed a dearth of task-based fMRI studies specifically examining pragmatic language processing in bilingual individuals ($n = 3$); in the absence of resting-state fMRI studies ($n = 0$), we conducted complementary meta-analyses to identify brain regions consistently implicated in pragmatic language processing in bilinguals.

META-ANALYSES: NEUROSYNTH

These meta-analyses were performed using Neurosynth,²⁷ a platform that automatically synthesizes the results across numerous neuroimaging studies. Since Neurosynth lacked a term specifically for pragmatics, the meta-analyses were conducted using two closely related terms: “communication” (271 studies with 9,047 activations) and “social cognition” (220 studies with 8,247 activations). To assess the effect of bilingualism, the term “bilinguals” (77 studies with 3,081 activations) was also included. Uniformity maps were extracted for each of the selected terms, displaying brain regions that are consistently active in studies associated with those terms. These maps were corrected using a false discovery rate (FDR) threshold of 0.01.²⁸

Together, the systematic review and Neurosynth meta-analyses provided a comprehensive framework for identifying brain regions consistently implicated in pragmatic language and bilingualism. While the systematic review confirmed the scarcity of task-based fMRI studies directly addressing pragmatic language in bilinguals, the complementary Neurosynth analyses leveraged large-scale data to capture regions associated with closely related domains (communication, social cognition) and bilingualism. These converging steps guided the selection of Regions of Interest (ROIs) that formed the basis for the subsequent functional connectivity analyses.

FUNCTIONAL CONNECTIVITY IN THE PRAGMATIC NETWORK: RESTING FMRI

PARTICIPANTS

The bilingual sample was obtained from an open-access dataset available on OpenNeuro²⁹ and included 92 adult participants distributed across three groups (early bilin-

gual, late bilingual, and monolingual). The early bilingual group comprised individuals who began on acquiring a second language at or before the age of ten. The late bilingual group included those whose second language exposure began after age 14. The monolingual group consisted of individuals who reported some foreign language exposure but rated their proficiency in the “Novice” range. For demographic information, see [Table 1](#); for additional methodological details see Gold et al., 2023).²⁹

MRI data was acquired on a 3T Siemens TIM Trio scanner using a 32-channel head coil (see Gold et al., 2023,²⁹ for additional acquisition details). Preprocessing was conducted using the CONN Toolbox (v22.a) in conjunction with SPM12²⁹. Functional and anatomical images underwent standard preprocessing steps, including realignment and unwarping, slice-timing correction, outlier detection, tissue segmentation, normalization to MNI space, and spatial smoothing with a 6 mm full-width at half maximum (FWHM) Gaussian kernel.

REGIONS OF INTEREST

ROIs for the functional connectivity analysis of the pragmatic language network were selected based on the results of the meta-analyses described in previous sections. To ensure comprehensive coverage of the network, we also included regions identified in prior meta-analyses on pragmatic language processing.^{23,25} All selected ROIs were mapped to their corresponding homologous areas using the Harvard-Oxford Cortical and Subcortical Structural Atlas. In total, 33 ROIs were included in the analysis (see Supplementary Figure 1).

FUNCTIONAL CONNECTIVITY ANALYSIS

The following steps were conducted using CONN Toolbox (v22.a) and SPM12.³⁰ Functional and anatomical data were preprocessed using a flexible preprocessing pipeline³¹ including realignment with correction of susceptibility distortion interactions, slice timing correction, outlier detection, direct segmentation and MNI-space normalization, and smoothing. Outliers were flagged using ART⁹ based on framewise displacement of > 0.9 mm or global signal de-

Table 2. Articles included in the systematic review.

