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Theory of Mind, pragmatics, and the brain: Converging evidence for the role of intention processing as a core feature of human communication

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Abstract

Theory of Mind (ToM) is a neurocognitive system that allows the perceiver to attribute mental states, such as intentions, beliefs, or feelings, to others' actions. The aim of the present work is to analyse the engagement of the ToM system in communication, in particular, in communicative intention processing. To this aim, we propose an Intention Processing Network (IPN) with its own principles and mechanisms, that is, a brain network differentially engaged according to the complex intertwining of the context, goal, and action involved. According to our IPN model, a set of brain regions of the ToM system (i.e. left and right temporoparietal junction, precuneus, and medial prefrontal cortex) are differentially involved in comprehending different types of intention, such as private or social intentions. We provide independent and convergent evidence on the role of the IPN model in communicative intention processing and we show that the engagement of the IPN does not depend upon the communicative means used, that is, written language, auditory language, or gesture. Evidence deriving from different experimental paradigms, including neuroimaging, lesion, neurodegenerative, and brain stimulation studies are discussed. In our view, this evidence establishes a link between ToM and pragmatics studies and suggests the role of intention processing as a core feature of human communication.

Keywords: Communication, Cognitive Pragmatics, Communicative intention, Intention Processing Network, Pragmatics, Theory of Mind

List of abbreviations:

bvFTD = Behavioral variant of frontotemporal dementia;

fMRI = functional Magnetic Resonance Imaging;

IFG = Inferior frontal gyrus;

IPN = Intention processing network;

MNS = Mirror neuron system;

MPFC = Medial prefrontal cortex;

pSTS = posterior superior temporal sulcus;

rTMS = repetitive transcranial magnetic stimulation;

tDCS = transcranial Direct Current Stimulation;

ToM = Theory of Mind;

TPJ = Temporoparietal junctions.

Introduction

Social life rests on the ability to understand other people's actions, in particular, their reasons for behaving as they do, and what they are likely to do next. However, most actions are just observable consequences of unobservable internal mental states, such as individual goals or intentions, as well as beliefs or desires. In the last two decades, students in social cognitive neuroscience have focused on the neural correlates of the human ability to make sense of others' social actions. Three neurocognitive systems play a pivotal role in social information processing: the social perception, action observation, and Theory of Mind (ToM) systems (Arioli and Canessa 2019; Quadflieg and Koldewyn 2017; Yang et al. 2015). The *social perception system* allows the perceiver to detect, encode, and analyse others' external behavioural signals to manage the complex information that constitutes a person's distinctive social appearance. This neurocognitive system mainly involves the occipital and fusiform face and body areas, along with the posterior superior temporal sulcus (pSTS), a region sensitive to dynamic facial and bodily input. The *action observation system* is dedicated to motor and action understanding, primarily embracing the perceiver's self, that is, it requires perceivers to go beyond merely decoding others' external signals to match observed actions to their own actions. This neurocognitive system mostly overlaps with the mirror neuron system (MNS) and involves the inferior parietal lobule, the ventral premotor cortex, and the inferior frontal gyrus (IFG), a region relevant to motor control and language processing. Finally, to comprehend and predict others' behaviours, the *ToM system* allows the perceiver to attribute mental states, such as intentions, beliefs, or feelings, to others' actions, primarily involving the medial prefrontal cortex (MPFC), the temporoparietal junctions (TPJ), and the precuneus (Abu-Akel and Shamay-Tsoory 2011; Schurz et al. 2014).

In recent years, the ToM system has attracted great attention within the social cognitive neuroscience domain, in particular for its role in intention processing, as it responds to the *why* of a social action in a particular context, especially when integration of complex contextual information is required for intention attribution (Spunt et al. 2011; Van Overwalle and Baetens 2009). The present paper focuses on the role of the ToM system in the elaboration of a particular kind of social action, that is, communicative action. In the last decade, we have performed a series of neuroimaging studies investigating the role of the ToM system in different social and non-social contexts. The aim of the present work is to analyse the engagement of the ToM neurocognitive system in communication, in particular, in processing communicative intention. We shall first examine the role of intention processing in the comprehension of general action and then of communicative action; we propose an intention processing brain network able to discriminate between social and non-social contexts and between future and present communicative intentions. Our aim is to clarify the crucial intersection between cognitive intrapersonal brain activity and the most important interpersonal domain, that is, communication.

Intention processing for general and communicative action

Intention processing of observed actions requires different attribution processes, such as agent attribution (*who*), which allow the attribution of an intention to its author; motor or action intention attribution (*what* or *how*), which enable identification of the motor intention from the observation of an action; and goal-representation (*why*), which permits the identification of the goal of an intended action within a specific context (Becchio et al. 2006; Spunt et al. 2010). These attribution processes roughly correspond to the neurocognitive systems previously described, in particular, the attribution of *what* plays a critical role in the social perception system, and the attribution of *how* plays a critical role in the action observation system. The attribution of *why*, in particular, understanding of the *why* vs. the *how* of action, is a social cognitive process that has recently been the subject of interesting research in social neuroscience (Spunt and Adolphs 2014). This ‘pragmatic’ approach to action understanding focuses on the role of ToM processing in intention attribution, as it represents what Frith and Frith (2006) called ‘what happens next’ in a social setting.

The pragmatic approach to action understanding is well represented by the works of Spunt and colleagues (Spunt et al. 2016), according to which the neural system recruited when people understand others’ actions depends on whether they are considering *how* or *why* the action is being performed. Although identifying *how* actions are being performed engages activity in premotor areas, identifying *why* actions are being performed mainly involves the brain regions of the ToM system (i.e. the MPFC, TPJ, and precuneus). In a seminal functional magnetic resonance imaging (fMRI) work using naturalistic videos of ordinary human actions, Spunt et al. (2011) induced three levels of action identification by instructing participants to describe *what* the character is doing (intermediate level, e.g. reading a book), *how* he is doing it (low level, e.g. flipping pages), or *why* he is doing it (high level, e.g. obtaining knowledge). As the level of identification increased, the demand on mental state inference also increased and, in turn, the activation of the brain areas of the ToM system; on the contrary, no significant increase in MNS activity (namely, the action observation system) was found. In a further study, Spunt et al. (2016) tested if the same action (e.g. ‘make a phone call’) could be represented at different levels and directions of abstraction, such as from *how* to *why* and vice versa: the higher level (from *how* to *why*) specifies the abstract intention that explains why the action is performed (e.g. ‘contact a friend’ or more abstract ‘feel connected’), while the lower level (from *why* to *how*) specifies the concrete stages that indicate how the action is performed (e.g. ‘dial numbers’). These authors found that conceptualizing actions by increasing the level of abstraction specifically recruited the ToM system. On the contrary, decreasing the level of abstraction did not recruit ToM brain regions but a broader network, including MNS core regions, which enable representation of the visual and somatomotor features of actions. Similarly, Van Overwalle (2009) and Van Overwalle and Baetens (2009) discussed which brain areas are responsible for understanding the actions of others and their underlying goals. These authors proposed a model in which actions and goals are organized hierarchically according to the level of abstractness, and that distinguishes between immediate goals that reflect the understanding of basic actions and long-term intentions that reflect the *why* of an action in a social context.

We adopt the *why* vs. the *what/how* distinction in the comprehension of social actions, applying it to the particular case of communicative actions, where it could guide the reconstruction of the reasons underlying the realization of a communicative intention. As we will discuss, this approach could be considered a cognition/pragmatics interface that links the *why* of action to the *why* of communicative action.

