Neural adolescent pragmatic development mirrors pragmatic differences in adulthood: an fMRI-study

Christoffer Forbes Schieche[1], Julia Uddén[1,2]

1. Department of Linguistics, Stockholm University
2. Department of Psychology, Stockholm university

Abstract

Pragmatic development is still ongoing during adolescence. However, the developmental trajectory during the adolescent years is understudied and the underlying neural correlates of pragmatic development are unknown. In this study, we used an established fMRI paradigm contrasting indirect and direct speech act processing in a newly acquired adolescent sample (n = 51) and a previously collected adult sample (n = 57). The adolescent sample was split into two groups: Young (ages 13-15) and Mid (ages 16-18); and the adult sample (Old, ages 18-36) into two groups based on pragmatic skill level, established in separate behavioral tests. We observed increased activity with age in the posterior medial prefrontal cortex, and a combination of age-related differences and individual differences in adults in the left posterior intraparietal sulcus (IPS) and the posterior cingulate cortex. These clusters were all located outside of the classical perisylvian language areas ("the language network"). The posterior cingulate cortex cluster overlapped with core nodes of the default mode network. We interpret the IPS finding in terms of its overlap with two relevant networks (one of them is the "multiple demand" network related to cognitive control). The results indicate that young adolescents and adults with low pragmatic skill may be over-interpreting direct speech acts as potentially indirect. The similarity between these two groups across results in turn indicate that a delayed adolescent development may lead to persistent difficulties in adulthood. We have shown that aspects of pragmatic development depend on cognitive abilities other than language and Theory of Mind. By studying adolescence, a presumably uniquely human extended developmental period, we provide a rare empirical angle on the question of which aspects of brain and cultural evolution contributed to the human communicative faculty.

Keywords: fMRI, pragmatics, adolescence, development

1. Introduction

Successful everyday communication requires more than retrieval of words or the application of syntactic rules. It also involves continuous interpretation beyond the literal content of a message, to understand others' communicative intentions. These pragmatic processes encompass a range of phenomena in comprehension, such as speech act interpretation and the integration of multimodal signals. While this article primarily focuses on pragmatic comprehension, several aspects of production and interaction—such as audience design and turn-taking—are also pragmatic.

Recent evolutionary accounts suggest that pragmatics plays a key role in what makes us human, enabling complex and flexible interaction on a level not observed in other species (Levinson, 2006). Based on studying communicative situations with infants and chimpanzees, it has been suggested that the uniquely human language faculty is rooted in evolved social and communicative contexts, which have provided a foundation for language use to emerge (Tomasello et al., 2012). Moreover, while linguistic universals have been difficult to establish at the level of coded meaning (Evans & Levinson, 2009), recent findings of pragmatic universals (Dingemanse et al., 2013) argue for a central role of pragmatics in the emergence of human communication.

Evidence for the unique role of pragmatics in the human lineage emerges already in early development. Infants as young as eight months appear sensitive to ostensive communicative behaviors and signals, such as gaze following and infant-direct speech (Senju & Csibra, 2008). Infants show increased attention and inferential behaviors when exposed to patterns that more closely resemble human communication (Movellan & Watson, 2002; Tauzin & Gergely, 2018). While young children (2-2.5 years) match adult and age-matched non-human primates in physical tasks, they outperform primates in areas involving social understanding and cooperation (Herrmann et al., 2007; Wobber et al., 2014).

Another trait often considered uniquely human is an extended childhood. Compared to other species, including our closest primate relatives, the period from human infancy to independence (i.e., adulthood) is significantly longer (Bogin, 1990, 1997). Among the proposed evolutionary advantages of this extended childhood are that it allows for continuous learning of cultural and other complex knowledge (Bogin, 1990, 1997; Uomini et al., 2020). Notably, the adolescent phase may be especially crucial for social learning and exploration (Gopnik, 2020; Gopnik et al., 2017), a view given support by observations of developmental changes in brain activity related to social processing and reasoning during this time (Crone & Dahl, 2012; Dumontheil, 2015)

This paper builds on the idea of combining these observations of uniquely human (1) pragmatic abilities and (2) extended childhood. What if pragmatics is one of the core abilities learned during this extended childhood—contributing to what makes us uniquely human? This question invites investigation into the function of brain structures and brain networks showing accelerated evolution in humans and continued development during adolescence (Arain et al., 2013; Bethlehem et al., 2022; Blakemore, 2012; Blakemore et al., 2007; Catani & Bambini, 2014; Dahl, 2004; Dumontheil, 2015; Giedd et al., 1999; Raffaelli & Duckett, 1989; Sowell et al., 2003; Stiles & Jernigan, 2010). To the extent that neural development supports pragmatic functions and indexes their maturation, we can not only begin to understand *what* makes us uniquely human, but also how this came about, by focusing on relevant aspects of brain evolution and development.

Considering the existing literature on pragmatic development, there is a relative gap in studies investigating the adolescent period, as most developmental accounts have focused on early childhood and the pre-adolescent period (e.g., Matthews et al., 2018). Nonetheless, both observational and experimental work support a general assumption of a continuous development of pragmatics during adolescence (Arvidsson et al., 2022; Garraffa & Mazzaggio, 2025; Nippold, 1993, 2000). Raffaelli and Duckett (1989) observed an increase in the sheer duration spent in conversation with peers in mid-adolescence (while the duration of other conversational partners stayed constant). The amount of distinct conversational exchanges—especially non-familial ones—also increase (Nippold, 1993). Successful navigation of differing conversational contexts demands increasingly flexible and sophisticated conversational skills. More recently, experimental work have provided evidence of increasing pragmatic maturity from early into mid-adolescence in pragmatic production (Arvidsson et al., 2022).

To better understand the cognitive architecture underlying pragmatic abilities, multiple fMRI studies (Bašnáková, 2019; Bašnáková et al., 2014; Bendtz et al., 2022; Egorova et al., 2016; Feng et al., 2021; Hellbernd & Sammler, 2016, 2018; van Ackeren et al., 2016) have investigated the neural basis of pragmatics by contrasting indirect speech acts (ISA) with direct speech acts. These studies have consistently shown increased activation within the canonical language and Theory of Mind (ToM) networks during the processing of ISA. This suggests that the processing of ISA engages both structural language processes and ToM-related abilities, such as perspective taking, to a greater extent than direct speech acts. However, findings from our previous study (Bendtz et al., 2022) indicate that these

two faculties do not fully account for pragmatic processing. In that study, the adult participants were divided into two groups based on behavioral tests of pragmatic production and comprehension. The groups consisted of those with the lowest scores on both measures (the LS group) and those with the highest scores (the HS group). When we compared the two groups in a test for interaction (HS > LS, Indirect > Direct), we observed higher activity in two clusters outside of the language and ToM networks: (1) the left anterior/mid intraparietal sulcus and (2) the bilateral dorsal precuneus (together referred to as the ParPrec-clusters). This made us conclude that pragmatics is at least partially segregable from language and ToM, a conclusion that we have further strengthened in a recent investigation using functional connectivity measures (Forbes Schieche et al., in press).