Article	Language	Pragmatic form	Bilingual		Monolingual		Stimuli modality
			n	age	n	age	
Sulpizio, S., et al. 2019	Italian and English	Socio-pragmatic knowledge	22 (13 F)	23.23 ± 2.41	22 (12 F)	23.5 ± 3.58	Written words
Citron et al. 2020	German and Italian	Metaphors	22 (19 F)	26 ± 5	25 (15 F)	26 ± 4	Written sentences
Yin, C. & Yang, F. 2022	Mandarin and English	Metaphors and Metonym	17 (12 F)	27.11 ± 4.56	N/A	N/A	Written sentences

viations of > 5 SD.^{32,33} Functional data were denoised using standard pipeline³⁴: regression of confounding signals (5 CompCor components each from white matter and CSF, 12 motion parameters, session effects, and linear trends), followed by bandpass filtering (0.01–0.1 Hz).³⁵ In the first-level analysis, seed-based connectivity (SBC) analyses were conducted using selected 28 Harvard-Oxford atlas ROIs.³⁶ Connectivity strength was computed using Fisher-transformed bivariate correlations modeled with weighted general linear models (GLM). Weights were adjusted to account for initial transient magnetization effects using HRF-convolved step functions. In the group-level, voxel-wise GLMs were estimated for each connectivity map, modeling between-subject variation and task/condition effects. Cluster-level inferences used Gaussian Random Field theory, with results thresholded at voxel-wise $p < 0.001$ and FDR-corrected cluster $p < 0.05$.³⁷

Results were corrected for multiple comparisons using Bonferroni correction. To assess group differences, a seed-based connectivity analysis assessing connectivity between each ROI and the rest of the brain was conducted. The analyses were thresholded at a voxel level significance of $p < 0.001$, with a cluster-level correction of $p < 0.05$. All results were corrected for multiple comparisons using the Bonferroni correction. To minimize motion-related artifacts, participants with head motion exceeding 0.5 mm were excluded from both samples: (1) the autistic and NT group, and (2) the bilingual and monolingual group.

RESULTS

SYSTEMATIC REVIEW: TASK-FMRI

A total of 31 articles were identified, with 22 duplicates removed. Of the remaining nine, five were excluded during screening for not meeting inclusion criteria. Four full-text articles were assessed, and one was excluded for not reporting effects of bilingualism, resulting in three articles (see Supplementary Figure 2). These studies examined four forms of pragmatic language in NT adults using written word stimuli. Participants included Italian-English, German-Italian, and Mandarin-English bilinguals. One study focused on socio-pragmatic knowledge, the second assessed metonymy, and the rest investigated metaphor comprehension. Experimental designs varied: testing L2 (second language) only, comparing L1 (first language) and L2, and contrasting monolingual and bilingual participants

processing in L2. All studies included participants with high second-language proficiency (see Table 2).

Although the studies reported activation in distinct brain regions, a consistent finding across all was increased activation in the secondary visual cortex (BA 18) during pragmatic language processing.^{18–20} Metaphor comprehension was specifically associated with greater activation in the right premotor and supplementary motor area (preSMA, BA 6),^{18,20} while L2 pragmatic processing involved increased activation in the right IFG.¹⁹

META-ANALYSES: NEUROSYNTH

COMMUNICATION

The meta-analysis employing the term “communication” demonstrated elevated activation particularly in the left hemisphere, especially in Heschl’s gyrus (BA 41), angular gyrus (AG, BA 39), visual association area (BA 19), posterior cingulate cortex (PCC, BA 24), ventral PCC (BA 23), and amygdala. There was also bilateral frontal activation, including IFGop and IFGtr. Additionally, increased activation was found in bilateral insula (BA 13), fusiform gyrus (FFG, BA 37), STG (BA 22) and MTG (BA 21; see Figure 1A and Supplementary Table 1).

SOCIAL COGNITION

The meta-analysis employing the term “social cognition” demonstrated elevated activation in 12 regions, primarily in the right hemisphere (9/12). Activation was found in the anterior prefrontal gyrus (PFC, BA 10), IFGtr (BA 45), and the preSMA. Increased activation was also found in the right MTG (BA 21), FFG (BA 37), dorsal PCC (BA 31), caudate, and amygdala. Both hemispheres demonstrated elevated activation in the insula (BA 13). In the left frontal lobe, increased activation was found in the dorsolateral prefrontal cortex (dlPFC, BA 9), and in IFGtr, extending to the temporal pole (TP, BA 38; see Figure 1B and Supplementary Table 2).