Intention processing and communication

Following Grice's proposals (Grice 1957, 1975), pragmatic theories of communication claim that human communication ability is specialized for the expression, recognition, and reconstruction of intentions via communicative actions, independently of the linguistic or extralinguistic modalities used to convey those intentions (Bara 2010). Accordingly, communication is a social action used to affect and modify the mental states of others, and communicative intention is the primary mental state involved in explaining other people's communicative actions. Philosophy of language and Cognitive Pragmatics define communicative intention as the intention to communicate a meaning to someone else, plus the intention that the former intention should be recognized by the addressee (Airenti et al. 1993; Bara 2010; Grice 1975).

Different authors argue that communicative intention processing does not simply consist in applying general ToM abilities to a particular communicative behaviour; rather, it involves a dedicated intention processing network, with its own principles and mechanisms (Bara et al. 2016). According to Sperber and Wilson (2002), the problem of applying a general procedure for inferring intentions from actions to the special case of inferring communicative intentions from communicative actions is that communicative intentions typically carry a vastly greater amount of information than more ordinary motor intentions. 'Quite simply, we can say so much more we can do' (Sperber and Wilson 2002, p.11). Hence, to describe the neural correlates of the pragmatic comprehension of communicative intentions, it is mandatory to explore which and how brain regions of ToM processing are engaged.

The Intention Processing Network

Action understanding requires inferential and mental attribution processes that assign a goal to action by evaluating its efficiency as a mean of obtaining the goal within specific context constraints (Brass et al. 2007). Within a social cognitive neuroscientific perspective, in recent years, we have performed a series of neuroimaging studies which led to the proposal of the Intention Processing Network (IPN) model. According to our model, a subset of regions of the ToM system is differentially involved in comprehending different types of intention, such as private or social intentions (Bara et al. 2016). The IPN model introduces a theoretical distinction that differentiates the social involvement of agents, namely private versus social dimensions of intention, and the temporal dimension, namely, the present or prospective dimensions of social interaction. Whereas private intentions only involve the actor satisfying a particular goal (e.g. grabbing a bottle of water to quench thirst), in social intentions, conversely, the goal of the actor is satisfied only if at least one other person is involved. Additionally, we can distinguish a temporal dimension of social intentions that are shared in present or prospective (future) interactions. When two agents interact, the social intention is shared in the present (e.g. asking a traffic policeman for directions), such as in communicative intention. When a given social interaction is not present at the moment but the action of a single agent leads to it, the social intention is potentially shared in the future (e.g. buying a Christmas present for a friend). We define this type of social intention as prospective social intention (Bara 2011).

In a set of fMRI studies (Bara et al. 2011; Ciaramidaro et al. 2007; Walter et al. 2004; Walter et al. 2009), we used a story completion task presented in a comic strip form to show the differential recruitment of the ToM network according to the IPN model described. The stories depicted one or two characters that were involved in private versus social situations, and required participants to represent private intentions based on observations of a character's isolated actions (e.g., observing a single person changing a broken bulb in order to read a book); prospective social intentions based on observations of a character's isolated actions aimed to interact with someone else in the future (e.g., observing a single person preparing a romantic dinner for another person who was not present in the scenario); communicative intentions based on observations of two characters interacting (e.g., observing a person obtaining a glass of water by asking another person to get it for her); and finally, non-intentional causal links among objects, namely, a physical causality control condition (e.g., a ball blown by a gust of wind knocking over a glass of water and breaking it).

The brain areas associated with the IPN included different fundamental regions engaged by ToM processing, namely the MPFC and precuneus, along with the bilateral pSTS and adjacent TPJ, brain areas referred to collectively as the TPJ in this work, for simplicity, although see Gobbini et al. (2007) and Saxe (2006) for a specific dissociation of these regions. The IPN model showed that the entire network was only activated during communicative intention processing when two characters were depicted in a communicative interaction. In contrast, the activated network was limited to posterior brain areas (i.e. the right TPJ and precuneus) when the character was acting according to a private intention. For prospective social intentions, our data showed that the recruitment of the right TPJ and precuneus does not suffice when an agent is manifesting a social intention to be shared in the future; in this case, recruitment of the MPFC is also necessary. Because of this pattern of activation, we define the IPN model as the progressive recruitment of the four key regions associated with ToM processing according to the different intentions involved: specifically, the precuneus and right TPJ for private intentions, the precuneus, right TPJ, plus the MPFC for prospective social intentions, and finally the precuneus, right TPJ, MPFC, plus the left TPJ for communicative intentions (Figure 1). Finally, it is important to note that the IPN showed no complete anatomo-functional overlap with the brain regions of the ToM system: for example, the IPN does not include the amygdala, the orbitofrontal regions, or the temporal pole that are mainly involved in affective ToM, that is, the ability to process other people’s emotions and feelings (see Abu-Akel and Shamay-Tsoory 2011; Carrington and Bailey 2009).

Insert Figure 1 about here

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Since Cognitive Pragmatics proposes that a communicative intention should be recognized by the addressee regardless of the communicative means used to convey it (Bara 2011), in two further fMRI studies (Enrici et al. 2011; Tettamanti et al. 2017) we specifically investigated whether the same communicative intention conveyed by language or gesture engages similar or different brain regions of the IPN, with the working hypothesis of a strong overlap between the two modalities. In the first neuroimaging study (Enrici et al. 2011), we adopted a modified version of the story completion task previously used, representing communicative intentions in either linguistic modality (simple and direct communication acts in written form) or gestural modality (depicted conventional ideational gestures, particularly emblem gestures). We compared these intentional conditions with two non-intentional control conditions (physical causality established among objects) (see Figure 2). Findings agreed with the Cognitive Pragmatics prediction as they revealed that the same pattern of brain areas belonging to the IPN was recruited for the comprehension of communicative intention, independently of the linguistic or gestural modality through which it was conveyed. Additional brain areas, outside those involved in intention processing, were specifically engaged in accordance with the particular communicative modality. Specifically, the linguistic modality recruited the perisylvian language network, including the pars opercularis of the left IFG. By contrast, the gestural modality recruited a sensorimotor network, including the pars opercularis of the right IFG. Based on these results, we suggested a modality-specific gateway hypothesis according to which the left and right IFG reflect modality-specific input gateways, conveying stimuli and associated high-order information to the IPN (Figure 2).

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Insert Figure 2 about here

In a second connectivity study (Tettamanti et al. 2017), we tested the modality-specific gateway hypothesis by using dynamic causal modelling to measure inter-regional functional integration dynamics between the IPN and left/right IFG gateways. We found strong evidence of a well-defined effective connectivity architecture mediating functional integration between the IPN and inferior frontal cortices. The analysis indicates a modality-specific propagation of information from the left IFG to the IPN for the linguistic modality, and from the right IFG to the IPN for the gestural modality. The findings corroborate the hypothesis that the left and right IFG represent modality-specific gateways that allow linguistic and gestural stimuli information, respectively, to be integrated into communicative intentions elaborated through the IPN (Figure 3).