The current study

While previous fMRI research has provided insights into the neural correlates of pragmatic processing, this body of literature has so far only used adult participants. The developmental period of adolescence is yet to be investigated from a neural perspective. In this study, we thus investigated the neural basis and developmental trajectory of indirect speech act (ISA) processing during adolescence and into early adulthood. We used a newly acquired sample of adolescents, further subdivided into two groups based on age (Young: ages 13—15 and Mid: ages 16—18), as well as our previously collected sample from Bendtz et al. (2022) (here called the Old group: ages 18—36). First, we examined whole-brain activation for indirect versus direct speech acts within adolescents, as well as differences between the two adolescent age groups. We expected to replicate previous findings from similar studies with adults: increased activation within the language network and regions part of the ToM network (such as the medial prefrontal cortex). Based on previous related literature (e.g., Blakemore et al., 2007; Burnett et al., 2009), we held regions such as the anterior temporal lobes (ATLs) and the medial prefrontal cortex as candidates for where potential differences from age would arise.

We also investigated developmental differences between adolescence and adulthood. This cross-sectional design allowed for direct group comparisons which have not been done before within neuropragmatics. Earlier, related, and unpublished, work has either not employed age as a factor (Asaridou et al., 2019), or in the case of cross-sectional designs, not looked at pragmatics specifically (e.g., social cognition/ToM, Blakemore et al., 2007; social emotion, Burnett et al., 2009). As to our expectations of differences between adolescents and adults: these were similar to those held to be different between the adolescent age groups, i.e., differences within the ATLs and medial prefrontal cortex.

We chose to conduct region of interest (ROI) analyses as a complement to the whole-brain approach. This allowed for more sensitive testing of our hypothesized age-related differences. Specifically, we focused on the dorsal aspects of the medial prefrontal cortex (divided into an anterior and posterior part) as well as the left ATL. For the ROI analyses, we used the two adolescent subgroups (Young and Mid) and tested for group differences between the Young and Mid groups and the Mid and Old groups within these ROIs (see hypothesized directions in our Supplementary materials, Table S1).

Finally, we explored whether adult pragmatic challenges can (partly) be explained by a delayed development. Here, we made use of the two groups from Bendtz et al. (2022) that were based on pragmatic skill level (i.e., the LS and HS groups). We examined similarities and differences between the two adolescent and the two adult groups to test whether individual variation in pragmatic skill may relate to developmental trajectories.

2. Method

2.1 Participants

55 participants (excluding six pilot participants) were invited to take part in the experiment in the MR-scanner (32 females, ages 13—18, mean age 15.5 ± 1.7). These were further subdivided into two age groups: the Young group aged 13—15 (n = 27, 13 females, mean age 13.9 ± 0.8) and the Mid group aged 16—18 (n = 28, 19 females, mean age 17.0 ± 0.7). Criteria for participation included that participants had to be native Swedish speakers (or native level at seven years old), no history of substance abuse, neurological impairment, brain surgery, ADHD or ASD diagnosis, or language impairment. Each participant received gift cards valued SEK 297 after completing the experiment. All data was acquired at Stockholm University Brain Imaging Center (SUBIC) and the data collection was approved by the Swedish Ethical Review Authority. Due to exclusion criteria, four participants were excluded from the final analysis, resulting in a final sample of n = 51 (Young, n = 24, and Mid, n = 27). Some individual runs were also excluded. For details on the basis for exclusion and exclusion criteria from data quality, see §2.4.2 and Supplementary Materials §S2.1.

The adult sample (again, referred to as the Old group) consisted of 57 participants (age 18—36, 29 females), and was collected and analyzed in a previous investigation within our lab (Bendtz et al., 2022). The sample can be further subdivided into two groups based on pragmatic ability measured through two behavioral tests at a prior date to acquisition of the MR data. Participants with the worst performance on both tests form a low-scoring group, LS (n = 28), and those with the highest performance form a high-scoring group, HS (n = 29).

2.2 Preregistration

Our research questions, hypotheses, and analysis plan were preregistered on OSF prior to performing the final analysis (https://osf.io/kb96c). We complemented our preregistration with an addendum in an early stage of the analysis (https://osf.io/wdbxq), see Supplementary Materials §S2.2 for further details.

2.3 fMRI paradigm and stimulus

We used the same paradigm as in Bendtz et al. (2022), with slight modifications. The paradigm consists of several conversations between interlocutors, all including an introductory context (explaining a situation), a question from one of the interlocutors, which the other one answers either in a direct or indirect manner, i.e., performs a direct or indirect speech act. The main interest of the paradigm are the answers which exist in pairs that are linguistically identical but rendered direct or indirect based on varying the question posed by one of the interlocutors. In some cases, the context was slightly altered to better facilitate either condition. No changes were made to the conversations, as the content was deemed suitable also for adolescent participants. Each participant heard only one version of each trial. Noteworthy is that all indirect speech acts were face-saving (Brown & Levinson, 1987). Behavioral studies have shown that the interpretation of indirect speech acts as such is more obvious when they are posed in a face-saving context (Holtgraves, 1998).

In addition to the experimental stimuli, the experiment included 14 filler trials and 12 compliance questions. The filler trials had the same structure as the experimental trials but ended with a direct yes/no reply to a question. The 12 control questions were paired with particular trials (regardless of direct or indirect). After these trials, a yes/no question was (auditorily) posed to the participant about some detail regarding the conversation they had just listened to. Participants replied to the question with a button box. Some of the control questions were changed from Bendtz et al. (2022), see Supplementary Materials §S2.3 for more details. Table 1 shows examples of each type of trial.

Table 1. Examples of each trial type used in the paradigm

Trial type	Context	Question	Answer
Direct	Magnus and Emilia are old friends. They are discussing how hard it is to find restaurants which both you and your partner fancy. Emilia asks Magnus:	Why doesn't your girlfriend like Japanese food?	She is not so used to Asian seasoning.
Indirect	Magnus and Emilia are old friends. They are talking about the last time Magnus visited Emilia in her student dormitory. Emilia asks Magnus:	Did your girlfriend like my vegan noodles?	
Control question	Was there someone who was not so used to Asian seasoning?		
Filler	Benny and Ellinor are doing their laundry. Benny went out walking the dog but is now back. He asks Ellinor, who was the last to visit the laundry room:	Is the washing machine done?	Yes, just put everything in the dryer.

2.4 fMRI data acquisition

This section describes acquisition and preprocessing specific to the adolescent data. The pipeline was close to identical to the one used for the adult data set, except for the settings for the structural images; for details, see Bendtz et al. (2022).