BILINGUALS

The meta-analysis employing the term “bilinguals” demonstrated elevated activation in 9 areas, particularly in the left hemisphere (7/9) and bilateral activation in the frontal cortex (e.g., IFGop) and insula (BA 13). Increased activation was also found in the left frontal eye fields (BA

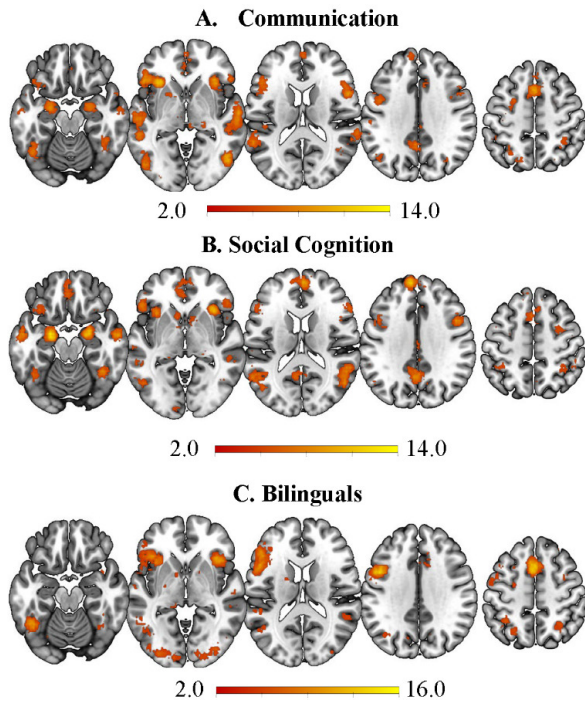


Figure 1. Results from the Neurosynth meta-analyses. Activation maps are shown for the terms Communication (A), Social cognition (B), and Bilinguals (C). Corresponding MNI coordinates and additional details are provided in Supplementary Tables 1, 2, and 3.

8), the STG (BA 22) and MTG (BA 21), and the FFG (BA 37). Furthermore, activation was also found in the AG (BA 41) and visual motor (BA 7) areas of the left parietal lobe (see [Figure 1C](#) and Supplementary Table 3).

FUNCTIONAL CONNECTIVITY IN THE PRAGMATIC NETWORK: RESTING FMRI

EARLY BILINGUALS VERSUS MONOLINGUALS

Early bilinguals, compared to monolinguals, showed decreased functional connectivity in seven ROIs. Specifically, the right SMG (BA 40) showed reduced connectivity with the left anterior superior temporal gyrus (aSTG), right aSTG, right Heschl's gyrus, and right planum temporale (PT). The precuneus showed decreased connectivity with premotor and the preSMA (BA 6). The right frontal pole also showed reduced connectivity with the primary somatosensory cortex (BA 1). Finally, the pars orbitalis (IFGor) aspect of right IFG had stronger connectivity with left primary somatosensory (BA 1), right primary motor (BA 4), and bilateral premotor and preSMA (BA 6) areas (see [Figure 2](#) and [Table 3](#)).

LATER BILINGUALS VERSUS MONOLINGUALS

Similarly, when comparing early bilinguals to late bilinguals, 4 fronto-temporal ROIs showed decreased connectivity. In particular, the left anterior middle temporal gyrus (aMTG) with the right the pars triangularis of the IFG