Insert Figure 3 about here

Taken together, these fMRI studies describe a well-defined set of brain regions, prominently associated with ToM processing, that form a network with its own principles and mechanisms, recruited for intention processing. The IPN model we proposed showed, first, that different brain areas associated with ToM processing are specifically involved in communicative contexts, in particular in the attribution of communicative intentions. Second, we showed that, in terms of ToM engagement, communicative intention processing is independent of the expressive modality through which communicative intentions are conveyed. Finally, we reported that two additional neural gateways in the inferior frontal cortices, regions mainly associated with the action observation system, are recruited by the modality through which communicative intentions are conveyed.

It is important to note that tasks assessing different cognitive functions outside communication, in both social and non-social domains, show the involvement of all or part of the ToM brain areas included in the IPN model (see for example Spreng et al. 2009). In particular, the MPFC has been interpreted in terms of different functional roles, either domain-specific or domain-general (Bzdok et al. 2013; Hartwright et al. 2014). For example, Gilbert et al. (2006; 2007) found that different regions of the rostral MPFC are differentially associated with social and non-social functions, such as attention and multiple task coordination, and episodic memory. Nonetheless, it is equally important to stress that the ToM brain areas included in the IPN model do not encompass a general reasoning network, that is, reasoning processes of both social and non-social entities. According to Van Overwalle (2011), there are many differences in the involvement of the ToM brain areas between social and non-social reasoning tasks. In particular, the MPFC is recruited much less often when the experimental stimuli do not involve ToM about human actions or mental traits. There is a decreased likelihood of MPFC activation when reasoning stimuli contain limited social intention processing. Van Overwalle (2011) suggested that claims of a common network for general and social reasoning are probably due to anatomical confounds between ToM core regions and other nearby brain areas. Although this evidence would allow for an even stronger claim, we prefer a more cautious position and thus do not claim that the individual ToM brain areas included in the IPN model are necessarily engaged only during intention processing; instead, we claim that, as a whole, these areas form a dedicated neurocognitive system with its own principles and mechanisms allowing intention processing in communication.

In the following paragraphs, we provide independent and convergent evidence on the role of ToM brain areas of the IPN model in communicative intention processing. We will discuss evidence deriving from different experimental paradigms, including neuroimaging, lesion, neurodegenerative, and brain stimulation studies.

Independent neuroimaging evidence for the IPN model

Important independent evidence on the role of ToM brain areas in communication comes from three related domains of neuroimaging research, such as studies on narrative and pragmatics processing, and studies using pseudo or real interactive paradigms.

Narrative processing

Stories are used extensively for human communication, and both the comprehension and production of oral and written narratives constitute a fundamental part of our experience, both interpersonal and intrapersonal. Mar (2004, 2011) has demonstrated that ToM processing and narrative comprehension of both written and auditory stories engage similar neurocognitive processes (see also Yuan et al. 2018 for production storytelling). The brain network involved in stories and narrative comprehension overlaps with both brain regions associated with story-based ToM studies, that is, studies that have investigated ToM using written stories, and with non-story-based ToM studies, that is, studies that have investigated ToM abilities via observed behaviours. The overlapping regions include different ToM areas of the IPN model, such as the bilateral MPFC, and the pSTS/TPJ, along with the left IFG, associated with linguistic processing. Accordingly, similar processes are involved in understanding the mental states of both real and fictional others (e.g. characters in a novel or a film) described in both written and auditory forms (Mar and Oatley 2008; Oatley 2016). Consistent with this idea, different authors have demonstrated that lifetime exposure to narrative fiction is positively associated with social abilities (e.g., Mar et al. 2006), and that fiction reading leads to a small but statistically significant improvement in social cognitive performance, in particular in ToM tasks (Kidd and Castano 2013), compared to non-fiction reading or no reading (Dodell-Feder and Tamir 2018).

Overall, this evidence is important for two reasons: first, the ToM brain areas associated with communicative intention processing are commonly involved in both observed behaviours and written stories scenarios; thus, not only by the direct observation of others' behaviours but also by the narration of others' behaviours. Second, this represents further evidence of the independence between the ToM system and processes associated with the specific communication means or narrative form used to describe a communicative action, that is, a written text or auditory story as well as observed actions.

Pragmatic processing

Significant independent evidence on the role of ToM brain areas in communication comes from neuroimaging studies on non-standard communication, that is, pragmatics phenomena in which the intended and the literal meaning do not correspond.

Irony comprehension is one of the most investigated pragmatics phenomena that requires inference processes to comprehend the speaker's meaning, starting from the literal meaning, and in which the communicative intention often corresponds to the opposite of the literal meaning. Shibata et al. (2010) reported specific activation in the right MPFC, left precuneus, left STS, and right precentral gyrus in the understanding of ironic vs. literal sentences. Similarly, Spotorno et al. (2012) compared participants' comprehension of brief stories in which a target sentence (e.g. 'Tonight we gave a superb performance') was made either ironically or literally, depending on the context in which it was expressed (e.g. a terrible performance in the ironic condition and an impressive performance in the literal condition). Their findings showed that all the ToM brain areas of the IPN model were active when participants understood verbal irony, suggesting a strong relationship between irony comprehension and ToM processing.

Another pragmatic phenomenon that presents a gap between the intended and the literal meaning is metaphor comprehension. Prat et al. (2012) manipulated figurativeness in metaphor comprehension using three figurative conditions of increasing difficulty and showed right TPJ and superior medial frontal activation for all figurative conditions compared with a literal condition. Moreover, a volumetric analysis showed that these regions were sensitive to figurativeness and not to difficulty manipulations. These authors suggested that these areas respond to the increased social processing demands of the figurative conditions, as in these conditions, 'insights into the intentions (or theory of mind) of the protagonist were relevant for comprehending the critical utterance' (Prat et al. 2012, p. 290).

Activation of both the MPFC and right TPJ were also found in comprehension of indirect speech acts, in which a pragmatic inference was necessary as the speaker's meaning was implicit (Basnakova et al. 2014). Compared with direct control utterances, in which the speaker's meaning was explicitly stated and corresponded to the literal meaning, the comprehension of indirect speech acts engages a set of brain areas mainly including the MPFC and right TPJ. The involvement of all the IPN nodes was found by van Ackeren et al. (2012) in the understanding of indirect speech acts. Comparing the brain activation underlying the comprehension of the same utterance such as 'It is very hot here' used as an indirect request to open a window or as a direct speech act in the context of a desert scene, these authors found significant left and right TPJ, precuneus, and MPFC activation, which strongly overlapped with the IPN.

The comprehension of implicated meanings in everyday conversations was investigated by Jang et al. (2013). These authors analysed, in particular, the comprehension of conversational implicatures, specifically focusing on the implicature in which the maxim of relevance is violated. Participants underwent an fMRI task with a series of conversational pairs, each consisting of a question (e.g. 'Is Dr. Smith in his office now?') and an answer, including explicit answers (e.g. 'Dr. Smith is in his office now'), moderately implicit answers (e.g. 'Dr. Smith's car is parked outside the building'), and highly implicit answers (e.g. 'The black car is parked outside the building'). Results showed that the comprehension of highly implicit answers increased activation of the left MPFC, left posterior cingulate cortex, and right anterior temporal lobe, along with the left IFG. Jang et al. (2013) suggested that the involvement of the MPFC and precuneus can be attributed to the ToM processes necessary to build coherence between literally irrelevant but pragmatically relevant utterances.

Overall, this evidence showed that the ToM brain regions included in the IPN model are crucially engaged in pragmatic phenomena when communicative intention has to be reconstructed starting with discrepancies between intended and literal meaning.