2.4.1 Acquisition settings

All data was collected at SUBIC (Stockholm University Brain Imaging Center) with a Siemens 3T Magneton Prisma MRI-scanner with a 20-channel surface coil. The functional volumes were acquired with a repetition time (TR) of 2.1 s and echo time (TE) of 30 ms, with 70 slices each 2 mm thick and a 1 mm slice gap. Voxel size was 2.2 x 2.2 x 2.2 mm^3 with a field of view (FOV) of 210 mm, and the flip angle was set to 70 degrees. Acquisition of the structural T1-weighted images was shortened for the adolescents and thus used different settings than Bendtz et al. (2022). The adolescents' structural images were acquired with a TR of 2.3 s and TE of 2.88 ms, with 176 slices each 1.2 mm thick and a FOV of 239 mm. The duration was 2 m 32 s and was acquired directly after the experimental paradigm.

2.4.2 Preprocessing, quality control, volume repair, and additional data exclusion

Preprocessing was performed with SPM12 (Friston et al., 2007) in MATLAB (The MathWorks Inc., 2019), and included realignment, coregistration of the functional images to the structural image, normalization, and spatial smoothing. Normalization utilized affine regularization, and all voxels were resampled to 2 x 2 x 2 mm^3 using 4th degree B-spline interpolation. White and grey matter segmentation and bias correction were carried out in the normalization step. Smoothing of the functional data was performed with a 3D isotropic Gaussian smoothing kernel of full-width-at-half-maximum = 8 mm.

We used MRIQC (v24.0.2, Esteban et al., 2017) to obtain quality metrics for each participant and run (to summarize over all participants and runs, we used v22.0.6). For each metric, outlier runs were checked manually whether there were any issues with a specific run's images. We excluded 5 runs from 3 participants based on MRIQC's estimated framewise displacement (FD), see Supplementary Materials (§S2.1) for details.

In addition to excluding data based on the FD metrics provided by MRIQC, we used ArtRepair (Mazaika et al., 2007) to repair individual volumes. We used default settings: volumes were flagged if volume-to-volume movement was above 0.5 mm (this measurement does not entirely match the algorithm used in MRIQC for FD) or if the volume-to-volume change in signal intensity exceeded 1.5%. The

flagged volumes were repaired by interpolation of surrounding volumes. We excluded 5 runs from 4 subjects as the number of flagged volumes in a row exceeded 7, see Supplementary Materials (§S2.1) for more details.

2.5 Whole-brain analysis

2.5.1 First level

We modelled the BOLD signal with eight conditions and six movement regressors. The introductory context in both the indirect and direct conditions were modelled as one regressor (regressor i). Bendtz et al. (2022) treated these as two separate regressors, however we respecified the model of the adult data to match the current setup. The question and answers were modelled separately per condition (regressors ii-v). The remaining regressors were (vi) filler trials and compliance questions; (vii) response to compliance questions, and (iix) inter-trial-interval (ITI, i.e., silence).

We modelled five different contrasts: indirect answers vs. direct answers (Indirect > Direct), direct answers vs. indirect answers (Direct > Indirect), indirect answers vs. implicit baseline (Indirect > Baseline), direct answers vs. implicit baseline (Direct > Baseline), and context vs. ITI. Our main analysis used the first two contrasts, though we included the contrasts with baseline to better understand the effect of each condition in the ROI analysis (rather than only the relative difference between them). We only used the context vs. ITI as an initial sanity check, by inspecting the individual results for this contrast in a sub-sample of the participants.

2.5.2 Second level whole-brain analysis

Second level analyses were conducted using the Indirect > Direct and Direct > Indirect contrasts defined at the first level. We performed the following second level tests: (i) Indirect > Direct, all adolescents, and (ii) Indirect > Direct, Young and Mid separately. These were also performed in the opposite direction, Direct > Indirect. Our main tests for group effects only used the Indirect > Direct contrast and included (iii) Young > Mid and Mid > Young; (iv) Adolescents > Old and Old > Adolescents. The cluster-forming threshold was set to $P_{\text{uncorrected}} = .005$ with FWE as a multiple comparison correction method on the cluster and peak level. We report clusters with $P_{\text{FWE}} < .05$ and test-statistics of each cluster's peak voxel if $P_{\text{FWE}} < .05$. Clusters with $P_{\text{FWE}} > .05$ are not reported, even if its peak voxel is $P_{\text{FWE}} < .05$.

2.6 ROI analyses

2.6.1 Literature-based ROIs

To test our hypotheses on developmental changes, we specified three ROIs: the (i) dorsal anterior medial prefrontal cortex (amPFC); (ii) dorsal posterior medial prefrontal cortex (pmPFC); and (iii) the left anterior temporal lobe (ATL). These ROIs are shown in Figure S5, 3, and S6, respectively.

The two ROIs in the dorsal aspects of the mPFC were derived from clusters identified in the Indirect > Direct contrasts from adolescents in Asaridou et al. (2019) (amPFC) and adults in Bendtz et al. (2022) (pmPFC), respectively. As these two clusters overlap, we edited the posterior ROI by removing all voxels anterior to the most posterior voxel in the anterior ROI (MNI coordinate y = 28) using FSLeyes (Jenkinson et al., 2012). The ATL ROI was similarly derived from Asaridou et al. We manually edited the ROI to only cover anterior temporal regions, based on the definition of the ATL from Rice et al. (2015) and further restricted it to voxels present in all participants (see Supplementary Materials (§S2.4) for more details).

We extracted individual beta values (here, contrast estimates for the Indirect > Direct contrast) from each ROI using Marsbar (Brett et al., 2006) in SPM12. We used the three groups (Young, Mid, and Old) and entered their beta-values into three separate ANOVAs. For ANOVAs with significant effects of

group (P < .05), we followed up with one- or two-sided T-tests (depending on our hypothesised direction of effect, see Table S1), testing Young against Mid, and Mid against Old, correcting for two tests within each follow-up. All analyses were conducted in RStudio (Posit Team, 2024).

2.6.2 ROI from the group effect Mid > Young

One ROI in the left intraparietal sulcus (IPS) came out of a test for group effect (see addendum to our preregistration, https://osf.io/wdbxq, §3.1.2, and Figure 4). We performed two one-sided T-tests (Young < Old and Mid < Old) and we corrected for two comparisons. Hence all ROIs were preregistered, along with all other statistical analysis in this paper.

2.6.3 Testing for potential developmental delay in the LS group

To investigate whether pragmatic difficulties in the LS group could reflect a developmental delay, we tested for similarities between the adolescents and LS group. In a stepwise testing procedure, we first compared the HS group and adolescents in both directions (HS > Adolescents, Adolescents > HS) in the Indirect > Direct contrast. Significant clusters from these contrasts were used as ROIs for follow-up testing.

