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Research Report

The neural mechanisms of reciprocal communication

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ABSTRACT

Imitation in humans has been attributed to increased activation of the mirror neuron system, but there is no neural model to explain reciprocal communication. In this study, we investigated whether reciprocal, communicative, imitative exchanges activate the same neural system as imitation of simple movements, and whether the neural network subserving communication is lateralized. Fifteen participants were tested using functional magnetic resonance imaging with an online interactive-imitative paradigm while they performed finger movements for three different purposes: (1) to imitate the experimenter, (2) to elicit an imitation from the experimenter, and (3) to simply perform the movement. Subtraction analysis (imitation > movement, initiation > movement) revealed the activation of a strongly lateralized network, where the infra-parietal lobule (IPL) activation was lateralized to the left, while the infero-frontal gyrus (IFG) activation was to the right. It is concluded that imitation in a communicative paradigm recruits a lateralized network, with left fronto- and right parietal activation, that overlaps with a network that subserves understanding of an Other's intentions in relation to the Self. This finding lends plausibility to the suggestion that the neural network for imitation evolved to support interpersonal communication.

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1. Introduction

The discovery that “mirror neurons” in ventral premotor cortex and parietal cortex of the rhesus monkey increase firing

not only during grasping of an object (such as a peanut), but also when the monkey watches the actions of someone else grasping the same object (Rizzolatti et al., 1996; Gallese et al., 1996; Rizzolatti and Craighero, 2004), and do so independent of

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Abbreviations: IPL, infra-parietal lobule; IFG, infero-frontal gyrus; Pre-SMA, supplementary motor area; SMA, supplementary motor area; fMRI, functional magnetic resonance imaging; TMS, transcranial magnetic stimulation; PET, Positron Emission Tomography; COMM-R, Response-Imitation condition; COMM-IMI, Initiation condition

sensory input (visual or auditory, such as to the sound of breaking peanuts: Kohler et al., 2002; Keysers et al., 2003) has provided a powerful framework to understand how the brain represents the actions, intentions, and the emotions of others (Rizzolatti and Fabbri-Destro, 2008; Fabbri-Destro and Rizzolatti, 2008; Rizzolatti and Sinigaglia, 2007).

Subsequent studies employing techniques such as functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS) have indicated that a similar but more widespread neural system may be present in humans (e.g., Iacoboni et al., 1999, 2001; Koski et al., 2003). Whether the human mirror neuron system is functionally homologous to the macaque's cannot be stated with certainty, given the different methodologies employed (direct measurements of electrical activity vs. indirect measures of regional blood flow) and the widely different spatial resolution. Logothetis et al. (2001), however, demonstrated that neuronal activity directly recorded using implanted electrodes highly correlated with the neural activity measured indirectly by fMRI. Logothetis et al.'s (2001) results and Mukamel et al. (2010)'s recordings of single-neuron responses with mirror properties in the supplementary motor area and in the hippocampus provide some reassurance for the notion that the mirror neuron system identified in humans and the macaque may be homologues, although they do not entirely overlap anatomically.

A growing body of fMRI research in human volunteers has indicated that elements of the mirror neuron system are active when people imitate simple finger movements (Iacoboni et al., 1999; Koski et al., 2002, 2003; Molnar-Szakacs et al., 2005; Aziz-Zadeh et al., 2006), mouth, hand and foot movements (Buccino et al., 2001), facial movements (Leslie et al., 2004), grasping movements (Grafton et al., 1996), or manipulate objects (Binkofski et al., 1999). Observation of highly complex motor sequences also engages the mirror neuron system. Ballet dancers, for example, selectively activated the premotor cortex, right superior parietal lobe, and left superior temporal sulcus while watching other dancers performing classical ballet (Calvo-Merino et al., 2005). Neurons in the mirror neuron system respond to a wide range of stimuli from the social environment, including facial and manual gestures, sounds of actions, and even actions performed with tools (Jarvelainen et al., 2004; Ferrari et al., 2005).

Rizzolatti and colleagues (e.g., Rizzolatti and Arbib, 1998) proposed that the mirror neuron system may have evolved to assist communication, serving as the foundation of human language. In support of this hypothesis, macaque monkey area F5 is a functional analogue of Brodmann area 44 (Broca's area), specialized for expressive speech. Arbib suggested (2005) that the mirror neuron system may have contributed to human brain evolution, transforming it into a "language-ready brain" by enabling increasingly complex communication, from simple observation and imitation of others' actions, to imitation of longer gestural and vocal sequences (proto-speech) and finally into language (Arbib, 2005).

Evidence on the nature and function of simple and complex imitations during ontogenesis seems to support

Arbib's hypothesis. Naturalistic studies with young infants have proposed that early imitation is best explained by its communicative functions (Uzgiris, 1981; Maratos, 1982; Nagy, 2006). Two-year-old toddlers, who have not yet mastered language, were found to use imitative exchanges to develop interactions. The spontaneous occurrence of imitative communication as preverbal language has been proposed to decline as language competence increases (Nadel and Baudonniere, 1982; Nadel, 2002). Newborn infants have been found to already possess a remarkable capacity to imitate facial and manual gestures (Meltzoff and Moore, 1977; Field et al., 1982; Heimann and Schaller, 1985). In a recent study, Nagy et al. (2005) found that neonates imitated index-finger-raising gestures (the movements that were used to describe the mirror neuron system in human adults) and more interestingly, they did so with an unexpected left-hand preference. Although no data are available on the activity of the mirror neuron system before six months of age (Nystrom, 2008), these behavioural data suggest a lateralized neural system underlying neonatal imitation. If newborns are born with a language-ready brain and simple imitations carry communicative functions, there is no reason why infants could not engage in communication soon after birth. Indeed, applying and extending the same imitation paradigm, newborns were found to participate in long-lasting two-way imitative exchanges, or "dialogues" (Nagy and Molnar, 1994, 2004).

Although behavioural results with neonates may suggest a possibly lateralized neural system underlying imitation, and the mirror neuron system is functional in young infants (Nystrom, 2008), no data are available to show that imitation in adults and neonates is indeed guided by the same neural system. Similarly, we do not know whether the result that neonatal imitation is behaviourally lateralized could indicate a potentially lateralized neural system subserving imitation in adults.