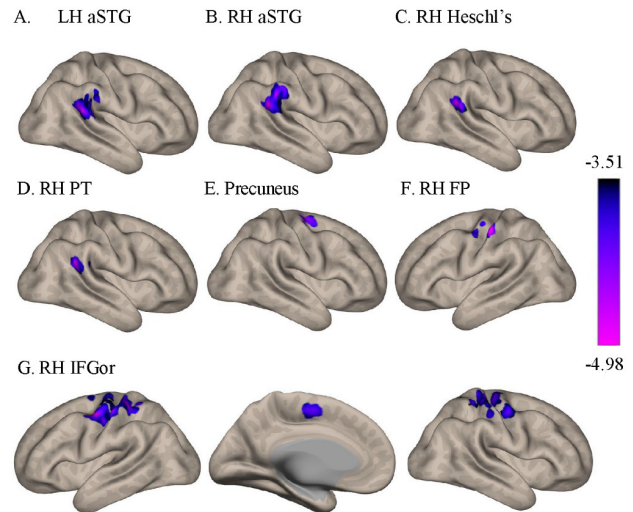


Figure 2. Significant seed-based connectivity differences between the early bilingual compared to monolingual group. Decreased functional connectivity was observed in the left anterior superior temporal gyrus (A), right anterior superior temporal gyrus (B), right Heschl's gyrus (C), right planum temporale (D), precuneus (E), right frontal pole (F), and right inferior frontal gyrus, pars orbitalis (G).

(IFGtr), and left aSTG with the right SMG. Furthermore, reduced connectivity was also seen between the left superior frontal gyrus (SFG) and the precuneus. Conversely, the right frontal pole- primary somatosensory cortex (BA 1) connectivity was stronger (see [Figure 3](#) and [Table 4](#)).

BILINGUALS VERSUS MONOLINGUALS

Finally, when comparing both bilingual groups (early and late) with monolingual controls, a common decrease in connectivity was found between right IFGor and bilateral premotor cortex and preSMA (BA 6; see [Figure 4](#) and [Table 5](#)).

DISCUSSION

This study leverages open-access neuroimaging resources to provide a comprehensive investigation into how bilingualism shapes the neural architecture underlying pragmatic language. Employing a multifaceted approach, comprising a systematic review, large-scale Neurosynth meta-analyses, and resting-state functional connectivity analyses of a publicly available fMRI dataset, we examined this question across converging lines of evidence. Accessing these openly shared datasets was crucial in enabling an interdisciplinary analysis without the constraints of new data collection, thereby enhancing reproducibility and transparency. While each method carries inherent limitations, together they yield a coherent account of how bilingual experience may influence the organization and function of higher-order pragmatic language networks. Our findings align with previous research on bilingualism, which

Table 3. The MNI coordinates from the early bilinguals compared to monolinguals in areas related to pragmatics and bilingualism.

Early Bilinguals > Monolinguals							
Size	Hem	Area	MNI Coordinates			t-value	size p-FEW
			X	Y	Z		
LH anterior Superior Temporal Gyrus							
481	RH	Supramarginal Gyrus (BA 40)	62	-40	24	-5.37	0
RH anterior Superior Temporal Gyrus							
481	RH	Supramarginal Gyrus (BA 40)	62	-40	24	-5.43	0
RH Heschl							
233	RH	Supramarginal Gyrus (BA 40)	60	-40	26	-5.42	0.00006
RH Planum Temporale							
225	RH	Supramarginal Gyrus (BA 40)	52	-40	28	-5.14	0.000068
Precuneus							
164	RH	Premotor + Supplementary Motor Area (BA 6)	30	-10	60	-4.72	0.000593
RH Frontal Pole							
201	LH	Primary Sensory (BA 1)	-52	-20	52	-4.85	0.000229
RH Inferior Frontal Gyrus orbitalis							
1453	LH	Primary Sensory (BA 1)	-32	-38	60	-7.00	0
517	RH	Primary Motor (BA 4)	26	-26	70	-5.71	0
206	RH	Premotor + Supplementary Motor Area (BA 6)	44	-10	52	-5.49	0.000144
183	LH	Premotor + Supplementary Motor Area (BA 6)	-2	-6	56	-5.45	0.000373