In a second step, we used Marsbar (Brett et al., 2006) to extract the beta values (contrast estimates) for all participants. We then conducted frequentist T-tests with the two adult groups, in the same direction as the cluster was revealed between the HS and adolescents, to test whether the adult groups were significantly different.

In a final step, we compared the LS group and the adolescents using both frequentist and Bayesian T-tests. The direction of these tests matched the original test where the clusters were found, with the LS group replacing the HS group. If the LS group shared similar activation patterns with the adolescents, we would expect non-significant frequentist result. To quantify a level of support of (no) difference, we included a Bayesian T-test. Both the frequentist and Bayesian T-tests were performed in RStudio; the latter using the BayesFactor library (Morey et al., 2024) with a default prior of $\sqrt{2}/2$.

2.6.4 Extraction of beta values for the Indirect and Direct conditions

To better understand the direction of our results, we also extracted individual beta values using the Indirect > Baseline and Direct > Baseline contrast. This was done for the literature-based ROIs, any clusters yielded by group comparisons, and the ParPrec-clusters from Bendtz et al. (2022). As mentioned in §2.5.1, we only used these contrasts for descriptive purposes: consequently, we did not perform any statistical testing on this data.

3. Results

3.1 Whole-brain analyses

3.1.1 Indirect > Direct: All adolescents, and Young and Mid groups separately

The Indirect > Direct speech act contrast revealed several significant clusters across the brain, both when analyzing the subgroups separately (Figure 1) and when pooling all adolescents together (Figure S2A). Significant clusters and statistics are reported in Table S2.

It is visible in the results from the two subgroups in Figure 1 that there was significant activity in both respective maps in the bilateral inferior frontal gyrus (IFG), anterior mPFC, bilateral ATL, left angular gyrus/supramarginal gyrus (AG/SMG), and the right mid-to-posterior superior temporal sulcus (STS). The Mid group additionally showed a cluster in the dorsal portion of the posterior mPFC and more extensive activation in (i) the right STS extending into the AG/SMG, and (ii) the left mid-to-posterior STS/superior temporal gyrus (STG) (see Figure 1B). The dorsal posterior mPFC cluster overlapped spatially with one of our planned ROIs (see Figure 3).

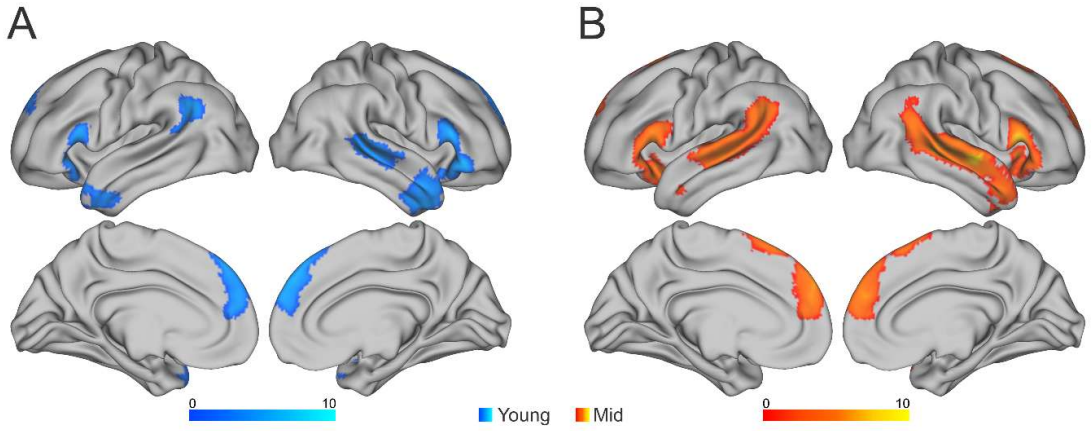

Figure 1. Significant clusters in the Indirect > Direct contrast for the Young (A) and Mid (B) groups separately. The figure shows clusters with a cluster-forming threshold of $P_{uncorrected} < .005$. We used family wise error (FWE) as a multiple comparison correction method on cluster and peak levels and only report clusters with a $P_{FWE} < .05$. The color scale represents *T*-values per voxel and uses the full range of *T*-values from all tests (including those in the Supplementary Materials). Significant clusters for all adolescents pooled together is provided in Figure S2A.

The overall pattern of the Indirect > Direct contrast is robust across all age groups (Young, Mid, and Old), however with important significant differences (see previous paragraph and following sections on group effects). For the Old group, the patterns are consistent with those originally reported in Bendtz et al. (2022), which is entirely expected due to using the same data (albeit with a slightly respecified model, see §2.5.1). The results of the contrast from the Old group are presented in Figure S3, alongside the original results from Bendtz et al. (2022).

3.1.2 Indirect > Direct: Group effects between the adolescent groups

Testing for group effects between the two adolescent groups revealed a significant cluster only in the test for Mid > Young, reported in Figure 4 and Table S2. This cluster was located in the left posterior intraparietal sulcus and extended into the superior parietal lobule (the cluster will be referred to as the IPS cluster). The cluster sits posterior to the parietal cluster from Bendtz et al. (2022) and in-between both of the ParPrec-clusters. The ParPrec-clusters are included in the presentation of the original results from Bendtz et al. in Figure S3B.

3.1.3 Indirect > Direct: Group effects between adolescents and adults

There were no significant clusters in the Indirect > Direct contrast in the Adolescents > Old direction. The Old > Adolescents direction yielded a single significant cluster in the bilateral posterior cingulate cortex (PCC) extending into the corpus callosum (Figure S4, Table S3, spatially overlapping with the cluster in Figure 5). When we performed the same test with white matter masked out, it resulted in a similar but smaller cluster (red outline in Figure S4), though it did not reach significance ($P = .38$).

3.1.4 Direct > Indirect: All adolescents and Young and Mid separately

The reverse contrast (Direct > Indirect) revealed no significant clusters in the Mid group. In contrast, the Young group showed several significant clusters (Figure 2 and Table S4). This included a cluster in the left mid-to-posterior parts of the intraparietal sulcus and superior parietal lobule, overlapping with the IPS-cluster found in the test for group effects between the Young and Mid groups. We observed further significant clusters in the left posterior ventral temporal lobe, bilateral anterior middle frontal gyrus (MFG), the left anterior superior frontal gyrus (SFG), bilateral posterior ventral mPFC, and the bilateral PCC/ventral-to-mid precuneus. Pooling all adolescents together gave a similar result as with

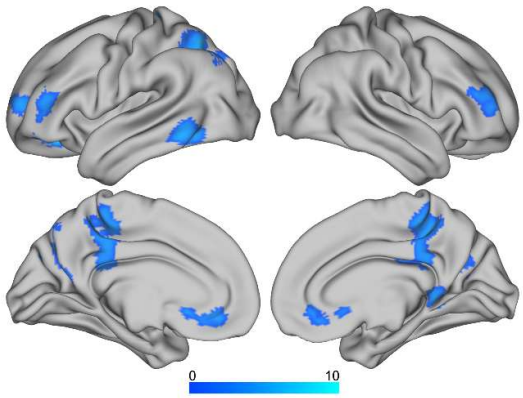

Figure 2. Significant (FWE corrected) clusters in the Direct > Indirect contrast for the Young group. There were no significant clusters in the same contrast in the Mid group. A cluster in the left intraparietal sulcus overlaps with the cluster from the Indirect > Direct, Mid > Young group comparison (Figure 4). Significant clusters for all adolescents pooled together are provided in Figure S2B.

the Young group, with additional clusters in the right posterior IPS/SMG and left posterior SFG: these results are reported in Figure S2B and Table S4.