The majority of the studies found no evidence of lateralization in the mirror neuron system (Aziz-Zadeh et al., 2006; Koski et al., 2002; Tanaka et al., 2001; Tanaka and Inui, 2002). Those that were positive yielded an inconsistent pattern: some using imitation of right finger movements reported a right lateralized frontal-parietal-temporal activity (Biermann-Ruben et al., 2008); others with the same task found activation in the left inferior-frontal and right superior parietal lobules (Iacoboni et al., 1999), and a left inferior parietal activation was reported in a task that involved bilateral hand movements (Muhlau et al., 2005). Wiese et al (2005) observed the activation of the right dorso- and ventrolateral prefrontal cortex, and the right inferior parietal lobe during self-initiated finger movements (Wiese et al., 2005).

An aspect of gesture imitation which has not been thoroughly investigated, yet is of great significance, is reciprocal imitation. A single study in the literature explored its neural correlates. Decety et al. (2002) using Positron Emission Tomography (PET) had participants imitate the experimenter manipulating an object, or manipulate an object, and then watch the experimenter manipulating the object in an image projected on a screen. However, although the latter study addressed reciprocal imitation, the paradigm was not interactive, communicative. The Experimenter-Participant or Participant-Experimenter exchange in Decety

et al. study (2002) constitutes to a two-sequence communication. Interactive communicative engagement consists of at least three consecutive components (i.e. Experimenter–Participant–Experimenter) within the same interaction sequence. The experimental paradigm by Decety et al. (2002) modelled communication that is to transmit information, but not live, non virtual, intersubjective engagement. No reciprocal, interactive imitation studies have been carried out employing finger movements, although finger movements have produced reliable activations of the mirror neuron system in humans (Brass et al., 2001; Iacoboni et al., 1999; Koski et al., 2002; Krams et al., 1998; Tanaka et al., 2001; Tanaka and Inui, 2002) and have been used to model reciprocal interactive communication in human neonates (Nagy et al., 2005).

Aims of the present study were twofold. The first goal was to investigate the neural basis of an online, reciprocal communication employing the same imitation paradigm used in studies of the mirror neuron system of monkeys and human adults and in behavioral studies with human neonates. The second aim was to investigate whether the neural network underlying imitative communication of finger movements is lateralized, as developmental studies would suggest.

2. Results

2.1. Imitative communication

Relative to a non-imitative movement, the imitative communication condition activated a lateralized fronto-parietal network. The main clusters in the activated network com-

prised the right premotor cortex (BA6), the right middle frontal gyrus (BA9), and the left inferior parietal lobule (BA40). The activation was strongly lateralized, with predominantly right prefrontal and left parietal components. The results are summarized in Table 1, and are demonstrated in Fig. 1a.

2.2. Initiative communication

When compared to non-imitative movement, when the subject initiated or solicited a response, this activated the largest cluster in the left inferior parietal lobule (BA40) (see Table 2 and Fig. 1b).

When COMM-R and COMM-INI were directly compared, there were no significant differences in the activation of any brain areas between these two conditions.

3. Discussion

3.1. Activation of the IPL on the left side

Since Liepmann's neuropsychological studies, it has been accepted that apraxic patients with left hemispheric lesions have greater deficits in imitation compared to patients with right hemispheric lesions (cited in Goldenberg, 2003). The left hemisphere must therefore be crucial in imitation, and the neural network underlying imitation has to be asymmetrical. Recent studies that further refined Liepmann's model, however, found left hemisphere dominance only for imitation of hand movements and a right hemisphere advantage for imitation of finger movements (Goldenberg, 2001; Goldenberg and Strauss, 2002). Even with this revised model, neuropsychological studies propose a lateralized network for imitation. Most neuroimaging studies with

Table 1 – Stereotaxic coordinates and peak t-scores of brain regions that showed significantly more activation during the imitation compared to the move condition. MNI coordinates generated using SPM2 were converted to Talairach coordinates using the WFU PickAtlas. Coordinates are in millimeters along the left–right (x), anterior–posterior (y), and superior–inferior (z) axes. After each brain region the Brodmann area is indicated in parenthesis.

	Region	Side	Cluster size	x	y	z	t	
Parietal	IPL (40)	Left	954	–52	–46	56	8.85	
	IPL (40)	Left		–54	–56	46	8.04	
	MTG (39)	Left		–58	–64	12	6.30	
	IPL (40)	Left		–40	–64	58	6.18	
	Angular gyrus (39)	Left		–52	–68	30	6.01	
	Precuneus (7)	Left		11	–4	–54	54	5.56
Frontal	SPL (7)	Right	33	24	–62	52	5.25	
	Middle frontal gyrus (6)	Right	259	38	16	58	7.54	
	Middle frontal gyrus (8)	Right		52	14	42	6.11	
	Middle frontal gyrus (6)	Right		34	26	58	5.09	
	Superior frontal gyrus (8)	Right		32	28	52	5.11	
	Middle frontal gyrus (9)	Right		24	52	34	32	5.59
	Superior frontal gyrus (10)	Left		10	–20	54	–8	5.05
	Inferior frontal gyrus (47)	Right		10	24	26	–6	5.30
	Inferior frontal gyrus (47)	Right			24	30	–4	4.89
	Temporal	Fusiform gyrus (37)		Left	67	–38	–44	–12
Parahippocampal gyrus (37)		Left			–34	–38	–10	6,40
Middle temporal gyrus (21)		Left	954*	–62	–60	4	5.65	
Middle temporal gyrus (21)		Left		–64	–56	0	5.30	
Occipital	Middle occipital gyrus (19)	Left	10	–54	–74	–4	5.07	