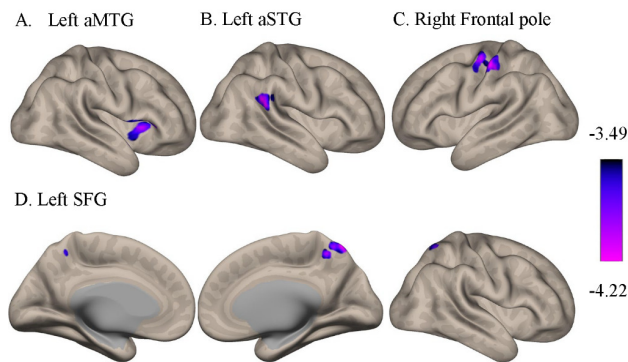


Figure 3. Significant seed-based connectivity differences between the early bilingual compared to late bilingual groups. Decreased functional connectivity was observed in the left anterior middle temporal gyrus (A), right anterior superior temporal gyrus (B), right frontal pole (C) and left superior frontal gyrus.

demonstrates that the experience of learning and using multiple languages leads to structural and functional adaptations in the brain.³⁸ This interpretation is further supported by behavioral research documenting enhanced pragmatic language abilities in bilingual individuals.¹¹ These findings also underscore the value of open science platforms in enabling interdisciplinary, large-scale neurocognitive investigations.

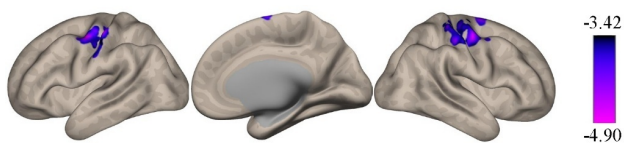
CONVERGING EVIDENCE FROM REVIEW, META-ANALYSES, AND EMPIRICAL DATA

Our systematic review identified a notable paucity of neuroimaging studies directly examining pragmatic language in bilingual populations, and the only three fMRI studies to date all focused on written language in NT adults. Despite variations in task design and language context, a consistent neural pattern emerged: increased activation in right-hemisphere frontal and motor-related regions, particularly the right IFG and preSMA, during metaphor and socio-pragmatic language tasks in a second language. These observations support the Coarse Semantic Coding Theory,³⁹ which posits that right-hemisphere regions play a critical role in processing semantically abstract meaning content, such as metaphors and indirect communication, perhaps due to increased computational demands.

Our empirical analysis of resting-state fMRI data revealed reduced functional connectivity within core pragmatic regions, including the IFG, anterior STG/MTG, SMG, and preSMA in early bilinguals. These findings suggest long-term, experience-driven reorganization of the pragmatic network, consistent with the view that managing two languages may streamline neural processes through adaptive efficiency. These findings align with the neural efficiency hypothesis, which proposes that more proficient or better-adapted neural systems can achieve equivalent or superior performance while utilizing fewer cognitive resources.^{40,41} Moreover, the dissociation between increased task-related activation and decreased resting-state connectivity suggests that while pragmatic processing in a second language may require greater cognitive effort during task

Table 4. The MNI coordinates from the early bilinguals compared to late bilinguals in areas related to pragmatics and bilingualism.

Early Bilinguals > Late Bilinguals							
Size	Hem	Area	MNI Coordinates			t-value	size p-FEW
			X	Y	Z		
LH anterior Middle Temporal Gyrus							
216	RH	Inferior Frontal Gyrus triangularis (BA 45)	38	22	6	-5.13	0.000103
LH anterior Superior Temporal Gyrus							
186	RH	Supramarginal Gyrus (BA 40)	62	-40	26	-4.73	0.000379
LH Superior Frontal Gyrus							
196	RH	Precuneus	2	-48	56	-5.13	0.000253
RH Frontal Pole							
350	LH	Primary Sensory (BA 1)	-52	-18	50	-4.92	0.000001

**Figure 4. Significant seed-based connectivity differences between the early and late bilingual compared to monolingual groups.**

performance, the underlying neural architecture may operate more efficiently at rest.

