Brain correlates of social cognition and interaction

Anne Mandel

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Abstract

Although humans spend a considerable amount of their time in interaction with other people, brain activity has mostly been studied in artificial and simplified settings without real social interaction. However, such conditions are not optimal for understanding how the brain really processes complex and often non-recurring information that arises during interaction with other people.

   This Thesis probes the brain basis of social observation and live interaction by studying how subtle facial movements (eye blinks) affect the brain activity of the viewer, and how brain rhythms, especially the rolandic mu rhythm, behave during natural conversation. Magnetoencephalography (MEG) was used to track the brain activity of the healthy adults.

   The results showed that the brain of the viewer responds to observed eye blinks, even if the blinks are embedded in other auditory and visual information (e.g. while watching someone telling a story). Brain responses to eye blinks remained equally fast and strong even when the blink video was considerably slowed down to 38% of the original speed. Moreover, the strength of the brain responses to eye blinks correlated positively with the empathy of the viewers. These findings indicate that even facial movements that often go unnoticed are relevant social cues and affect the brain activity of the viewers in an empathy-related manner.

   For studies of live social interaction, we developed a dual-MEG system. Using this new setup, we recorded MEG from 9 pairs of healthy adults during natural conversation. The sensorimotor cortex was activated in a left-hemisphere-dominant manner when the subjects were speaking, indicated by the suppression of rolandic mu-rhythm both in 10- and 20-Hz frequency bands. The power of the 10-Hz mu rhythm increased transiently 1–3 s before the end of previous speaker's turn, suggesting that the subjects predicted the turn changes to prepare for their own turns.

   The results of this Thesis broaden the knowledge about how different aspects of social interaction, ranging from perceiving trivial facial movements to turn changes in conversation, modulate the brain activity of the interacting participants.

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Contents

List of Abbreviations and Symbols

ASD	autism spectrum disorder
AUD	audio story + still frame of the video (P2)
AUDVIS	audiovisual; video presented with sound (P2)
EEG	electroencephalography
EOG	electro-oculogram
fMRI	functional magnetic resonance imaging
IRI	Interpersonal Reactivity Index
MEG	magnetoencephalography
PET	positron emission tomography
ROI	region of interest
STS	superior temporal sulcus
TFR	time–frequency representation
VIS	video presented without sound (P2)

List of Publications

This doctoral dissertation consists of a summary and of the following publications that are referred to in the text by their numerals

1. Mandel, A., Helokunnas, S., Pihko, E., Hari, R. (2014). Neuromagnetic brain responses to other person's eye blinks seen on video. *Eur. J. Neurosci., 40*, 2576–2580. doi: 10.1111/ejn.12611

2. Mandel, A., Helokunnas, S., Pihko, E., Hari, R. (2015). Brain responds to other person's eye blinks in a natural setting: the more empathetic the viewer the stronger the responses. *Eur. J. Neurosci., 42,* 2508–2514. doi: 10.1111/ejn.13011

3. Baess, P., Zhdanov, A., **Mandel, A.**, Parkkonen, L., Hirvenkari, L., Mäkelä, J.P., Jousmäki, V., Hari, R. (2012). MEG dual scanning: A procedure to study interacting humans. *Front. Hum. Neurosci., 6*: article 83. doi: 10.3389/fnhum.2012.00083

4. Mandel, A., Bourguignon, Parkkonen, L., Hari, R. Sensorimotor activation related to speaker vs. listener role during natural conversation. *Neurosci. Lett., under revision*.

Author's Contribution

Publication 1: "Neuromagnetic brain responses to other person's eye blinks seen on video"

The research topic was suggested by the senior author. I designed the experiment together with other co-authors, prepared the stimuli and conducted the experiments together with the second author. I analysed the data, interpreted the results and wrote the manuscript together with the co-authors.

Publication 2: "Brain responds to other persons eye blinks in a natural setting: the more empathetic the viewer the stronger the responses"

I planned the experiment together with the co-authors, prepared the stimuli and conducted the experiments together with the second author, analysed the data, and wrote the manuscript together with the co-authors.

Publication 3: "MEG dual scanning: A procedure to study interacting humans"

This work was part of a large project involving many scientists of different backgrounds. I actively participated in the planning meetings, contributed to the experimental design by creating the auditory stimuli for test measurements, conducted the MEG measurements together with other members of the research team, analysed the evoked response data, and participated in writing the manuscript together with other co-authors.

Publication 4: "Sensorimotor activation related to speaker vs. listener role during natural conversation"

I planned and conducted the experiment together with the other members of the research team and analysed the data. I interpreted the results and wrote the manuscript together with the co-authors.