One-sided interaction: communicative production vs. comprehension processing

Communicative exchange requires the construction of an acceptable interpretation of the reciprocal communicative actions at all levels that participants consider significant (Bara 2010). Although we can consider a single agent when we refer to intention attribution to actions in general, we should always refer to at least one actor and a partner to whom the act is directed in the domain of intention attribution in communication (Bara et al. 2016). The meaning of a communicative exchange emerges then from the mutual interplay of interactive agents embedded in a specific context (Adenzato and Bucciarelli 2008; Adenzato and Garbarini 2006; Vicari and Adenzato 2014).

Few neuroimaging studies have examined full communicative exchanges that include the act proposed by an actor and the concurrent reaction of a partner. The majority of studies, including our previous works, almost exclusively analysed communicative comprehension, that is, when the communicative intention has to be reconstructed by the addressee. Most communicative comprehension studies have focused their analysis on processes that take place outside a communicative exchange or on early phases of communicative interaction. For example, some neuroimaging studies examined comprehension of early signals that convey an intention to communicate or attempt to initiate a communicative interaction, such as pointing a finger directly at the subject, looking directly at someone, or calling their name (Kampe et al. 2003; Materna et al. 2008). Other studies asked subjects to passively observe communicative actions performed by a single actor, for example, a gesture directed toward someone or placing a cup in front of them (Andric et al., 2013; Tylen, Allen, Hunter, & Roepstorff, 2012; but see also Arioli et al., 2018; Canessa et al., 2012). Finally, an interesting study examined the perception of being personally addressed in a communicative exchange matching the same communicative intention (e.g. 'I'm cold. Are you?') expressed by linguistic vs. gestural modalities, and showed shared processing of gesture and language (Redcay et al. 2016). In these studies, different ToM brain areas included in the IPN (such as the MPFC, TPJ, or pSTS)—but not necessarily the whole network—were recruited according to the kind of signal used to elicit a communicative interaction. It is important to underscore that within these experimental situations a communicative exchange between agents is merely put forward by the actor or character, but does not actually take place.

Other studies on communicative comprehension used interactive paradigms with a one-sided interaction situation, that is, without a concurrent reaction from a partner (Gallagher et al. 2002; Kircher et al. 2009; McCabe et al. 2001). In these works, the interaction was mediated by a game interaction, for example, cooperative or competitive games in which participants were directly involved in social interaction, but without a real communicative exchange. Results of these studies reported activation of brain areas of the ToM system, such as the MPFC and right TPJ, in particular when participants were playing, or thought they were playing, with a human counterpart rather than with a computer.

Very few studies have investigated communicative production, that is, when the communicative intention is formed by the agent to communicate, using real interactive situations where a full communicative exchange was presented. Most studies that have examined communicative production processing again used a one-sided interaction. For example, Calarge et al. (2003) proposed an imaginative communicative scenario that required participants to invent and say aloud stories describing imaginary encounters with strangers. The results showed that compared with a control condition in which participants read aloud stories requiring no mental state attribution, the imaginative communicative scenario was associated with ToM brain activations quite similar to those of the IPN.

One of the first fMRI studies that used a linguistic interaction paradigm, even though one-sided, is probably the work by Sassa et al. (2007). Using short video clips of daily actions in which an actor used a tool or handled an object and glanced at the camera, participants were required to respond to clips by talking to the person on the screen in a casual communicative manner (communicative condition) or verbally described the actor's situation (descriptive condition). Both conditions involved speech production, but only the communicative condition required a specific and explicit communicative intent directed to the actor. Accordingly, only communicative trials showed increased activation in the MPFC, and bilateral TPJ, along with temporal poles. Moreover, MPFC and precuneus activation were stronger for video clips where the actor was a close friend of the subject compared to clips where the actor was unfamiliar. Another one-sided interaction was proposed by Willems et al. (2010) in which participants were engaged in a communicative interaction through an interactive game (Taboo). The participant inside the MRI scanner generated verbal descriptions of target words without using predetermined 'taboo' words, while the other player outside the MRI scanner listened to these descriptions and guessed the target word. Interestingly, manipulating communicative intent, that is, changing whether the listener already knew the target word or not, and linguistic difficulty, influenced activation patterns in different brain regions. Most importantly, while MPFC activation was sensitive to the communicative intention manipulation, irrespective of linguistic difficulty, activation of the left IFG was sensitive to manipulations of linguistic but not of intention demands. These findings critically converge with the assumption of independence between ToM and communicative means processing adopted in our IPN model.

Finally, a recent and interesting study of one-sided communicative production (Kuhlen et al. 2017) examined the preparatory neural activity associated with the intention to speak, in the seconds that preceded a communicative exchange. The study analysed two distinct conditions of speech production: in one, participants thought a conversational partner would hear them, in another, the speech production was a technical calibration in which a conversational partner was absent. Results showed that the activity of the MPFC and ventral prefrontal cortex (bilaterally) was the only brain activation that differentiated the two conditions, specifically encoding the intention to speak with a conversational partner.

Two-sided interaction: the two-brain approach

A novel neuroimaging approach to the study of neural correlates of intention processing in communication is what Konvalinka and Roepstorff (2012) have called the two-brain approach (see also Chatel-Goldman et al. 2013), an interactive approach in which the fMRI setting involves a two-person interaction. These authors distinguished two paradigms, online and offline interaction: the first one uses a simultaneous recording of brain activity from both interactive partners at the same time (also known as hyperscanning, see Montague et al. 2002), whereas the second one recorded the two partners one after another.

Unfortunately, almost all studies that have recently adopted this two-brain approach have tested non-social or non-communicative exchange, for example, joint attention during eye contact (Saito et al. 2010), or a task that required simply observing the sender's emotional facial expression (Anders et al. 2011), as well as economic exchange (King-Casas et al. 2005). Not surprisingly, these studies reported brain activation outside the ToM system. To the best of our knowledge, only two studies used the two-brain approach with real interactive communicative situations, both in offline interaction: one with communicative gestures (Schippers et al. 2009) and one using language (Stephens et al. 2010, but see also Gordon, Rigon, Covington, Voss, & Duff, 2019). Schippers et al. (2009) used an interactive paradigm that represents a communicative interaction situation, such as playing charades. In this game, participants were presented with a word on the screen and instructed to communicate this word to a partner using gestures. Activation in a combination of MNS and ToM brain areas was found. Stephens et al. (2010) examined the brain activity of a speaker telling a story related to a personally relevant experience and the brain activity of a listener listening to a recording of the story. These authors found a spatial and temporal coupling between production and comprehension across speakers' and listeners' brains during this kind of verbal communication. This neural coupling during communication was observed at different levels, including production-based areas (e.g. Broca's area), comprehension-based areas (e.g. Wernicke's area), and, most importantly, ToM areas (e.g. the precuneus, TPJ, and MPFC).

Once again, taken together, these results represent strong evidence of the role of the IPN in communicative intention processing in both linguistic and gestural modalities.

Convergent lesion and neurodegenerative evidence for the IPN model

Neuroimaging evidence seems to support the role of ToM regions of the IPN model as a neural substrate for the pragmatic comprehension of a speaker's intended meaning. Nevertheless, it is important to note that while neuroimaging techniques provide relevant information about the involvement of a brain area in a given task, they are silent with respect to whether the brain structure is necessary for the task. Sufficient and necessary neural systems can only be identified by an iterative approach that integrates functional imaging studies of normal subjects with lesion and neuropsychological models provided by neurologically damaged subjects. Thus, the neuropsychological approach plays an important role in complementing functional imaging techniques and in testing theoretical hypotheses about cognitive architecture (Rorden and Karnath 2004). In the following sections we examine independent, and most importantly, convergent evidence for the IPN model, deriving from patients with neuropsychological and neurodegenerative pathological conditions that affect ToM brain regions.