3.2 ROI analyses

3.2.1 ANOVA results and follow-up T-tests

We performed three ANOVAs on the Indirect > Direct contrast for ROIs in the pmPFC, amPFC, and ATL. The ANOVA for the pmPFC revealed a significant main effect of age group ($F(2, 105) = 3.62$, $P = .03$, see Figure 3). Neither of the two ANOVAs in the amPFC or the left ATL reached significance ($F(2, 105) = 1.78$, $P = .17$ (Figure S5) and $F(2, 105) = 2.33$, $P = .10$ (Figure S6)), resulting that no *T*-tests were performed for these ROIs. One of the follow-up *T*-tests in the pmPFC (one-tailed, Old > Mid) was nominally significant but did not survive Bonferroni correction ($T(71) = -1.93$, $P_{raw} = .03$). The other *T*-test (Mid > Young) did not reach significance ($T(47) = -0.83$, $P_{raw} = .21$).

We performed additional *T*-tests in the IPS-cluster revealed in the Indirect > Direct contrast in the Mid > Young test. As we had already observed an effect between these two groups, we performed the tests Old > Young and Old > Mid. Neither test turned out significant ($T(79) = -1.09$, $P = .14$ and $T(71) = 0.96$, $P = .83$).

The mean contrast estimates and standard deviations for each ROI and group are reported in Table 2 and the data for the pmPFC is visualized in Figure 3 (panel B). Plots with contrast estimates for the IPS, amPFC and ATL are provided in Supplementary Materials, Figure S8, S5 and S6.

Table 2. Mean contrast estimates for the Indirect > Direct contrast in the included ROIs.

ROI	Young	Mid	LS	HS	Adolescents	Old
pmPFC	0.27 ± 0.60	0.41 ± 0.55	0.72 ± 0.72	0.67 ± 0.87	0.35 ± 0.57	0.70 ± 0.79
amPFC	0.79 ± 0.80	0.72 ± 0.74	1.05 ± 1.00	1.09 ± 0.98	0.75 ± 0.76	1.07 ± 0.98
ATL	0.36 ± 0.46	0.15 ± 0.36	0.42 ± 0.46	0.36 ± 0.62	0.25 ± 0.42	0.39 ± 0.54
IPS	-0.66 ± 0.64	-0.30 ± 0.77	-0.80 ± 0.83	-0.16 ± 0.74	-0.47 ± 0.72	-0.48 ± 0.84
PCC	-0.28 ± 0.48	-0.10 ± 0.46	-0.16 ± 0.72	0.47 ± 0.74	-0.18 ± 0.47	0.16 ± 0.79

Note: The ROIs covering the pmPFC, amPFC, and ATL were defined based on previous studies. The ROIs in the IPS and PCC were also preregistered, as all analysis in this paper, but they came from tests for group effects in the Indirect > Direct contrast in the present study, for Mid > Young and HS > Adolescents, respectively.

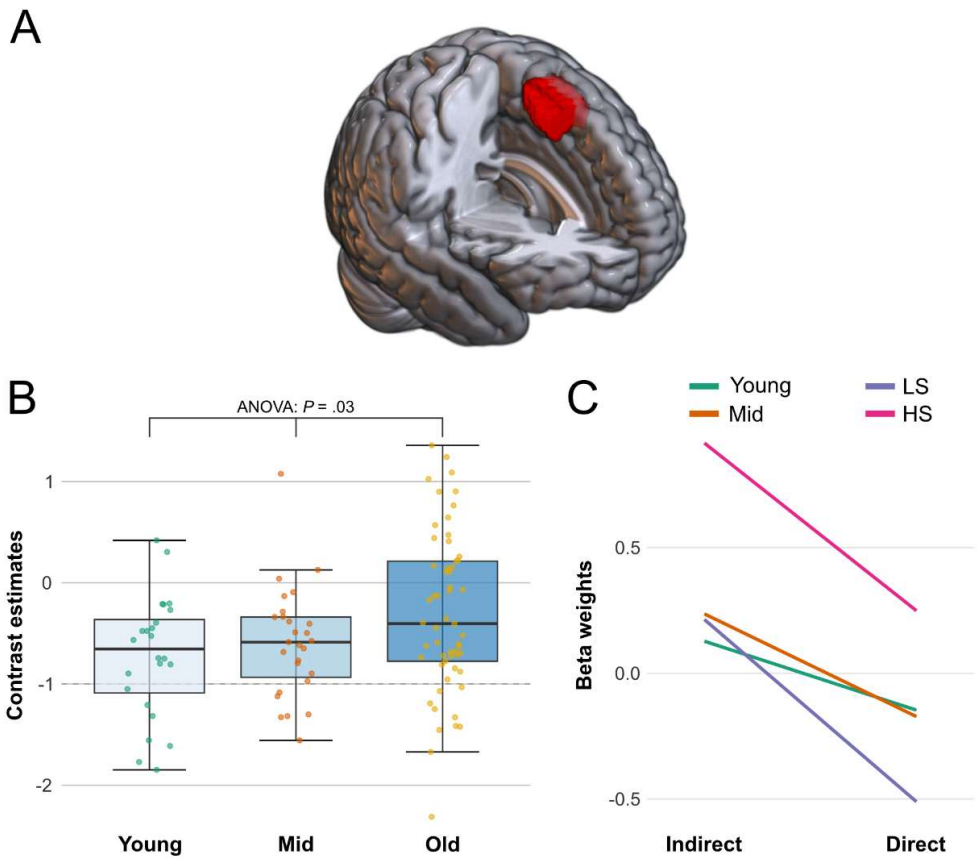

Figure 3. (A) Location of ROI in the posterior medial prefrontal cortex (pmPFC). (B) Contrast estimates (Indirect > Direct) and result from ANOVA test. One of two follow-up *T*-tests (Old > Mid) was nominally significant (P_{raw} = .03) but did not survive Bonferroni correction. Box plots for all groups are provided in Figure S7. (C) Mean beta weights from each condition per group.