1. Introduction

The ability to interact with other people is crucial in human life: our development, wellbeing and even survival depends on whether we are able to communicate our needs and understand the intentions of others. Social deprivation in children can lead to severe mental and physical problems, such as reduced facial expressions, repetitive movement behaviour, slowed physical growth, and disturbed stress-hormone regulation (Carlson & Earls, 1997; Wismer Fries *et al.*, 2009).

However, the brain basis of social interaction has only recently risen to the focus of neuroscience, mainly because it requires new research approaches. Human interaction consists of unique verbal and non-verbal signals that rarely repeat themselves, or, when repeated, would at least not be perceived in the same way by the interacting partners (e.g. each smile occurs in its own context that seldom fully matches with the context of other smiles). Therefore, in addition to conventional experimental methods, we need to find new ways to study the brain processing of these unique events.

This Thesis probes human brain processing both during passive social observation and live interaction by studying the perception of subtle movements in another person's face and scrutinizing the modulation of brain rhythms during free conversation. To be able to study the brain activity during real interaction, we developed a two-person magnetoencephalography (MEG) system that allows brain activity and behaviour to be measured from two communicating participants. The development of this dual-MEG system forms part of this Thesis.

2. Background

In the following, I will examine the aspects that make social interaction special and the challenges of studying social communication experimentally. I will discuss the significance and brain correlates of those aspects of social cognition that are studied in the current Thesis, such as the signs derived from other person's eyes and the mechanism of turn-taking in conversation. Then, I will focus on mu rhythm as an indicator of sensorimotor brain reactivity, especially during speaking, listening, and turn-taking in conversation, ending with an introduction of MEG for studies of social cognition and interaction.

2.1 Uniqueness of social interaction

Social interaction is a fundamental part of human life. Babies strive to interact as soon as they are born: they prefer to look at faces that display eye contact (Farroni *et al.*, 2002), they try to communicate their own needs by vocal and facial expressions, and they respond to other person's actions in various ways.

Although we perceive social stimuli with the same senses as all other types of stimuli, there is something that makes humans specifically "tuned" for socially relevant information. For example, people attend automatically to information relevant to themselves, such as their own name or the name of their hometown (Cherry, 1953; Gray *et al.*, 2004). Sometimes people perceive even non-social stimuli as social, for example, seeing a face on the moon or perceiving arrangements of inanimate objects (e.g. flowers, vegetables, books) as portraits of humans (e.g. the art of Giuseppe Arcimboldo). Some emotions, such as embarrassment, guilt, and pride, are felt only in social context, in relation to other people.

Another crucial aspect of social communication is reciprocity. In contrast to merely responding to environmental stimuli, social interaction evolves through mutual exchanges: each participant affects the behaviour of others. This reciprocity is the main reason why many current experimental setups where the participants are presented with predefined artificial stimuli, do not enable studying social communication in its most natural form.

Brain disorders, such as autism, that specifically affect the person's ability to take part in social interaction demonstrate that social skills are distinct from other abilities. People with autism spectrum disorders (ASD) lack interest in

other people and have difficulties understanding the mental states of others (Frith, 2001). Even people with ASD whose intelligence is within normal range have difficulties with social relationships (Howlin, 2000).

2.2 Challenges in studying the brain basis of social interaction

Despite the clear importance of social skills for humans, the brain basis of social interaction has only recently become a focus of neuroscience research (for reviews see Hari & Kujala, 2009; Hari *et al.*, 2015).

Technical challenges have largely hindered studies of social *interaction* in naturalistic experimental setups that involve unrepeatable stimuli or require measurements of brain activity and behaviour from two persons at the same time. Many features of social *cognition* can, however, be studied in one person at a time.

While technical possibilities are evolving rapidly so that neuroimaging of dyads instead of single individuals has been possible already for some years (Montague *et al.*, 2002), an even more important question arises concerning the characteristics of *natural social interaction*. Does one need to sacrifice some of the traditional experimental replicability (e.g. through repeated measurements and control conditions) to ensure the genuineness of the social situation and cognition arising from it?

Some researchers claim that social communication should be primarily studied in interactive settings because of the cognitive differences during participation vs. observation of interaction (Hari & Kujala, 2009; Schilbach *et al.*, 2013; Hari *et al.*, 2015), while others assert that only the mental representation of oneself in relation to others is necessary e.g. for studying social emotions (Krach *et al.*, 2013).