Lesion studies

Few studies have analysed how lesions in prefrontal regions affect intention processing in communication. One of the first studies (Lee et al. 2010) found that people with MPFC lesions show specific deficits in inferring speaker intentions using the Faux-pas Test, that is, communicative situations where a speaker says something he or she should not have said. Differentiating patients with traumatic brain injury to the prefrontal cortex (PFC) into dorsolateral and ventromedial groups, Geraci et al. (2010) found that both groups performed equally poorly on the Reading the Mind in the Eyes test, which presentation via photographs of human eye regions permits assessment of the affective component of ToM, but only patients with ventromedial lesions performed poorly on the Faux-pas Test. According to these authors, both the dorsolateral and ventromedial PFC play an important role in interpreting social information encoded in the eye region, but only the ventromedial PFC plays a key role in the inferential components of intention attribution. Finally, Roca et al. (2011) analysed intention and multitasking processing on patients with lesions to the rostral PFC, that is, the Brodmann Area 10, and found that deficits in multitasking were specifically related to the extent of damage in the right lateral part, while deficits on the Faux-pas Test were related to damage of this brain area in general.

Other convergent evidence comes from patients with lexico-semantic impairments, such as in aphasia. These patients present profound language impairments with extensive damage to the traditional frontotemporal language network, but without specific ToM deficits (see Willems and Varley 2010, for a review). For example, Varley and Siegal (2000) reported the case of S.A., a patient with severe agrammatic aphasia but with preserved ToM reasoning, tested with false-belief tasks, that is, tasks that required the attribution of different orders of false beliefs. This dissociation was also reported by Varley et al. (2001), who discussed the case of M.R., a patient with impaired performance in linguistic tasks but preserved ToM reasoning, and by Apperly et al. (2006), who described the case of. P.H. in which severe agrammatical aphasia did not prevent this patient from solving non-verbal first-order and second-order false-belief tasks. Accordingly, using alternative communicative resources, such as drawing, facial expressions, and gestures, these patients were able to appropriately convey quite sophisticated communication contents (Siegal and Varley 2006; Varley and Siegal 2000). If language is crucially involved in communicative intention generation, aphasic patients should not perform well on pragmatic tasks. However, patients with aphasia exhibited communication strategies that were comparable to those observed in the neurologically healthy population (Willems et al. 2011). Thus, patients with aphasia show evidence of independence between ToM and grammatical abilities as ToM reasoning in communicative contexts is possible even when specific grammatical constructions are impaired (Fontana et al. 2018).

Neurodegenerative studies

An interesting domain of research in communicative intention processing is neurodegenerative conditions that mainly affect the ToM brain regions (Adenzato et al. 2010; Adenzato and Poletti 2013; Cavallo et al. 2011b; Pezzati et al. 2014; Poletti et al. 2012). The behavioural variant of frontotemporal dementia (bvFTD) is the most frequent clinical form of frontotemporal lobar degeneration and the medial frontal cortex was identified as the brain region mainly affected in bvFTD (Schroeter et al. 2008). An interesting and novel area of research in bvFTD is the analysis of inference processes in communication, such as pragmatic and intention processing (Kipps et al. 2009; Shany-Ur et al. 2012; Spotorno et al. 2015). Impairment in the comprehension of insincere communication, such as sarcasm and lie processing, has been found in patients with bvFTD compared to both patients with Alzheimer's disease and healthy controls (Kipps et al. 2009; Shany-Ur et al. 2012). In particular, Shany-Ur et al. (2012) found that patients with bvFTD, compared to healthy controls, failed to comprehend the intentions behind insincere speech, as in deception and sarcasm. A brain imaging analysis specifically linked the bvFTD patients' sarcasm impairment to atrophy in the medial and lateral orbitofrontal cortex (Kipps et al. 2009). Further support derives from the study of Spotorno et al. (2015), who found impairment in processing of pragmatic inference, such as scalar implicature. These authors pointed out a deficit in patients with bvFTD in producing alternative interpretations beyond a logical reading, and linked this deficit particularly to atrophy in ventromedial PFC.

In a recent study, Carotenuto et al. (2018) found a specific association between pragmatic abilities and functional connectivity of the ToM brain areas in patients with multiple sclerosis. These authors suggested that disruption of the neuronal network encompassing the bilateral TPJ and MPFC might underlie pragmatic breakdowns in these patients. Similar results were found by

Broicher et al. (2012) in patients with mesial temporal lobe epilepsies compared with patients with epilepsy not originating within the frontal or mesial temporal lobe, as well as with healthy controls. Performance on the Faux-pas Test significantly differed among groups, but performance in the Reading the Mind in the Eyes did not. Moreover, patients with mesial temporal lobe epilepsies were impaired in the Faux-pas Test compared to healthy controls, but not compared to extra-mesial temporal lobe epilepsies patients (whose performance lay between that of healthy controls and mesial temporal lobe epilepsies patients). Finally, Cavallo et al. (2011a) used a paper-and-pencil version of the comic strip task previously adopted in fMRI settings by our group, in patients with amyotrophic lateral sclerosis, a clinical condition closely related to fronto-temporal dementia (Bigio et al. 2003). Compared to healthy controls, worse performance was found on tasks requiring comprehension of social intentions, such as communicative intentions, in these patients, but comparable performance on tasks requiring comprehension of non-social intentions.

Convergent brain stimulation evidence for the IPN model

Different studies have used brain stimulation techniques, such as repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS), to analyse the role of ToM brain areas in communication in clinical and non-clinical populations.

Brain stimulation techniques have gained increasing interest in the field of cognitive neuroscience as they are non-invasive and painless tools that allow researchers to induce transient alterations of normal brain activity in a relatively restricted area of the brain and thus produce transient functional lesions without actual damage to neural structures. The behavioural effects produced by these transient functional lesions allow researchers to better comprehend the causal role of a brain area in a specific cognitive function (Marini et al. 2018).

Costa et al. (2008) investigated the effect of inhibitory rTMS over the MPFC and right TPJ during performance of the false-belief and the Faux-pas Test, and found significantly worsened accuracy in inferring speaker intentions in the Faux-pas Test. Schuwerk et al. (2014) showed that posterior MPFC inhibition through rTMS impaired the ability to distinguish another's from one's own perspective, a component of ToM reasoning (but for different findings see Krause et al. 2012). rTMS over the ventral MPFC was used by Lev-Ran et al. (2012) to test whether normal functioning of this brain region is necessary for ToM functioning, and showed that rTMS did not induce a general learning deficit, but rather a specific learning deficit associated with ToM.

Other studies found that altering cortical excitability in the right TPJ could crucially influence ToM abilities of healthy participants. Young et al. (2010) reported that inhibitory TMS to the right TPJ led participants to rely less on an actor's mental states, which then affected their intention processing. An important effect was shown in particular in judging attempted harm (e.g. actors who intended but failed to do harm) when asked for a moral evaluation of an act of violence, that led participants to judge attempted harms as less morally forbidden and more morally permissible. Mai et al. (2016) showed that accuracy of both intention and emotion processing decreased after tDCS on right TPJ. Finally, an interesting and recent study on deceptive production performance, that is, deceiving another participant to obtain monetary rewards, reported that tDCS over the right TPJ of the performer induced a significant decrease in the rate of successful deception, indicating that cortical stimulation of this region influence deceptive performances (Noguchi and Oizumi 2018).