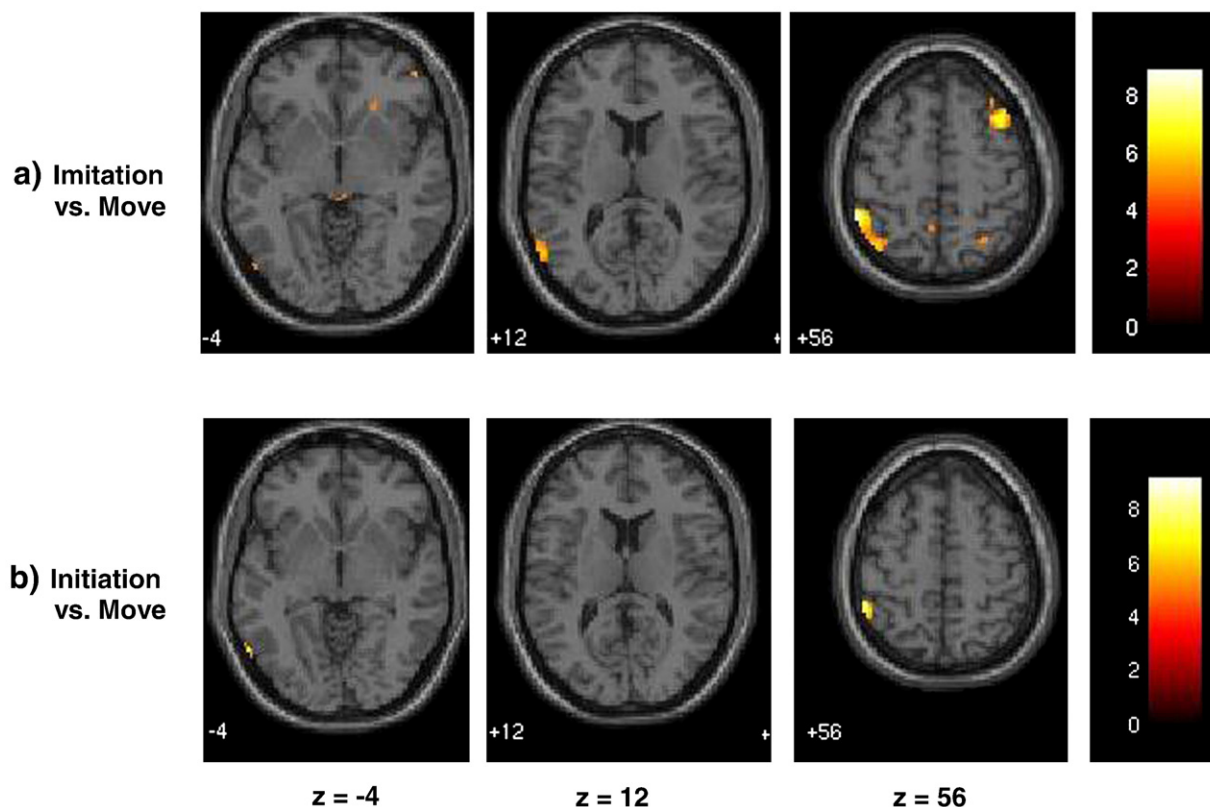


Fig. 1 – (a) Results from the Imitation vs. Move contrast showing a lateralized network activated during imitation involving the right frontal and the left inferior parietal lobules. (b) The Initiation vs. Move contrast shows the activation of the left inferior parietal lobule during initiation. Results are superimposed on the MNI MRI template, with z coordinates given below each slice. Z coordinate under first column: $z = -4$, Z coordinate under second column: $z = 12$, Z coordinate under third column: $z = 56$.

healthy participants, however, reported symmetrical neural network activity during imitation. Those that reported asymmetry have not shown a consistent pattern across

Table 2 – Stereotaxic coordinates and peak t-scores of brain regions that showed significantly more activation during the initiation compared to the move condition. MNI coordinates generated using SPM2 were converted to Talairach coordinates using the WFU PickAtlas. Coordinates are in millimeters along the left–right (x), anterior–posterior (y), and superior–inferior (z) axes. After each brain region the Brodmann area is indicated in parenthesis.

	Region	Side	Cluster size	x	y	z	t
Parietal	IPL (40)	Left	411	-52	-46	54	9.17
	IPL (40)	Left		-54	-54	46	8.56
	IPL (40)	Left		-50	-46	40	7.35
	Angular gyrus (39)	Left		-54	-58	34	6.95
Temporal	Inferior temporal gyrus (37)	Left	36	-60	-64	-4	6.72
	Inferior temporal gyrus (19)	Left		-58	-68	-2	5.89
	Middle temporal gyrus (37)	Left		-64	-56	-2	5.41

different studies. A direct comparison of the results from neuropsychological and neuroimaging studies to date is difficult because of methodological differences (Muhlau et al., 2005); both the subject population and the gestures used were different for the two methods. Most neuroimaging studies used simple finger movements, unlike the complex hand and finger gestures used in the neuropsychological batteries for testing apraxic patients. Additionally, while neuropsychological studies examined the non-lesioned side of the patients only, the majority of the neuroimaging studies tested right-sided movements (Brass et al., 2001; Decety et al., 2002; Iacoboni et al., 1999; Koski et al., 2002; Krams et al., 1998; Tanaka et al., 2001; Tanaka and Inui, 2002). Muhlau et al.'s (2005) fMRI study, which employed bilateral movements and used the same gestures as those used for testing apraxic patients, reported a bilateral network for imitation with increased activation in the left infra parietal cortex. Although these results do not support Goldenberg's results showing a right hemisphere advantage in imitation, they support Della Sala et al.'s (2006) finding that left hemispheric lesions particularly impaired the imitation of meaningful gestures, but not the imitation of meaningless gestures that were used in Goldenberg's studies. Consistent with Muhlau's proposal, when imitation of meaningful and meaningless gestures was compared in Rumiati et al.'s study (2004), imitation of meaningful gestures positively correlated with the activity of the left inferior

temporal gyrus, while imitation of meaningless gestures was associated to activity in the right parieto-occipital junction.

Finger agnosia, a symptom of the Gerstmann syndrome, is also known to be linked to a left parietal lesion. This can either be seen as further support for Muhlau's findings, or raises an alternative suggestion, that the left hemisphere supports only the recognition of the fingers, and perhaps their intentional movement, but not necessarily imitation *per se*. The results from the present study show that it is neither intentional movement itself, nor merely the recognition of the fingers that activates the left IPL. The activity of the left IPL was measured after the neural activation caused by movement was subtracted from the neural activity during imitation of the finger movements.