To extend these findings and corroborate the regions consistently associated with pragmatic language processing and bilingual experience, our meta-analyses revealed convergent activation in regions previously implicated in pragmatic language, including the bilateral IFG, STG, MTG, and MPFC.^{22–25} Notably, only the “communication” search map overlapped with the “bilinguals” search map, particularly in the bilateral IFG, STG, MTG, AG, and precuneus, highlighting a convergence between networks supporting pragmatic language and those shaped by bilingual experience.

NEURAL EFFICIENCY AND CORE NETWORK INVOLVEMENT

Across our systematic review, empirical functional connectivity analysis, and meta-analyses, a consistent set of brain regions emerged as central to both pragmatic language processing and its modulation by bilingual experience. These regions map onto a broadly distributed frontotemporal and

parietal network - including the IFG, preSMA, precuneus, STG, MTG and SMG - that supports semantic control,^{42–46} a core process involved in pragmatic comprehension. Importantly, several of these regions not only showed convergence across methods but also demonstrated functional differences specific to bilingual exposure, suggesting that lifelong language experience is associated with different architecture of this network.

It is noteworthy that the bilateral IFG was consistently implicated across all analyses. The systematic review revealed increased right IFG activation when processing pragmatic language in the second language, consistent with the 2018 meta-analysis,²⁴ while the Neurosynth meta-analyses highlighted bilateral IFG involvement in both the “communication” and “bilinguals” categories. Additionally, the OpenNeuro resting state data revealed that early bilinguals exhibit decreased functional connectivity between the right IFG and premotor regions, including the preSMA. The IFG has been well established as supporting semantic processing,^{21,39,47} integration⁴⁸ and selection of socially appropriate interpretation,⁴⁹ key mechanisms for resolving ambiguity and inferring speaker intent in nonliteral or context-dependent communication.²⁵ Differences in bilingual experience likely reflect the heightened executive demands of managing multiple linguistic systems,¹² which may lead to refined neural mechanisms of selection and suppression during communication.

The preSMA also showed robust and consistent engagement across both systematic-review of task-based and connectivity analyses. Specifically, task-fMRI results indicated consistent activation of the preSMA during metaphor pro-

Table 5. The MNI coordinates from the early bilinguals and late bilinguals compared to monolinguals in areas related to pragmatics and bilingualism.

Early Bilinguals+Late Bilinguals > Monolinguals							
Size	Hem	Area	MNI Coordinates			t-value	size p-FEW
			X	Y	Z		
RH Inferior Frontal Gyrus orbitalis							
874	RH	Premotor + Supplementary Motor Area (BA 6)	42	-8	58	-6.10	0
545	LH	Premotor + Supplementary Motor Area (BA 6)	-44	-6	52	-5.80	0

cessing, while resting-state data revealed reduced connectivity in bilinguals. Notably, the preSMA was the only region to show decreased connectivity in the conjunction analysis of early and late bilinguals relative to monolinguals. Although traditionally associated with motor planning, the preSMA is increasingly recognized for its role in embodied semantics and action-related language processing. It has also been proposed to contribute to value-based decision-making.⁵⁰ Its activation during metaphor tasks may reflect the sensorimotor grounding of abstract concepts, e.g., interpreting metaphors such as “grasping an idea”, which rely on motor simulation. The observed connectivity reductions in bilinguals may reflect more efficient, streamlined recruitment of embodied simulation networks, potentially shaped by the dual demands of interpreting figurative language across two linguistic systems. Furthermore, the bilateral preSMA showed decreased connectivity with the right IFG, regions anatomically linked via the frontal aslant tract.⁵¹ This is consistent with models suggesting that the preSMA supports task configuration (e.g., preparing networks for goal-directed action), while the right IFG is involved in monitoring external cues and implementing inhibitory control.⁵²