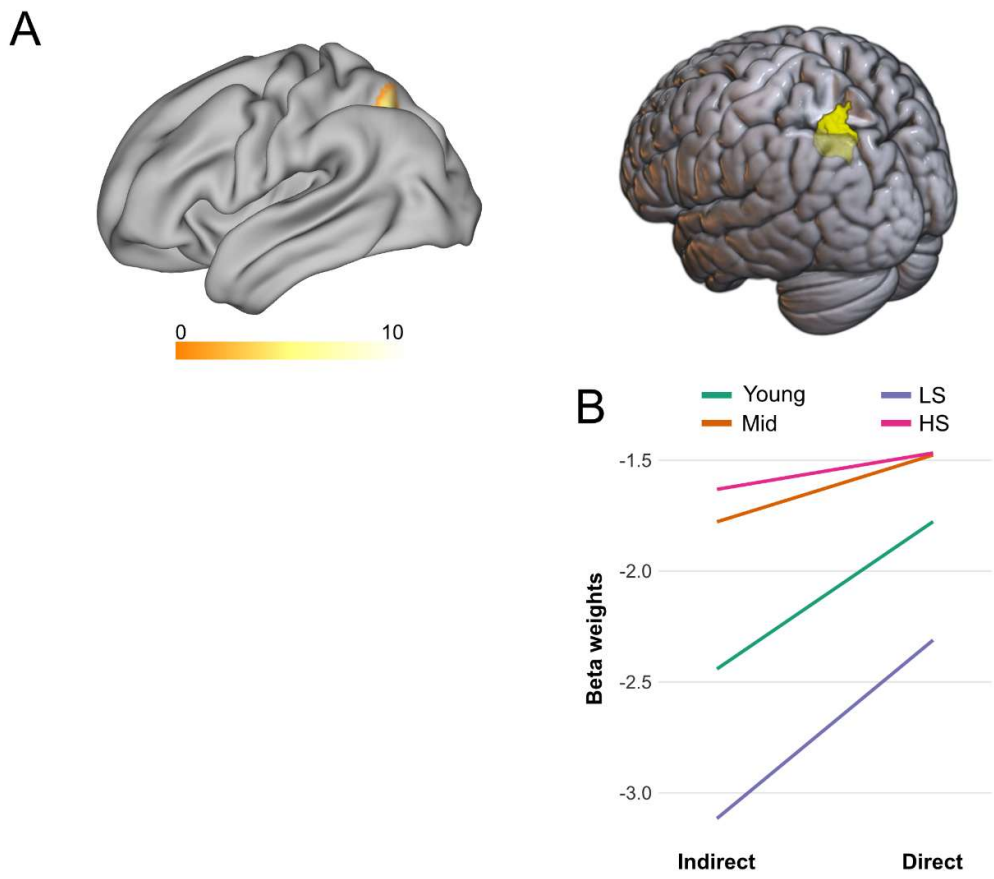

Figure 4. (A) Significant (with FWE-correction) cluster from whole-brain Indirect > Direct, Mid > Young comparison, in the left posterior intraparietal sulcus (IPS). (B) Mean beta weights from each condition per group

3.2.2 Testing for a potential developmental delay in the LS group

Testing for group effects between the HS group and adolescents (Young and Mid together) in the Indirect > Direct contrast revealed a single significant cluster, located in the posterior cingulate cortex (PCC) in the direction HS > Adolescents (Figure 5, Table S3). The location of this cluster was similar to the one found in the group effect Old > Adolescents (Figure S4), although more extensive in size, spanning further both posteriorly and dorsally. We extracted beta values (i.e., contrast estimates) from this cluster for all participants, separating into HS, LS, and adolescents. A one-tailed *T*-test (HS > LS) showed a significant difference between the two Old sub-groups ($T(55) = 3.24$, $P < .001$). Following up, we performed both frequentist and Bayesian *T*-tests in the direction LS > adolescents. The frequentist *T*-test was not significant ($T(40) = 0.16$, $P = .44$) and the Bayes Factor indicated moderate support for no group difference (BF = 0.28). Descriptive statistics for this ROI, also separating adolescents into the two subgroups are reported in Table 2. The data used in the tests is presented in Figure 5 (panel B).

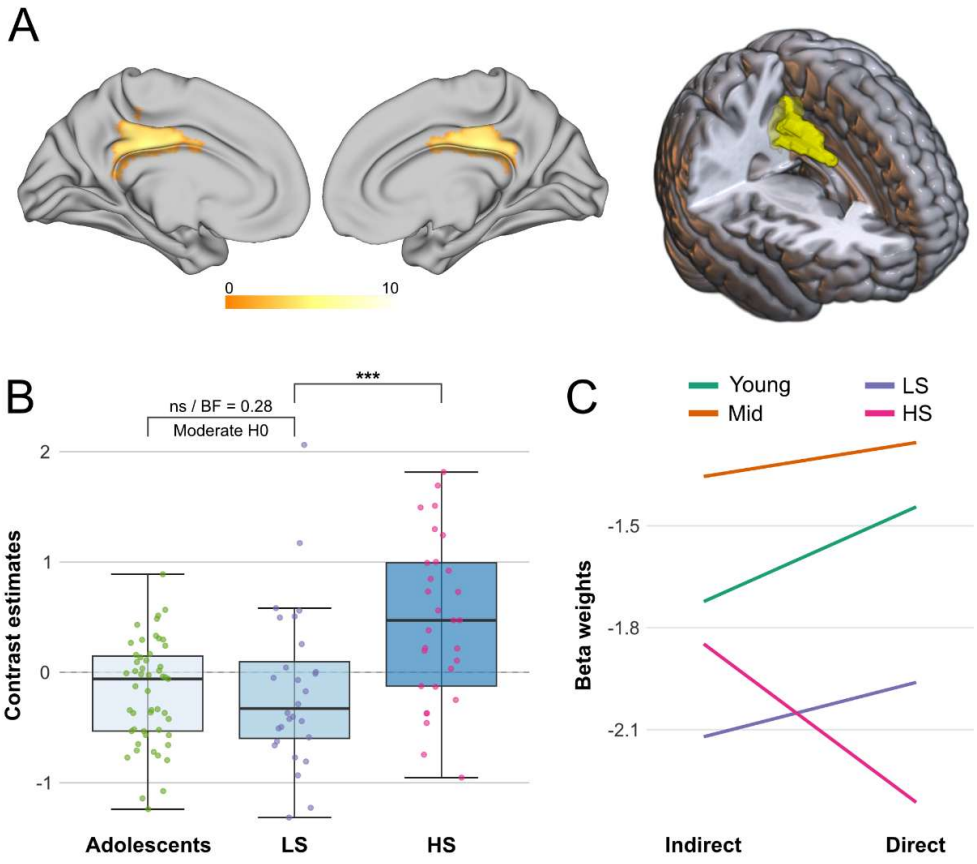

Figure 5. (A) Significant (with FWE-correction) cluster from whole-brain Indirect > Direct, HS > Adolescents comparison in the posterior cingulate cortex (PCC). White matter was masked out prior to running the group test. (B) Contrast estimates (Indirect > Direct) with results from *T*-tests (Bayesian *T*-test to assess support for the null-hypothesis when comparing the Adolescents and LS groups). Star notation: *** P_{raw} < .001. Box plots for all groups are provided in Figure S9. (C) Mean beta weights from each condition per group.