The IPL has been reported as having the ability to distinguish the actions of the self and the other. In Decety et al.'s study (2002), the left IPL was activated when participants imitated actions, and the right IPL was activated when the participants' actions were imitated in an object manipulation task. The left IPL was also activated when participants mentally simulated an action from their own perspective, while the right IPL was activated when they simulated from a third person perspective (Ruby and Decety, 2001). Our study found no activation of the right IPL during the initiation condition. The task, however, was markedly different from the one employed in Decety et al.'s study (2002). While the task in Decety et al.'s study was 'offline' and used one-time object manipulation, the task in the present study was an online, interactive communication task that used a simple movement.

3.2. The right frontal network

The frontal areas activated in the current study, the middle frontal gyrus and the inferior frontal gyrus, had been found to be involved in inhibitory processes. Kelly et al. (2004) found a predominantly right hemispheric network activation during No-Go trials. Their results showed the activation of a widely distributed, but predominantly right-sided, network comprising of the right superior frontal, the right inferior frontal, and the bilateral but predominantly right middle frontal gyri. Aron et al. (2003) and Rubia et al. (2003) suggested that the "stop signal" in the Go-No-Go task is generated in the inferior frontal gyrus; Konishi et al. (1998); Garavan et al. (1999); and Zubicaray et al. (2000), found increased activation in the right middle frontal and inferior frontal gyri.

Similarly, in Brass et al.'s study (2001), when participants were instructed to move (lift or tap) their index finger after watching movies that were congruent or incongruent with the instruction; the "interference" (incongruent) over "imitation" (congruent) subtraction revealed the activation of the right frontopolar, right middle frontal, and left middle frontal gyri. Finally, in neuropsychological studies patients with lateral prefrontal (de Renzi et al., 1996) and frontomedial prefrontal (Lhermitte et al., 1986) lesions were found to show spontaneous imitative tendencies, possibly the result of release from inhibitory motor control.

Self-awareness and discrimination of the self from the other have also been linked to these frontal areas. Generally, a right hemisphere advantage has been reported in representing the self (Breen et al., 2001; Keenan et al., 2005; Platek and

Gallup, 2002; Molnar-Szakacs et al., 2005) and responding to self-relevant stimuli (Keenan et al., 1999, 2000). The right MFG and right IFG have also been found to be involved in recognition of others' intentions (de Lange et al., 2008; Gallagher and Firth, 2003). Iacoboni et al. (2005) found a stronger right IFG activation as a response to grasping a mug in the context of eating, as opposed to grasping in a more ambiguous context, a result further indicating the IFG's role in decoding intention. The right IFG was activated when people were looking at their own faces (Keenan et al., 2001), and when generating self-relevant, autobiographical memories (Fink et al., 1996).

Inhibitory functions, working memory and self-other discrimination therefore are overlapping in the right middle and inferior frontal gyri, and are likely to contribute to the communication paradigm employed in the current study. Participants in the imitation condition were likely to suppress their own movement, the finger movement that they knew they are going to execute, until the experimenter had completed the movement. Participants also needed to keep in mind the agent of the movements from the perspective of the self in order to maintain the responding or initiating paradigm. As both participants and the experimenter were allowed to move any of their fingers, this relative freedom of response selection may have further emphasized self-other discrimination.

The control "MOVE" condition involved the same movements as the communicative conditions, without the communicative context. Moreover, participants were exposed to comparable visual input as the experimenter's fingers were always visible; thus the communicative conditions were well controlled for the movement itself. Movements in the 'MOVE' condition, however, were self-initiated, and at a higher rate than in the communicative conditions. In imitative/responding condition the participants' movements were triggered by the experimenter's movements, and in the initiation condition they were self-triggered. The results from the COMM-R vs. Move contrast therefore may be attributable to the difference in brain activation to externally triggered versus self-paced movements. Self-paced finger movements were found to activate a broad network, including the right middle frontal gyrus, but not the inferior or superior frontal gyrus, and the left inferior parietal lobule but not the right (Joliot et al., 1999). While both externally triggered and self-paced movements activate the medial motor areas; the pre-supplementary motor area (pre-SMA) and the supplementary motor area (SMA); the rostral cingulate cortex, and primary motor, superior parietal and insular cortices (Cunnington et al., 2002); and the activation in the pre-SMA is more extensive for self-initiated than visually triggered movements (Deiber et al., 1999), none of these activations overlap with the activation measured in the current study.

3.3. The left IPL and right IFG network

In summary, results in the current study of a right IFG-left IPL network active when participants are engaged in an imitative-communicative task are consistent with current literature suggesting a partially lateralized network for intentional imitative behaviour.

The communicative condition employed in this study raises questions about the definition of true imitation. In this study, both the participants and the experimenter were allowed to move any finger. That is, they responded with the same body part, the same movement, but without the need for spatial matching of the finger. Though the participant was imitating the experimenter, we have used the term responding/imitating instead of 'imitating' to describe COMM-R. The fronto-parietal mirror neuron network responds more strongly when imitations are spatially compatible as opposed to when they are spatially incompatible, such as in the case of anatomical imitations (Koski et al., 2003). The purpose of the experiment was to examine the reciprocal aspects of communication, not the exact spatial matching of the other's movement. We hoped the responding paradigm was relatively naturalistic to trigger communication engagement, e.g., less a task of matching the finger and more of communication. Note that the communicative intent of responding and initiating could, however, be better measured in future studies using event-related fMRI rather than a block-design. These limitations could also account for the lack of differences between the responding and initiation conditions. Either the number of responding and initiating movements were low in the blocks, or the paradigm was communicative but the block design was not powerful enough to differentiate the responding and initiative intention. That is, after the first few movements, just as was shown in studies with young infants using this paradigm to elicit reciprocal communication (Nagy and Molnar, 2004; Nagy, 2006), after the first few exchanges, responding and initiating blended into reciprocal interaction. Event-related design could perhaps more sensitively detect the difference between the two conditions.