The precuneus also emerged as a relevant region in both the bilingual-related meta-analyses and resting-state analysis. Bilingual individuals showed altered connectivity between the precuneus and motor-related areas. The precuneus is known to support theory of mind,⁵³ self-referential processing, mental imagery, and perspective-taking,^{53–58} functions critical for pragmatic understanding. Furthermore, it has been implicated in processing different pragmatic forms, including irony^{59–61} and metaphor processing.⁶² It is also implicated in higher-order cognition through its role in integrating multimodal information.⁶³ Additionally, the precuneus showed decreased connectivity with preSMA, with both regions connected via the medial portion of the superior longitudinal fasciculus.⁶⁴ Structural connectivity between the preSMA and precuneus has also been demonstrated in both humans and macaques,⁶⁵ supporting the view that these regions jointly contribute to pragmatic and executive processing in bilinguals.

The STG and MTG, particularly in the anterior and posterior subdivisions, also emerged as central nodes in the Neurosynth maps for “communication” and “social cognition,” and showed altered resting-state connectivity in early bilinguals relative to monolinguals. The STG and MTG are implicated in auditory-semantic processing, theory of mind,^{54,57} action observation during social interaction,⁶⁶ social information extraction^{49,67} and integration of contextual cues.⁴⁹ These functions are critical for both literal and pragmatic language comprehension.²⁵ In particular, the anterior STG and MTG have been associated with processing figurative language, irony, and semantic incongruity, all of which demand flexibility in interpreting speaker intent beyond surface meaning. The bilingual experience, which entails frequent code-switching and navigation of diverse pragmatic norms, may enhance the functional specialization of these regions, supporting more

efficient and adaptable processing in communicative contexts.

The SMG and AG, regions in the inferior parietal lobule (IPL), also demonstrated overlapping involvement. The right SMG showed reduced connectivity in bilinguals, while the AG emerged in the meta-analytic maps for “communication.” The IPL has been identified as a convergence zone for social cognition and language processing.^{68,69} Furthermore, these regions are implicated in theory of mind,^{53,70,71} perspective-taking,⁷² and semantic association,^{68,73,74} functions essential for interpreting implied meaning and understanding indirect speech acts. The right SMG, in particular, has been associated with empathic processing and social prediction,⁷⁰ which may be more finely tuned in bilinguals who routinely adapt to differing sociocultural communication norms.

BROADER IMPLICATIONS

Together, these findings support the view that pragmatic competence is associated with language experience, with early bilingualism leading to functional reorganization of key brain networks. From a theoretical perspective, this supports the idea that bilinguals develop more refined or efficient mechanisms for selecting and integrating meaning from complex communicative contexts. These findings extend cognitive models of pragmatic language by highlighting how experience with two languages may scaffold broader cognitive abilities, such as executive control, mentalizing, and semantic flexibility, that underpin pragmatic competence.

This work opens important avenues for populations with social communication difficulties, such as autistic individuals. Behavioral studies suggest bilingualism may serve as a cognitive and social benefit within autism; however further investigation is needed for consensus amongst clinicians and researchers.^{75–77} Given the foundational role of pragmatic language in autism-related communication challenges, the possibility that bilingualism may influence neural efficiency in this domain offers promise and invites further investigation. Nevertheless, as this study relied on a single dataset, additional research directly examining the impact of bilingualism on the brain's processing of pragmatic language will be essential for assessing the consistency and generalizability of these findings. Ultimately, examining whether and how bilingual exposure might support pragmatic development in clinical groups remains an important, open question.