From the brain-imaging perspective, there are several steps between these extremes (Hari *et al.*, 2015): In the most limited approach to studying social cognition, one could present excerpts from naturalistic stimuli (e.g. photos of faces) to individual subjects and study which brain regions are functionally specific to the processing of such stimuli. As the next step, it is possible to use dynamic, real-life-like stimuli such as movies to study the temporal dynamics of brain activity while still being able to compare the results between viewers in a fairly straightforward manner, because all the subjects have been presented the same stimuli and they have been in the same role (viewer). Simultaneous two-person studies could either allow limited, slowly-paced interactions between the participants (e.g. text message communication), which Hari and colleagues (2015) describe as reactive rather than interactive, because each partner can only react to the previous action of the other without readily being able to influence it (e.g. with a disruption). The most complex form of experimental setup in this continuum involves real-time dynamic interaction between the participants. This scenario allows the brain basis of very fast social dynamics to be probed, such as turn-taking during conversation.

This Thesis includes both single-person studies, where the participants were watching another person on a video (P1, P2), as well as two-person studies, where the participants were interacting in real time (P3, P4).

Studies involving only one person (passively) perceiving pre-defined but socially-relevant stimuli have the advantage that exactly the same controlled stimuli can be repeated and presented to all subjects, and it is possible (although not always straightforward) to create control conditions that are otherwise similar but lack socially relevant aspects. Achieving social involvement of the participants is a challenge in one-person studies. This might not be a concern when the aim of the research is to probe automatic processing of some socially-relevant cues, but it is an issue if the targeted brain processes require social immersion of the participants (e.g. the brain basis of feelings such as embarrassment). Still, such one-person studies have considerably improved our understanding of brain activity related to social interaction. For example, Stephens and colleagues (2010) showed that a listener's brain activity (as measured with functional magnetic resonance imaging, fMRI) is coupled with the speaker's brain activity with a delay of about 1–3 s, and that this coupling mostly disappears (with the exception of primary auditory cortex) when the listener does not understand the speaker's language.

From an experimental point of view, studies of live interaction, although high in ecological validity, involve many difficulties. Certain types of live interactions, e.g. conversations, cannot be directly repeated—even if the words remained the same, the interpretation could change. It is still possible to modify the communication in such a way (e.g. by imposing certain rules) that some aspects of the interaction, such as certain movements or utterances, are repeated. However, one has to be careful in pooling such events, because the context or meaning of these behaviourally similar events might be different. For example, even a simple Finnish conjunction "*niin*" could be used in a conversation to indicate agreement ["yes"], to confirm understanding ["I see"] or to give a go-ahead response to the conversation partner (e.g. after an opening sentence, the respondent may say "*niin*" to signal that the speaker can continue) (Sorjonen, 2001).

It is also very difficult to find control conditions that would be otherwise similar to the spontaneous interaction situation, but lack only the interaction part. Several studies (Babiloni *et al.*, 2007; Astolfi *et al.*, 2009; Lindenberger *et al.*, 2009; De Vico Fallani *et al.*, 2010; Sänger *et al.*, 2012, 2013) have so far tried to extract the brain activity related to social interaction by calculating different indices of inter-brain synchronization between the interacting partners. Unfortunately, this approach may not guarantee the functional significance of the findings: the observed similarities in the brain activity of the interacting partners could reflect merely being in a similar environment and being engaged in a similar task, or there could be something that especially reflects the qualities of the interaction. For example, for guitar duets (Lindenberger *et al.*, 2009), the inter-subject connectivity was highest during the metronome sound that both players heard when the interaction had not yet started; thereafter the correlation weakened. Comparing the similarities in

brain activity between actual interaction partners vs. participants who did not interact with each other but with someone else does not completely solve the problem. Each interaction is unique and it is thus obvious that there would be also more purely sensory-driven similarities in the brain activity of those people who were in the same situation than in the brain activity of people who where in different situations.

Therefore, although neither predefined stimuli nor live interaction are perfect methods for studying the brain basis of social interaction, these approaches can complement each other: single-person experiments can serve as more controlled "base-experiments" through which we can learn about the basic building blocks of social perception. Fully interactive setups, on the other hand, enable aspects of social interaction (e.g. turn-taking) that only emerge during communication to be studied.

2.3 Brain processing of socially relevant information

It is nearly impossible to draw a clear boundary between socially relevant and irrelevant information—almost everything can become socially relevant in certain situations if it has gained a certain meaning (e.g. the colour green does not inherently have meaning out of context, but when next to someone's name in social media, it can signal willingness to communicate, whereas the colour red can indicate that one does not want to be disturbed). Similarly, it is impossible to exclude any brain areas or functions when considering the brain basis of social cognition and interaction: sensory perception, memories, emotions, and the ability to act are all important.