Nonetheless, based on the results of this study, we can propose that reciprocal communication with the other activates a lateralized network comprising the left IPL and right IFG. This result is consistent with the behavioural lateralization of imitation with human neonates (Nagy et al., 2005), a result that suggests a lateralized system subserving imitation.

Interestingly, perception of rhythmic stimuli, such as rhythmic drumming, was found to activate a similarly lateralized network in the frontal and parietal lobes, comprising the left IPL, right frontal operculum, and right superior frontal gyrus (Limb et al., 2006). Musicians in this study additionally activated perisylvian language areas. Prediction of nonverbal sequences was also found to activate the Wernicke area, a part of the brain that is specialized for language perception (Bischoff-Grethe et al., 2000). The IPL, which codes actions according to their respective goals, enables us to perceive complex, successive actions fluidly as one, without gaps, like a "perception of a kinetic melody" (Fogassi et al., 2005). Rhythmic stimuli like drumming, or communicative cycles, such as cycles of finger movement exchanges between the experimenter and the participant, resemble the rhythmic sequences of language, from which we create an infinite variety of combinations from the limited number of elements and cycles. Although it is somewhat speculative without further comparative studies, we propose that both reciprocal communication and perception of rhythm activate a lateralized network in the mirror neuron system. This conclusion is consistent with Rizzolatti and Arbib's

model (Rizzolatti and Arbib, 1998; Arbib, 2005) of a network that evolved to subserve communication.

4. Experimental procedures

4.1. Subjects

Fifteen right handed subjects (12 females, 3 males), with no psychiatric or neurological illness, with a mean age of 30.9 years (SD=12.1), participated in the study. The study was approved by the Ethical Committee of the University of Aberdeen. Participants signed an informed consent and were compensated £20 for their time.

4.2. Experimental setup

The participants were tested at the MRI Research Centre of the University of Aberdeen. Participants were lying on their backs, resting both hands on their thighs with palms down, fingers relaxed, extended. Their head was firmly secured, and they were wearing earphones. Participants saw the experimenter through an angled mirror placed on the head coil. The verbal instruction commands were presented using Presentation software (Neurobehavioural Systems™, Albany, CA, USA).

The experimenter (the same for all participants), stood in front of the supine participant, resting her hands on a high platform, with palms down, fingers relaxed, extended. A Panasonic NVGS27B digital video camera mounted on a tripod in the corner of the room recorded the experiment. The videotapes were later reviewed by two researchers who were not involved in the planning, execution, analysis of the data, to ensure that all participants engaged in all tasks correctly throughout the three blocks. Participants' non-involvement (no behavioural response) in a condition would have resulted in the exclusion of their data. The behavioural practice session prior to the experiment ensured that all participants were engaged in the task, thus all data were included in the analysis.

4.3. Behavioural procedure

The experiment consisted of three blocks of trials, each lasting 9 min. Each block consisted of 18 events, each lasting for 30 seconds, presenting four conditions. Each block contained the eighteen events in different order, and the order of the blocks was randomized among the participants.

4.4. Conditions

Participants were tested in four conditions: two communication conditions—(1) a response-imitation condition (COMM-R), in which the subject responded to the experimenter by matching movements, and (2) an initiation condition (COMM-INI), in which the subject solicited a response; two control conditions: (3) a control movement condition (MOV); and (4) a control observation condition (WATCH).

The following information was given to the participants prior to the testing:

“Your task is to communicate with the experimenter without language simply using your fingers like this (and the experimenter demonstrated a finger extension movement, when a finger moved upwards, while the rest of the fingers did not move). You can use any fingers, one at a time. During the experiment, through the earphones, you will hear commands. If you hear the command ‘talk,’ then either you have to respond to the experimenter using your fingers, or if the experimenter does not do anything, your task is to move your finger to invite her to communicate with you. If you hear ‘move’ you have to move your fingers by yourself, one finger at a time, any fingers. If you hear “watch,” you have to watch the experimenter moving her fingers.”

In the COMM-R condition, after the ‘talk’ command the experimenter moved one of her fingers, and waited for the participant to respond with a finger movement. There were approximately 10 finger movement exchanges, lead by the experimenter throughout the 30-second period.

In the COMM-INI condition after the “talk” command, the experimenter did not move until the participant moved his/her finger. At this point, the experimenter responded by moving one of her fingers. There were approximately 10 finger movement exchanges led by the participant in this 30 s.

The command was the same for both the imitation and initiation conditions to mimic everyday reciprocal interactions. The participant had to decide based on the behaviour of the experimenter (whether she was waiting or acting) which one of the communication conditions is taking place.

In the MOVE control condition, after the “move” command the participant moved her/his fingers, one finger at a time, with the rate of approximately 20 movements during the 30-s period. The experimenter did not move, but rested her hands palms down, with relaxed but extended fingers on the platform, visible to the participant.

In the WATCH control condition after the “watch” command, participants did not move but were watching the experimenter’s fingers moving. The experimenter moved her fingers, one finger at a time approximately 20 movements in the 30-s period.

Before the scanning session started, the participants had a brief practice of all four conditions. All participants understood the conditions. Although command “talk” usually refers to communication with sounds, this command was chosen over the longer “communicate.” Thus all auditory commands, “talk,” “move,” “watch” that were delivered through the headphones were about the same length.

Any one finger of either hand had been allowed to use in the conditions that is, participants were not required to spatially match the movement of the experimenter in the COMM-R and MOVE conditions, or the experimenter of the participants’ movements in the COMM-INI condition, there were no rules to define which particular finger to be used. The same principle has been employed in the WATCH condition by the experimenter.