OPEN ACCESS AS A CATALYST FOR ADVANCING THE NEUROBIOLOGY OF LANGUAGE

A major strength of this study lies in its strategic use of open-access resources, including the OpenNeuro and the Neurosynth platforms. These publicly available resources enabled a large-scale, multimethod investigation that would not be feasible within the scope of a single-lab study due to constraints posed by limits in funding, resources, and personnel. By leveraging shared data, we achieved the statistical power and generalizability necessary to rigor-

ously test hypotheses about the neural underpinnings of pragmatic language in bilingual individuals. Importantly, the integration of empirical data, meta-analytic approaches, and systematic review techniques was made possible by open science practices that promote transparency, reproducibility, and interdisciplinary collaboration. This is especially vital in the relatively nascent field of neurobiology of bilingualism and pragmatic language, where primary data are scarce and fragmented. By adopting an open science framework, this study not only deepens our understanding of how bilingualism shapes neural networks involved in pragmatic competence, but also underscores the transformative role of data sharing in driving innovation, inclusivity, and equity in cognitive neuroscience.

LIMITATIONS AND FUTURE DIRECTIONS

Despite the strengths of this study, several limitations must be acknowledged. The task-fMRI literature remains sparse, and the empirical resting-state data do not include task-specific pragmatic measures. Moreover, the absence of behavioral metrics paired with fMRI to assess alterations in pragmatic language proficiency represents a significant gap in the field. To partially address this limitation, we incorporated Neurosynth meta-analyses and a prior meta-analysis of pragmatic language in NT adults. However, because these resources did not include information on bilingualism, relevant regions specific to bilingual populations may have been overlooked. Within the sample of the systematic review, bilinguals are of different ethnicities, from different regions, and speak different languages. This may be a confounding factor and should be considered when interpreting findings. Another limitation is that our neuroimaging analyses relied on a single open dataset. While this dataset provided a relatively large sample compared to many individual neuroimaging studies, dependence on one resource inevitably constrains the scale and generalizability of our findings.

Despite these challenges, our combined approach yielded a coherent account of how bilingual experience may influence the organization and function of higher-order pragmatic language networks. To advance our understanding of the effect that bilingualism has on pragmatic language we need more studies that: 1) Use task-based fMRI to assess pragmatic processing directly in bilinguals across different pragmatic forms, including metaphor, irony, and indirect speech tasks; 2) Include clinical populations such as autistic bilinguals to assess potential compensatory effects; 3) Conduct longitudinal studies to examine developmental timing effects and how to shape the brain through time of exposure; 4) Include behavioral measures of pragmatic language in resting-state studies, like the present one, to help quantify the relationship between individual pragmatic skills and brain function patterns, thereby clarifying whether bilingualism enhances network efficiency. Incorporating our current findings with future research has

great potential to inform future applied research, such as guiding pragmatic language interventions in childhood, especially in autistic populations where difficulties with social communication are a core symptom.

CONCLUSION

This multi-method investigation shows that bilingualism, particularly when acquired early, modifies the neural architecture of pragmatic language. These findings are aligned with the Dynamic Restructuring Model, which suggests that the acquisition of demanding skills can trigger dynamic changes in the brain,³⁸ and with the neural efficiency hypothesis.^{78,79} In alignment with this proposal, bilingualism may enhance brain coordination and reduce reliance on overt control processes through more efficient neural resource allocation. These findings advance our understanding of how language experience shapes the brain function and provide a foundation for future studies targeting pragmatic language in both typical and clinical populations. Regarding applied research, the findings support the implication of bilingualism in pragmatic language interventions. The findings have clinical implications for populations that present with social language difficulties, such as autistic population, and this may support bilingualism as an early intervention strategy. More broadly, this work illustrates how open science can catalyze progress in the cognitive neuroscience of language, accelerating discovery and fostering collaborative research.

DATA AND CODE AVAILABILITY STATEMENT

No new code was developed for this study. The analyses were conducted using two data sources: (1) publicly available neuroimaging data obtained from OpenNeuro (dataset ID: ds001747, version 1.1.0; DOI: 10.18112/openneuro.ds001747.v1.1.0) and (2) meta-analytic activation maps retrieved from the NeuroSynth platform (<https://neurosynth.org>), a large-scale, open-access database of functional neuroimaging results derived from published studies.

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CONFLICTS OF INTEREST

The authors declare no competing interests.

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SUPPLEMENTARY MATERIALS

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