Two recent studies applied tDCS to the frontal regions of the IPN model in patients with different neurodegenerative conditions, such as bvFTD and Parkinson's disease (Adenzato et al. 2019; Cotelli et al. 2018, but see also Adenzato et al., 2017 for ToM sex differences in healthy population). Cotelli et al. (2018) applied tDCS over the MPFC to selectively enhance ToM processing in patients with bvFTD using a communicative task previously adopted in fMRI settings by our group. In the placebo condition, a specific impairment in communicative intention processing was found in the bvFTD group compared to healthy controls. Interestingly, significant and selective accuracy improvement in the comprehension of communicative intentions after tDCS on MPFC was observed in patients with bvFTD. Recently, Adenzato et al. (2019), used tDCS over the MPFC in patients with Parkinson's disease with mild cognitive impairment and found that ToM performance was worse in the patients' group than in the healthy controls group and that tDCS over the MPFC enhanced ToM performance only in the patients' group.

Discussion

The pragmatic approach to the understanding of an other's action that has emerged in recent years emphasizes the role of ToM in the attribution of social intentions. Such approach focused the analysis on the *why* of an action in a specific context. Similarly, Cognitive Pragmatics analyses the ability to reconstruct the *why* of a communicative action within a specific social context, namely communicative intention processing. In recent years, we proposed an IPN model according to which four key brain areas of the ToM system, that is, the MPFC, right and left TPJ, and precuneus, are fully engaged for intention processing in communicative contexts. In the present work we provide neuroimaging, lesion, neurodegenerative, and brain stimulation evidence demonstrating the key role of the ToM system in processing communicative intention. Different authors, such as Sperber and Wilson (2002), have converged on the idea that within the ToM network, a specialized sub-module has evolved which is dedicated to the pragmatic comprehension of communicative intentions, with its own proprietary concepts and mechanisms. In a narrow sense, we do not propose a specific ToM sub-module, because all the brain regions of the IPN are core areas of the ToM system. Nonetheless, in a wide sense, our model details a network of brain areas with its own principles and mechanisms, that is, a system differentially engaged according to the complex intertwining of the context, goal, and action involved. A further significant aspect emerging from the findings discussed herein is that engagement of the IPN does not depend upon the communicative means used, that is, written language, auditory language, or gesture. From a Cognitive Pragmatics view, the information acquired by different communicative modalities is equivalent from a mental processing standpoint, particularly when a communicative intention has to be reconstructed: hence, communicative intention processing may utilize different sources of information to infer the speaker's intended meaning (Bara 2010; Enrici et al. 2011).

Different important aspects remain open to discussion and are of potential interest for future research on the role of ToM brain regions as a pragmatics/cognition interface in communication. In the current study, we primarily analysed evidence concerning how the ToM system is recruited by intention processing in communication. How the other two main social neurocognitive systems, that is, social perception and action observation, are recruited in communicative contexts remains open to a more in-depth analysis. Although some studies have already explored comprehension of signals that convey either an intention to communicate or attempts to engage in a communicative interaction, thus linking the ToM with the social perception system, further investigation of the specific interplay amid the three systems in communication is needed. Interestingly, Yang et al. (2015) recently proposed the pSTS as the crucial region set at the intersection of the three overall systems, because this region is anatomically and functionally linked to the brain regions that implement these three systems. Our findings concerning the involvement of the IFG regions in processing communicative intention, regions mainly associated with the MNS, add new evidence to Yang's proposal and shed new light on the role of these regions as crucial gateways between the action observation system and ToM system.

A second issue worth discussing is whether the IPN is specific to communicative intention attribution or it has a more general application to different mental states attribution. Different studies report activation of nodes of the IPN beyond communication, such as the attribution of belief (e.g. through the false-belief task) or comprehension of affective mental states (e.g. through the Reading the Mind in the Eyes task) (see Carrington and Bailey 2009; Schurz et al. 2014). Future investigations will clarify how the ToM system could be differently engaged in the comprehension of distinct mental states processing. For example, a recent study by Koster-Hale et al. (2017) distinguished between epistemic (such as belief) and motivational (such as intention) components of ToM processing, showing a spatial and functional dissociation between epistemic features of another person's mental states, represented in the right TPJ, and its motivational valence, represented in the ventral part of the MPFC. As noted by Schaafsma et al. (2015) the current definition of ToM abilities does not permit easy downward translation to more basic neural processes such as those studied by social cognitive neuroscience, leaving the interpretation of neuroimaging results opaque. Accordingly, these authors argue for deconstruction and reformulation of ToM into a comprehensive set of basic cognitive components (see also Butterfill and Apperly 2013). From our perspective, deconstructing the ToM system could be a useful procedure to identify the role of ToM processing in different contexts and cognitive domains, and we suggest that communicative intention processing should be considered as a basic cognitive component and included in the reformulation, at least regarding its pragmatics/cognition interface role.

A third significant topic of discussion is the progressive recruitment of ToM brain areas proposed in our IPN model. Neuroimaging findings discussed earlier provide robust evidence for the full involvement of the IPN in the elaboration of communicative intentions, but less stringent evidence about the restricted recruitment of the IPN for private intentions (i.e. the precuneus and right TPJ) and for prospective social intention (i.e. the precuneus and right TPJ, plus the MPFC). Few studies have used experimental paradigms that critically compare communicative vs. private intentions. For example, Egorova et al. (2016) analysed the neural correlates of speech acts in which the same critical utterances were used with a communicative partner in different communicative contexts, that is, to name objects or to request them. Their results showed that requesting an object from a partner activated the right pSTS and left IFG, as well as premotor and inferior parietal regions, whereas naming them engaged the left angular gyrus of the posterior parietal cortex. The crucial point here is that no IPN core areas were reported. This apparent falsification of our model is easily explained by noting that both conditions required communicative intention processing. In our model, the MPFC, right and left TPJ, and precuneus were activated when comparing the communicative scenario to private or non-intentional scenarios (i.e., social vs. non-social situations). When two communicative scenarios are compared, both with two agents engaged in a communicative interaction (e.g., requesting an object vs. requesting the name of it), as in Egorova et al. (2016), the common brain areas of a specific system, such as the IPN, do not emerge, as a consequence of the common functional role of these brain area in both experimental conditions. Finally, it is important to underline that neuroimaging studies that have used specific comparative conditions, such as those of Sassa et al. (2007), Spotorno et al. (2012), van Ackeren et al. (2012), and Stephens et al. (2010), reported activation equivalent to that predicted by our IPN model. Considering the involvement of communicative, private as well as prospective social scenarios in conceiving the experimental paradigm remains a crucial aspect for the progressive recruitment of ToM.