4.5. Imaging procedures

Functional MRI imaging was performed using a 1.5 T scanner (NVi, General Electric Medical Systems, Milwaukee, WI). A quadrature head coil was used to obtain high-resolution

gradient echo 3D volumetric images and three sets of functional images using blood oxygenation level dependent contrast. The high-resolution anatomical images were collected using a T1 weighted sequence with the following parameters: field of view, 24 cm; 20/6 ms, TR/TE; flip angle, 35°; slices, 124; slice thickness, 1.6 mm; matrix, 256×256. Functional MR images were acquired in axial planes with a T2*-weighted single shot, gradient-echo, echo-planar pulse sequence with the following parameters: field of view, 24 cm; 3000/33 ms, TR/TE; flip angle, 90°, slices, 24; slice thickness, 5 mm; matrix, 128×128. The head was firmly stabilised between two foam pads.

Image processing was carried out using SPM2 (Wellcome Department of Imaging Neuroscience, London, UK), implemented in MATLAB (Mathworks, Natick, MA).

Preprocessing of the data included reorientation of the images to the EPI template of SPM2, and correction for head motion by realignment to the first image volume. As a result, a mean functional image was computed for each session. The mean image was subjected to spatial normalization to the template of the Montreal Neurological Institute (MNI, [Friston et al., 1995](#)). The normalized functional images, 4 mm isotropic voxels, were smoothed using an 8 mm isotropic Gaussian kernel.

Following preprocessing, Beta weights associated with the modelled hemodynamic responses were computed to fit the observed BOLD-signal time course in each voxel for each subject using the General Linear Model, as implemented in SPM2. Contrast images for each task (COMM-R and COMM-INI) -versus-control (MOVE) analysis for each subject were entered into a random effects analysis, where a significance level of $p < 0.05$ was employed. Voxels reaching the statistical threshold of $p < 0.05$ were considered statistically significant. Because of the common movement element in all three, only the MOVE condition has been employed as control condition, while WATCH has not been used.

The coordinates were converted into the coordinates of [Talairach and Tournoux \(1988\)](#), as implemented in the WFU PickAtlas ([Maldjian et al., 2003](#)).

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REFERENCES

- Arbib, M.A., 2005. From monkey-like action recognition to human language: an evolutionary framework for neurolinguistics. *Behav. Brain Sci.* 28, 105–167.