3.2.3 Follow-up descriptive statistics for Indirect > Baseline and Direct > Baseline

The mean beta weights of the Indirect and Direct conditions are reported in Table S5 for each ROI and group, including the PCC cluster from the HS > adolescent test reported in §3.2.2. We extracted these to get a better understanding of which condition and/or group was driving the results observed in our statistical analyses. The direction of the difference between the conditions per group are plotted in each ROIs respective figure (pmPFC: Figure 3C; IPS: Figure 4B; PCC: Figure 5C; amPFC: Figure S5C; and ATL: Figure S6C). It should be noted that the contrast estimates reported in Table 2 and presented with boxplots in the figures reflect the relative difference between the two conditions' beta weights (in the Indirect > Direct contrast).

Across all ROIs except the IPS and PCC, the Indirect condition showed overall positive mean beta values. In contrast, all groups exhibited negative mean betas in the IPS and PCC for both conditions. While negative betas here reflect relative deactivation compared to an implicit baseline, we will refer to less negative beta values in one condition relative to another as indicating higher activation, for simplicity.

In the IPS (Figure 4, panel A), the observed group effect (Indirect > Direct, Mid > Young) should thus not be interpreted as indicating higher IPS activation in the Mid group during Indirect speech act processing. Rather, the effect arises because the Young group showed relatively higher activation within the IPS during the Direct condition compared to the Indirect condition, whereas the Mid group responded more similarly to both conditions in this area (albeit still higher activity in the Direct condition). We observed a similar pattern within the Old participants: the LS group showed the most negative mean beta values in the Indirect condition and a larger difference between the two conditions, while the HS group had more similar responses across conditions.

In the PCC, only the HS group showed higher activation (i.e., less negative betas) in the Indirect relative to the Direct condition. This pattern reflects a directional reversal for the HS group relative to the other groups. Mean betas of each condition in the PCC are shown in Figure 5 (panel C). Plots for the remaining ROIs can be found in Figure 3 (pmPFC) and our supplementary materials, Figure S5-6.

As the extraction of the individual beta values for the two conditions provided deeper insight into what drove the effect in the group tests in the current study, we decided to revisit the data from Bendtz et al. (2022), i.e., the ParPrec-clusters, in a similar manner. We extracted betas for the Indirect > Baseline and Direct > Baseline contrasts using the ParPrec-clusters as separate ROIs. The parietal cluster showed a pattern between conditions and groups similar to the anatomically adjacent IPS-cluster. The precuneal cluster resembled the pattern of the PCC-cluster, though the mean betas were much more negative overall. The corresponding data are reported in Table S6 and the data is shown in figure S10.

4. Discussion

In the current study, we have found age-related differences in pragmatically relevant neural processes that underlie comprehension of indirect and direct speech acts. We observed an increased recruitment with age during indirect speech act (ISA) processing in the dorsal aspects of the posterior medial prefrontal cortex (pmPFC), which we suggest as a potential marker of pragmatic development. Furthermore, we found that the two adolescent groups (Young and Mid) differed in their activation patterns in a cluster in the left posterior intraparietal sulcus (IPS). This pattern was mirrored across the two adult groups (LS and HS), where the adults with pragmatic challenges (LS) resembled the Young group. Finally, we found differences between the HS group and the adolescents within the posterior cingulate cortex (PCC). In this latter cluster, we also gathered Bayesian support for the absence of differences between the adolescents and the LS group. Interestingly, these three clusters fall outside of the language network and mainly outside the ToM network, which have often been implicated in ISA tasks (Bašnáková et al., 2014; Bendtz et al., 2022). These findings are in line with the idea that pragmatic difficulties in adulthood are partially explained by a delayed adolescent development.

The posterior medial prefrontal cortex: Increasing activity with age

Our whole-brain analysis of the Mid group in the Indirect > Direct contrast yielded a cluster in the dorsal aspects of the posterior medial prefrontal cortex (pmPFC), which was absent in the Young group's results. This cluster overlapped with one of our ROIs, which we used to test for differences with age, also including the Old group. In the ROI-based analysis, we observed a trend of increased involvement of this cluster in indirect speech acts, whereas the anterior parts of the medial prefrontal cortex (amPFC, also used as a ROI) showed no significant differences with age.

What role may the pmPFC play in pragmatic processing, and why is it increasingly involved with age? We have previously suggested (Forbes Schieche et al., in press) that activity in posterior medial prefrontal areas can be interpreted in line with accounts of an abstract-to-context-specific gradient along the anterior–posterior axis in the frontal lobe (Badre & D'Esposito, 2009; Uddén & Bahlmann, 2012). The increased engagement of the pmPFC with age could indicate a developmental trajectory

towards more context-specific processing and expertise—in this case driven by repeated encounters of conversational contexts where the adolescent is highly socially motivated (e.g., peer conversations, Nippold, 1993, 2000; Raffaelli & Duckett, 1989). Notably, we did not observe any significant age-related differences in the amPFC, although all groups activated this region during ISA processing. This suggests that the posterior activity is not necessarily a replacement of anterior processes, but an additional mechanism recruited when interpreting indirect speech acts. This is consistent with our view that the anterior portion of this structure may govern general purpose/abstract ToM processes, relative to the more context-dependent posterior aspect.

While we have outlined a potential function for this cluster in the context of pragmatic comprehension, its broader functional identity is uncertain. A recent study has proposed that this area is a node in an extended language network (referred to as the medial superior frontal gyrus, Wolna et al., 2025). The location of the cluster (based on our ROI definition) also shows some overlap with one of six clusters from a recent meta-analysis of non-literal language comprehension (including ISA, Hauptman et al., 2023), most of which covered language and ToM areas.

The left posterior intraparietal sulcus: Different activation patterns based on adolescent age and adult pragmatic skill

Recall that we observed a significant difference between the adolescent groups (Mid > Young) in the Indirect > Direct contrast in a cluster in the left posterior intraparietal sulcus (IPS). At first, this may be interpreted as increased engagement during indirect speech act processing for the Mid group. However, closer examination of the data revealed that both groups showed higher activity for the direct compared to the indirect speech acts. The observed group effect was rather driven by the Mid group exhibiting a smaller difference between the two conditions compared to the Young group. A similar mirrored pattern was found when comparing the LS and HS groups, where the activation of the LS group resembled the Young group and the HS group the Mid group.