In the prospective social intention of our IPN model, we consider the relation between something that will presumably happen in the future and something happening in the present. This form of intention underlines the importance of the prediction dimension in which the potential social value of an ongoing action, such as, buying a gift, is anticipated. This topic links intention processing with the role of prediction in communication. In recent years, Pickering and colleagues (Pickering & Gambi, 2018; Pickering & Garrod, 2013) proposed a predictive approach to explain the rapid human processing of language. According to these authors, in language processing, humans may not only analyse each word as they encounter it, but also predict what they are going to encounter (Pickering & Gambi, 2018). In a similar way, ToM could be considered relevant in prediction at the pragmatic level, since ToM is frequently considered as the ability not only to understand but also to predict action based on attribution of mental states in an ongoing interaction (Heil et al. 2019; Koster-Hale and Saxe 2013). Koster-Hale and Saxe (2013) discussed how predictive coding could be applied to ToM processing, examining, in particular, the ToM brain regions included in our IPN model. According to these authors, predictive coding posits that ToM neural responses contain information not about the value of a currently perceived stimulus, but about the difference between the stimulus value and the expected value. This could be particularly informative for ToM processing in every context in which the literal and the intended meanings, that is, the stimulus value and the expected value, do not correspond. Moreover, according to ToM predictive coding proposed by Koster-Hale and Saxe (2013), ToM neural responses to more predictable inputs are generally reduced, whereas they are usually enhanced to less predictable ones. Evidence examined herein seems to converge with this approach: ToM neural responses are enhanced precisely in those pragmatic conditions in which the stimulus value and the expected value do not match. Further evidence on the role of the IPN in communicative prediction is provided by the previously discussed findings of Stephens et al. (2010), who examined a real two-sided communicative interaction using a two-brain approach. Interestingly, these authors found that linking the extent of the speaker-listener neural coupling to a quantitative measure of story comprehension, that is, the communicative content of the communicative exchange, revealed that the greater the anticipatory coupling, the greater the understanding. They argued that the observed alignment of communicative production and comprehension-based processes serves as a mechanism by which brains convey (and predict, in our perspective) communicative information.

In general, we assume that predictions in dialogue are straightforward, a simplified version of what is going to happen in concrete situations, where the partner may say or do something that has not been predicted. Real life is more complex than abstract schemes of interaction, and it requires full activation of the IPN network.

Conclusion

In the present work, we discussed a theoretical model describing a set of brain areas differently involved in the comprehension of different types of intention, that is, the IPN model. According to this model, we should expect progressive recruitment of four key brain regions of the ToM system (i.e. left and right TPJ, precuneus, and MPFC) in the comprehension of private, prospective, and communicative intentions. Although literature investigating the neural correlations of different types of intentions is still scarce, our findings are congruent with the reported activations of ToM regions in comparable tasks and with theories dedicated to explore the subtleties of the temporal dimension. Independent and converging evidence we presented from neuroimaging experiments, neuropsychological observations and brain stimulation studies support the hypothesis of the recruitment of a specific brain network. No surprise from a theoretical point of view: intentions, especially communicative intentions, are the heart of communication, which in turn is a core feature of human interpersonal dimension, for dealing with the social brain is evolved. Our final claim therefore is that the IPN has to be considered an essential constituent of a revised ToM system.

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Figure Captions

Figure 1. Signal time course for the three experimental conditions, private, prospective social, communicative intention, and for a non-intentional control condition (physical causality established among objects) relative to rest for the IPN brain regions. The brain picture depicts the contrast communicative intention versus physical causality condition showing the progressive recruitment of the four regions of interest, i.e., the precuneus, right TPJ, MPFC, and left TPJ. Time courses were calculated by averaging across conditions within each participant (red curve for communicative intention, violet curve for prospective social intention, green curve for private intention, and blue curve for physical causality). The pink area represents the story phase and the grey area represents the choice phase of the comic strips task. Adapted from Ciaramidaro et al. (2007) with permission from the publisher.

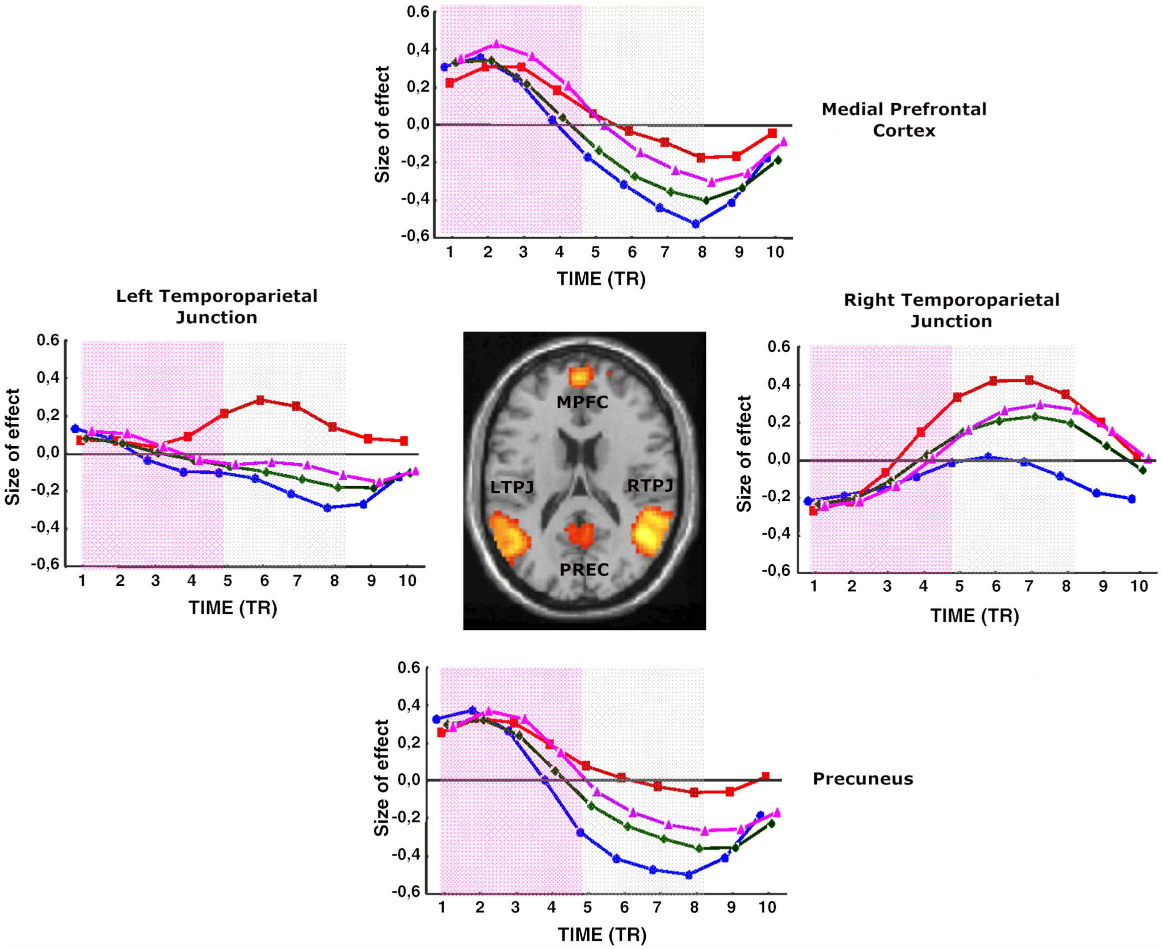
Medial prefrontal cortex = MPFC; PREC = precuneus; Temporoparietal junctions = TPJ

Figure 2. (A) In red, brain areas involved in both linguistic and extralinguistic communicative intention conditions, including the four ToM brain regions of the IPN model, i.e., MPFC, left TPJ, right TPJ, precuneus. In blue, brain areas involved in physical causality conditions established among objects (a non-intentional control condition) represented by both linguistic (the causal link is described by a sentence) and extralinguistic (the causal link is depicted in the scene) modalities. (B) In green, brain areas involved in processing linguistic communicative modality, including the left IFG. In yellow, brain areas involved in processing extralinguistic (gestural) communicative modality, including the right IFG. Adapted from (Enrici et al. 2011) with permission from the publisher.