- Aron, A.R., Fletcher, P.C., Bullmore, E.T., Sahakian, B.J., Robbins, T.W., 2003. Stop-signal inhibition disrupted by damage to right inferior frontal gyrus in humans. *Nat. Neurosci.* 6, 115–116.
- Aziz-Zadeh, L., Koski, L., Zaidel, E., Mazziotta, J., Iacoboni, M., 2006. Lateralization of the human mirror neuron system. *J. Neurosci.* 26, 2964–2970.
- Biermann-Ruben, K., Kessler, K., Jonas, M., Siebner, H.R., Baumer, T., Munchau, A., Schnitzler, A., 2008. Right hemisphere contributions to imitation tasks. *Eur. J. Neurosci.* 27 (7), 1843–1855.
- Binkofski, F., Buccino, G., Posse, S., Seitz, R.J., Rizzolatti, G., Freund, H., 1999. A frontoparietal circuit for object manipulation in man: evidence from an fMRI-study. *Eur. J. Neurosci.* 11, 3276–3286.
- Bischoff-Grethe, A., Proper, S.M., Mao, H., Daniels, K.A., Berns, G.S., 2000. Conscious and unconscious processing of nonverbal predictability. *J. Neurosci.* 20 (5), 1975–1981.
- Brass, M., Zysset, S., von Cramon, D.Y., 2001. The inhibition of imitative response tendencies. *Neuroimage* 14, 1416–1423.
- Breen, N., Caine, D., Coltheart, M., 2001. Mirrored-self misidentification: two cases of focal onset dementia. *Neurocase* 7, 239–254.
- Buccino, G., Binkofski, F., Fink, G.R., Fadiga, L., Fogassi, L., Gallese, V., Seitz, R.J., Zilles, K., Rizzolatti, G., Freund, H.J., 2001. Action observation activates premotor and parietal areas in a somatotopic manner: An fMRI study. *Eur. J. Neurosci.* 13 (2), 400–404.
- Calvo-Merino, B., Glaser, D.E., Grèzes, J., Passingham, R.E., Haggard, P., 2005. Action observation and acquired motor skills: an fMRI study with expert dancers. *Cereb. Cortex* 15, 1243–1249.
- Cunnington, R., Windischberger, C., Deecke, L., Moser, E., 2002. The preparation and execution of self-initiated and externally triggered movement: a study of event-related fMRI. *Neuroimage* 15, 373–385.
- De Lange, F.P., Spronk, M., Willems, R.M., Toni, I., Bekkering, H., 2008. Complementary systems for understanding action intentions. *Curr. Biol.* 18, 454–457.
- De Renzi, E., Cavalleri, F., Facchini, S., 1996. Imitation and utilisation behavior. *J. Neurol. Neurosurg. Psychiatry* 61, 396–400.
- Decety, J., Chaminade, T., Grezes, J., Meltzoff, A.N., 2002. A PET exploration of the neural mechanisms involved in reciprocal imitation. *Neuroimage* 15, 265–272.
- Deiber, M., Honda, M., Ibanez, V., Sadato, N., Hallett, M., 1999. Mesial motor areas in self-initiated versus externally triggered movements examined with fMRI: effect of movement type and rate. *J. Neurophysiol.* 81, 3065–3077.
- Della-Sala, S., Faglioni, P., Motto, C., Spinnler, H., 2006. Hemisphere asymmetry for imitation of hand and finger movements, Goldenberg's hypothesis reworked. *Neuropsychologia* 44, 1496–1500.
- Fabbri-Destro, M., Rizzolatti, G., 2008. Mirror neurons and mirror systems in monkeys and humans. *Physiology* 23, 171–179.
- Ferrari, P.F., Rozzi, S., Fogassi, L., 2005. Mirror neurons responding to observation of actions made with tools in monkey ventral premotor cortex. *J. Cogn. Neurosci.* 17 (2), 212–226.
- Field, T.M., Woodson, R., Greenberg, R., Cohen, D., 1982. Discrimination and imitation of facial expressions by neonates. *Science* 218, 179–181.
- Fink, G.R., Markowitsch, H.J., Reinkemeier, M., Bruckbauer, T., Kessler, J., Heiss, W.D., 1996. Cerebral representation of one's own past: neural networks involved in autobiographical memory. *J. Neurosci.* 16, 4275–4282.
- Fogassi, L., Ferrari, P.F., Gesierich, B., Rozzi, S., Chersi, F., Rizzolatti, G., 2005. Parietal lobe: from action organization to intention understanding. *Science* 308, 662–667.
- Friston, K.J., Ashburner, J., Frith, C.D., Poline, J.-B., Heather, J.D., Frackowiak, R.S.J., 1995. Spatial registration and normalization of images. *Hum. Brain Mapp.* 3, 165–189.
- Gallagher, H.L., Firth, C.D., 2003. Functional imaging of “theory of mind”. *Trends Cogn. Sci.* 7, 77–83.
- Gallese, V., Fadiga, L., Fogassi, L., Rizzolatti, G., 1996. Action recognition in the premotor cortex. *Brain* 119, 593–609.
- Garavan, H., Ross, T.J., Stein, E.A., 1999. Right hemispheric dominance of inhibitory control: an event-related functional MRI study. *Proc. Natl. Acad. Sci. U. S. A.* 96, 8301–8306.
- Goldenberg, G., 2001. Imitation and matching of hand and finger postures. *Neuroimage* 14, S132–S136.
- Goldenberg, G., 2003. Apraxia and beyond: life and work of Hugo Liepmann. *Cortex* 39 (3), 509–524.
- Goldenberg, G., Strauss, S., 2002. Hemisphere asymmetries for imitation of novel gestures. *Neurology* 59 (6), 893–897.
- Grafton, S.T., Arbib, M.A., Fadiga, L., Rizzolatti, G., 1996. Localization of grasp representations in humans by positron emission tomography. 2. Observation compared with imagination. *Exp. Brain Res.* 112, 103–111.
- Heimann, M., Schaller, J., 1985. Imitative reactions among 14–21 day old infants. *IMHJ* 6 (1), 31–39.
- Iacoboni, M., Woods, R.P., Brass, M., Bekkering, H., Mazziotta, J.C., Rizzolatti, G., 1999. Cortical mechanisms of human imitation. *Science* 286, 2526–2528.
- Iacoboni, M., Koski, L.M., Brass, M., Bekkering, H., Woods, R.P., Dubeau, M.C., Mazziotta, J.C., Rizzolatti, G., 2001. Reafferent copies of imitated actions in the right superior temporal cortex. *Proc. Natl. Acad. Sci. U. S. A.* 98 (24), 13995–13999.
- Iacoboni, M., Molnar-Szakacs, I., Gallese, V., Buccino, G., Mazziotta, J.C., Rizzolatti, G., 2005. Grasping the intentions of others with one's own mirror neuron system. *PLoS Biol.* 3, e79.
- Jarvelainen, J., Schurmann, M., Hari, R., 2004. Activation of the human primary motor cortex during observation of tool use. *Neuroimage* 23 (1), 187–192.
- Joliot, M., Papathanassiou, D., Mellet, E., Quinton, O., Mazoyer, N., Courtheoux, P., Mazoyer, B., 1999. fMRI and PET of self-paced finger movement: comparison of intersubject stereotaxic averaged data. *Neuroimage* 10, 430–447.
- Keenan, J.P., McCutcheon, B., Sanders, G., Freund, S., Gallup, G.G., Pascual-Leone, A., 1999. Left hand advantage in a self-face recognition task. *Neuropsychologia* 37 (12), 1421–1425.
- Keenan, J.P., McCutcheon, N.B., Pascual-Leone, A., 2001. Functional magnetic resonance imaging and event-related potentials suggest rich prefrontal activation for self-related processing. *Brain Cogn.* 47, 87–91.
- Keenan, J.P., Freund, S., Hamilton, R.H., Ganis, G., Pascual-Leone, A., 2005. Hand response differences in a self-face identification task. *Neuropsychologia* 38, 1047–1053.
- Kelly, A.M.C., Hester, R., Murphy, K., Javitt, D.C., Foxe, J.J., Garavan, H., 2004. Prefrontal-subcortical dissociations underlying inhibitory control revealed by event-related fMRI. *Eur. J. Neurosci.* 19, 3105–3112.
- Keysers, C., Kohler, E., Umiltà, M.A., Nanetti, L., Fogassi, L., Gallese, V., 2003. Audiovisual mirror neurons and action recognition. *Exp. Brain Res.* 153, 628–636.
- Kohler, E., Keysers, C., Umiltà, M.A., Fogassi, L., Gallese, V., Rizzolatti, G., 2002. Hearing sounds, understanding actions: action representation in mirror neurons. *Science* 297, 846–848.
- Konishi, S., Nakajima, K., Uchida, I., Sekihara, K., Miyashita, Y., 1998. No-go dominant brain activity in human inferior prefrontal cortex revealed by functional magnetic resonance imaging. *Eur. J. Neurosci.* 10 (3), 1209–1213.
- Koski, L., Wohlschlagel, A., Bekkering, H., Woods, R.P., Dubeau, M.C., Mazziotta, J.C., Iacoboni, M., 2002. Modulation of motor and premotor activity during imitation of target-directed actions. *Cereb. Cortex* 12, 847–855.
- Koski, L., Iacoboni, M., Dubeau, M.C., Woods, R.P., Mazziotta, J.C., 2003. Modulation of cortical activity during different imitative behaviors. *J. Neurophysiol.* 89, 460–471.
- Krams, M., Rushworth, M.F., Deiber, M.P., Frackowiak, R.S., Passingham, R.E., 1998. The preparation, execution and