Potentially, the increased activation during direct speech act processing within this region, especially for the Young and LS groups, could reflect an increased recruitment of cognitive control functions. These functions, including working memory and cognitive flexibility, are supported by the fronto-parietal multiple demand (MD) network (Cole, 2024; Cole & Schneider, 2007; Diachek et al., 2020), which the IPS-cluster overlaps with. Notably, while only the IPS-cluster emerged in our test for group effects between the adolescent groups, the Direct > Indirect contrast for the Young group (Figure 2) yielded several clusters that overlap with regions commonly associated with the MD network. Thus, the Young group (and LS) may engage the MD system more when processing direct speech acts, perhaps because they are less sure whether a direct speech act should be interpreted as such and possibly attempting to apply an indirect interpretation. This might engage working memory processes, to revisit the previous conversational context or organizing one's thoughts to try to understand what an implicit meaning could be. As we see the same relation between the conditions in the Mid and HS group, albeit with less relative difference, they may at first consider the possibility that a direct speech act may be an indirect one, though they may quicker conclude that the direct interpretation is sufficient to understand what the speaker meant.

We also note the recent findings of a network, functionally dissociated from (though partially overlapping with) the MD network, anatomically spanning not only the IPS but also the dorsal precuneus (part of the ParPrec-clusters) (Fischer et al., 2016; Kean et al., 2025). While the function of this network has hitherto been described as intuitive physical reasoning, i.e., making inferences about physical objects, we do not preclude that future work may broaden the functional description of this network (possibly even to also include inferences about social situations). This may provide additional

perspectives on why we find the IPS to be relevant for (1) adolescent pragmatic neural development and (2) pragmatic individual differences in adulthood; and the dorsal precuneus relevant for (2).

The posterior cingulate cortex: Increased indirectness activity for the HS group and similarities between adolescents and the LS group

Like our findings in the IPS, activity in the posterior cingulate cortex (PCC) appears to reflect both developmental changes across adolescence and individual differences in adulthood. Specifically, adults in the HS group significantly differed from the adolescents, while our Bayesian analysis provided moderate support for no difference between the LS group and the adolescents. As shown in Figure 5C: the HS group showed greater activation in this cluster in the indirect condition relative to the direct one, while both the LS group and the adolescents showed the exact opposite pattern. These findings indicate that the PCC may serve as a marker of pragmatic development from adolescence into adulthood, while at the same time capturing pragmatic individual differences in adults. The similarity between the LS group and adolescents suggests that the LS group may exhibit delayed development and/or an extended immaturity, at least for pragmatic functions subserved by this region.

The PCC is one of the key hubs of the default mode network (DMN, Andrews-Hanna et al., 2010; Raichle, 2015), which has been implicated in introspective processing and the construction of situation models (Menon, 2023; Ranganath & Ritchey, 2012). One tentative interpretation of the increased activation in this area in the HS group during ISA processing may be that they make skillful use of previous experience and are flexible in their use of efficient situation models, all of which support pragmatic inferencing in difficult situations.

Extending results on partial segregation between pragmatics versus language and ToM

The original results in Bendtz et al. (2022) showed two clusters where the ISA effect was greater for HS compared to LS participants: the left anterior intraparietal sulcus and another in the bilateral dorsal precuneus (the ParPrec-clusters). These findings were taken to suggest that certain aspects of pragmatic processing can be, at least partially, segregated from language and ToM processes. Here we replicate and extend these results in several directions. First of all, the main ISA contrast is highly similar in the adolescent and adult groups (see supplemental materials Figure S2-3), which shows the robustness of the experimental and analytical methods used. Furthermore, all three described clusters were located outside the classical perisylvian language network. The locations compared to the ToM network are more complex (particularly in respect to the PCC), but it is far from a complete ToM network that we observe.

The proposed segregation of pragmatics from ToM and language is further supported by our recent investigation (Forbes Schieche et al., in press), which examined resting-state functional connectivity in the same sample. Mean connectivity between the ParPrec-clusters significantly differed between the LS and HS groups (HS > LS), and connectivity between the ParPrec-clusters and the ToM network was near zero (i.e., no correlated activity). These findings reinforce the view that the ParPrec-clusters are pragmatically relevant and that they should *not* be considered an extension of the ToM network (nor the language network), highlighting a partial segregation of pragmatic processing from these systems. Preliminary results from a pilot sample however show some overlap (and connectivity) with the MD network, in particular for the cluster in the intraparietal sulcus (see further Forbes Schieche et al., in press).

Adolescent pragmatic development beyond ISA

Our results are limited by only using one aspect of pragmatics (ISA) to study neural development of pragmatics. A valid concern is how findings from such ISA-based paradigms generalize to pragmatic processing more broadly. The recent meta-analysis of fMRI studies by Hauptman et al. (2023), which

included ten types of non-literal language (including ISA), identified six clusters in the left hemisphere. These clusters were generally located within either the language or ToM networks. Notably, four of these clusters overlap with the general findings of the Indirect > Direct contrast in Bendtz et al. (2022), including the anterior superior temporal gyrus and sulcus (STG/STS), inferior frontal gyrus (IFG), temporoparietal junction (TPJ), and dorsomedial prefrontal cortex (dmPFC).

While the different iterations of the ISA paradigms target a specific pragmatic phenomenon (as would be the case in any experimental study), the observed overlap with Hauptman et al.'s (2023) meta-analysis suggests that they engage some general mechanisms shared by different forms of non-literal language (which can be considered to be part of the pragmatic domain). However, as shown in both Bendtz et al. (2022), Forbes Schieche et al. (in press), and the current paper certain aspects of pragmatics appear to extend beyond the language and ToM networks.

Conclusion

The outcomes of the present study provide evidence for the continuous development of pragmatic processing throughout adolescence and into adulthood. We have also shown that the neurobiological site of this development is not in core regions of the language and ToM networks but may rather involve cognitive control functions and the mid posterior node of what is sometimes called the core default mode network. Moreover, as we have investigated pragmatic processing in both adolescents and adults and observed a similarity between individuals with challenged pragmatic functioning and younger adolescents, we have shown that pragmatic challenges in adulthood may reflect a delayed developmental path.

Acknowledgements

The authors want to thank Katarina Bendtz and Josephine Schneider for their role in the early phase of this project, e.g., collecting the behavioural and MR data of the adult sample, and Josephine Schneider for her contribution to the ethical application supporting the adolescent data acquisition. We also thank Ronja Roll, Johanna Sundström, Naira Sardarian, and Annika Andersson for their assistance in collecting the adolescent data. Data acquisition was supported by a grant to the Stockholm University Brain Imaging Centre (SU FV-5.1.2-1035-15).

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