Inferior frontal gyrus = IFG; Intention processing network = IPN; Medial prefrontal cortex = MPFC; Temporoparietal junctions = TPJ; Theory of mind = ToM.

Figure 3. (On the top) Schematic view of the brain regions included in the effective connectivity models. The four ToM brain regions included in the IPN model, i.e., MPFC, left TPJ, right TPJ, PREC, in dark grey. The linguistic and gestural input gateways, i.e., the LIFG in blue and the RIFG in green. (On the bottom) Schematic connectivity architecture with the significant random-effects parameters of the optimum model. Blue lines indicate stronger direct input (thick arrows) or modulatory (thin arrows) effects induced by linguistic input. Green lines indicate stronger direct input effects induced by gestural input. Adapted from (Tettamanti et al. 2017) with permission from the publisher.

Intention processing network = IPN; Left inferior frontal gyrus = LIFG; Medial prefrontal cortex = MPFC; PREC = precuneus; Right inferior frontal gyrus = RIFG; Temporoparietal junctions = TPJ; Theory of mind = ToM.


Medial Prefrontal Cortex
Left Temporoparietal Junction
Right Temporoparietal Junction
Precuneus
MPFC
LTPJ
RTPJ
PREC
Size of effect
TIME (TR)
0.6
0,4
0,2
0,0
-0,2
-0,4
-0,6
1
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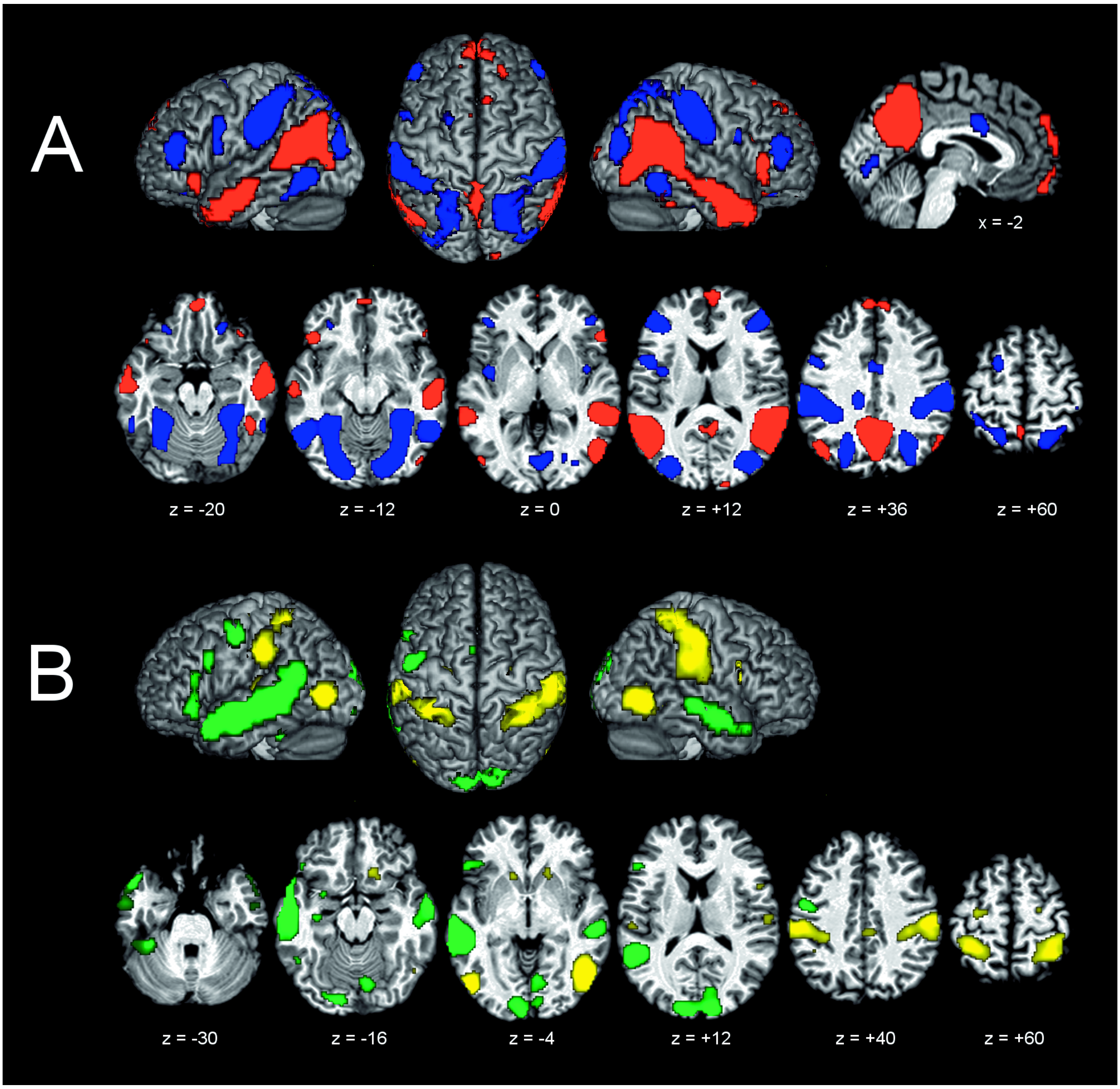
A
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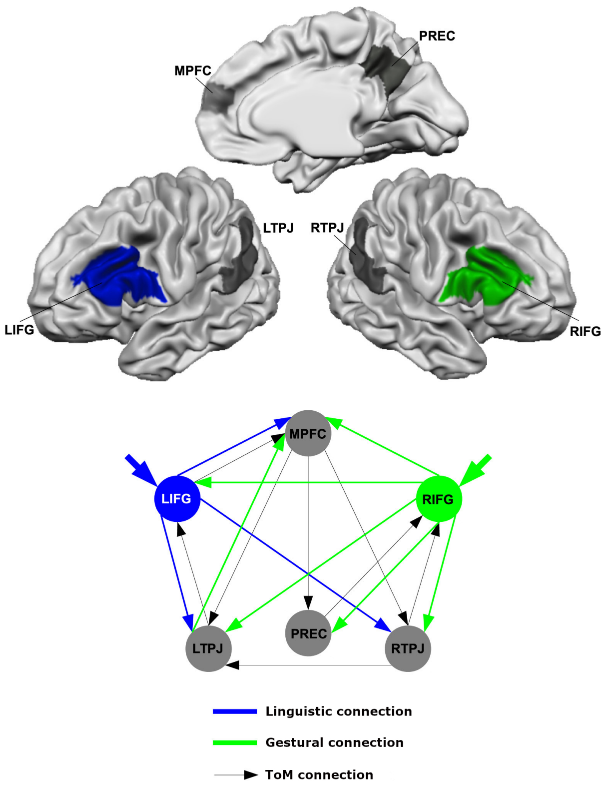
PREC
MPFC
LTPJ
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LIFG
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PREC
LTPJ
RTPJ
Linguistic connection
Gestural connection
ToM connection