- suppression of copied movements in the human brain. *Exp. Brain Res.* 120 (3), 386–398.
- Leslie, K.R., Johnson-Frey, S.H., Grafton, S.T., 2004. Functional imaging of face and hand imitation: towards a motor theory of empathy. *Neuroimage* 21, 601–607.
- Lhermitte, F., Pillon, B., Serdaru, M.D., 1986. Human anatomy and the frontal lobes. Part I: imitation and utilization behaviour: a neuropsychological study of 75 patients. *Ann. Neurol.* 19, 335–343.
- Limb, C.J., Kemeny, S., Ortigoza, E.B., Rouhani, S., Braun, A.R., 2006. Left hemispheric lateralization of brain activity during passive rhythm perception in musicians. *Anat. Rec. A Discov. Mol. Cell. Evol. Biol.* 288, 382–389 (A).
- Logothetis, N.K., Pauls, J., Augath, M., Trinath, T., Oeltermann, A., 2001. Neurophysiological investigation of the basis of the fMRI signal. *Nature* 412, 150–157.
- Maldjian, J.A., Laurienti, P.J., Kraft, R.A., Burdette, J.H., 2003. An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. *Neuroimage* 19, 1233–1239.
- Maratos, O., 1982. Trends in the development of imitation in early infancy. In: Bever, T.G. (Ed.), *Regressions in Mental Development: Basic Phenomena and Theories*. Erlbaum, Hillsdale, NJ, pp. 81–101.
- Meltzoff, A., Moore, M.K., 1977. Imitation of facial and manual gestures by human neonates. *Science* 198, 75–78.
- Molnar-Szakacs, I., Iacoboni, M., Koski, L., Mazziotta, J.C., 2005. Functional segregation within pars opercularis of the inferior frontal gyrus: evidence from fMRI studies of imitation and action observation. *Cereb. Cortex* 15, 986–994.
- Muhlau, M., Hermsdorfer, J., Goldenberg, G., Wohlschlagler, A.M., Castrop, F., Stahl, R., Rottinger, M., Erhard, P., Haslinger, B., Ceballos-Baumann, A.O., Conrad, B., Boecker, H., 2005. Left inferior parietal dominance in gesture imitation: an fMRI study. *Neuropsychologia* 43, 1086–1098.
- Mukamel, R., Ekstrom, A.D., Kaplan, J., Iacoboni, M., Fried, I., 2010. Single-neuron responses in humans during execution and observation of actions. *Curr. Biol.* 20, 750–756.
- Nadel, J., 2002. Imitation and imitation recognition: Functional use in preverbal infants and nonverbal children with autism. In: Meltzoff, A.N., Prinz, W. (Eds.), *The imitative mind: development, evolution and brain bases*. Cambridge University Press, Cambridge, pp. 42–63.
- Nadel, J., Baudonniere, P.M., 1982. The social function of reciprocal imitation in 2-years-old peers. *Int. J. Behav. Dev.* 5, 95–109.
- Nagy, E., 2006. From imitation to conversation: The first dialogues with human neonates. *Infant. Child Dev.* 15, 223–232.
- Nagy, E., Molnar, P., 1994. Homo Imitans or Homo Provocans? *Int. J. Psychophysiol.* 18 (2), 128.
- Nagy, E., Molnar, P., 2004. Homo imitans or homo provocans? The phenomenon of neonatal initiation. *Infant Behav. Dev.* 27, 57–63.
- Nagy, E., Compagne, H., Orvos, H., Pal, A., Molnar, P., Janszky, I., Loveland, K., Bardos, Gy., 2005. Index finger movement imitation by human neonates: Motivation, learning and left-hand preference. *Ped Res.* 58, 749–753.
- Nystrom, P., 2008. The infant mirror neuron system studied with high density EEG. *Soc. Neurosci.* 3 (3–4), 334–347.
- Platek, S.M., Gallup Jr., G.G., 2002. Self-face recognition is affected by schizotypal personality traits. *Schizophr. Res.* 57 (1), 81–85.
- Rizzolatti, G., Arbib, M.A., 1998. Language within our grasp. *Trends Neurosci.* 21 (5), 188–194.
- Rizzolatti, G., Craighero, L., 2004. The mirror-neuron system. *Annu. Rev. Neurosci.* 27, 169–192.
- Rizzolatti, G., Fabbri-Destro, M., 2008. The mirror system and its role in social cognition. *Curr. Opin. Neurobiol.* 18 (2), 179–184.
- Rizzolatti, G., Sinigaglia, C., 2007. Mirror neurons and motor intentionality. *Funct. Neurol.* 22 (4), 205–210.
- Rizzolatti, G., Fadiga, L., Gallese, V., Fogassi, L., 1996. Premotor cortex and the recognition of motor actions. *Cogn. Brain Res.* 3, 131–141.
- Rubia, K., Smith, A.B., Brammer, M.J., Taylor, E., 2003. Right inferior prefrontal cortex mediates response inhibition while mesial prefrontal cortex is responsible for error detection. *Neuroimage* 20, 351–358.
- Ruby, P., Decety, J., 2001. Effect of subjective perspective taking during simulation of action: A PET investigation of agency. *Nat. Neurosci.* 4 (5), 546–550.
- Rumiati, R.I., Weiss, P.H., Shallice, T., Ottoboni, G., Noth, J., Zilles, K., Fink, G.R., 2004. Neural basis of pantomiming the use of visually presented objects. *Neuroimage* 21 (4), 1224–1231.
- Talairach, J., Tournoux, P., 1988. *Co-planar stereotaxic atlas of the human brain*. Thieme Medical Publishers, New York.
- Tanaka, S., Inui, T., 2002. Cortical involvement for action imitation of hand/arm postures versus finger configurations: an fMRI study. *NeuroReport* 13 (13), 1599–1602.
- Tanaka, S., Inui, T., Iwaki, S., Konishi, J., Nakai, T., 2001. Neural substrates involved in imitating finger configurations: An fMRI study. *NeuroReport* 12 (6), 1171–1174.
- Uzgiris, I.C., 1981. Two functions of imitation during infancy. *Int. J. Behav. Dev.* 4, 1–12.
- Wiese, H., Stude, P., Nebel, K., Forsting, M., de Greiff, A., 2005. Prefrontal cortex activity in self-initiated movements is condition-specific, but not movement related. *Neuroimage* 28 (3), 691–697.
- Zubicaray, G.I., Andrew, C., Zelaya, F.O., Williams, S.C.R., Dumanoir, C., 2000. Motor response suppression and the prepotent tendency to respond: a parametric fMRI study. *Neuropsychologia* 38, 1280–1291.