In the following sections, I will concentrate on the significance and brain processing of social signals that are studied in this Thesis, namely the other person's eyes and turn-taking in verbal interaction. I will also discuss the role of sensorimotor activation during conversation.

2.3.1 Perception of other person's eyes

Eye gaze
Humans have exceptional eyes. Unlike other primates, the human sclera is white, and humans also have the largest ratio of exposed sclera in the eye outline (Kobayashi & Kohshima, 1997). This helps us detect open eyes and monitor the gaze direction of others (Tomasello *et al.*, 2007). Gaze direction indicates a person's focus of attention and it is therefore an important signal in social communication. Already at four months of age, infants can follow the eye gaze of others (Farroni *et al.*, 2003), and at four years, normally-developing children understand that when someone looks at a certain object, that person might prefer that object to others. Instead, children with ASD—although they are able to detect the gaze direction—cannot infer the preference of the other person (Baron-Cohen *et al.*, 1995).

During social interaction, eye contact (direct gaze) is a sign of willingness to interact, whereas averted gaze is related to avoidance. Viewers report higher

arousal and have higher skin conductance when experiencing direct than averted gaze, but only when they see a real person, not an image of the same person (Hietanen *et al.*, 2008). Observing averted gaze can involuntarily shift the attention of the viewer to the same location (Frischen, 2007).

Face-sensitive neurons in anterior superior temporal sulcus (STS) that are tuned to different head and gaze orientations were first discovered in macaque monkeys (Perrett *et al.*, 1985). Both direct and averted gaze activate STS in humans (Puce *et al.*, 1998), and, in addition, a larger occipitotemporal network involving fusiform gyrus, inferior temporal gyrus, parietal lobule and middle temporal gyri (Wicker *et al.*, 1998). The STS is more active during judgments of gaze direction than identity whereas fusiform gyrus and inferior occipitotemporal regions are more active while subjects are judging identity (Hoffman & Haxby, 2000).

Social context also modulates processing of gaze movement: for example, 150–160-ms MEG responses in V5 region were stronger when the gaze (in "dynamic" stimuli composed of successive photographs) turned towards rather than away from the viewer (Watanabe *et al.*, 2006). On the other hand, in electroencephalographic (EEG) recordings, the 170-ms temporal-lobe response was weaker when the subjects were viewing a direct vs. averted gaze (Puce *et al.*, 2000).

Eye blinks

Eye blinks are subtle facial movements that generally last 200–400 ms. Their main physiological function is to moisten the cornea. Still, blinking rate can give information about the vigilance of others: people blink more when they are drowsy (Bentivoglio *et al.*, 1997) and less when they concentrate on something (Fukuda, 1994; Oh *et al.*, 2012) or when they are telling a lie (Leal & Vrij, 2008)—the latter has also been connected with high cognitive load. Blinking rate rises after a lie is told (Leal & Vrij, 2008).

People who watch a video tend to blink more during scenes that contain less new or relevant information (Nakano *et al.*, 2009). People also blink more during pauses in speech when they watch someone talking, but the effect emerges only when the sound is heard (Nakano & Kitazawa, 2010).

Blinking behaviour affects the impression an actor makes on the observer: people who blink very often are perceived as nervous, or careless, whereas unfriendliness has a U-shaped relationship with the blinking rate; people who blink very rarely (around three times per minute) and very often (more than 36 times per minute) are perceived less friendly than those who exhibit a blinking rate between these extrema (Omori & Miyata, 2001). A study of the televised presidential election debate between Walter Mondale and Roland Reagan associated eye blink behaviour to Mondale's less favourable rating: Mondale blinked very frequently (more than once per second) and made less gaze and head movements than did Reagan (Patterson *et al.*, 1992).

The development of interacting robots further emphasizes the social importance of blinking: robots who blink after making eye contact with a human create in the human a stronger feeling of being looked at than robots who only make an eye contact but do not blink (Hoque *et al.*, 2014).

Little is known about how eye blinks activate the viewer's brain. In an EEG study (Brefczynski-Lewis et al., 2011), a sequence of images with open–closed–open eyes elicited several evoked potentials peaking at 100–600 ms. The responses evoked by eye blinks were significantly smaller than responses to 100-ms gaze movements. However, this study used very short-lasting (33 ms) artificial blink stimuli, and it thus remains unclear how the brain would respond to normal eye blinks (lasting 200–400 ms).

2.3.2 Turn-taking during conversation

One of the best examples of smooth social coordination is turn-taking during conversation. It is remarkable that most turn changes occur within ±250 ms with respect to the end of the turn of the previous speaker. This pattern is universal across languages (Stivers *et al.*, 2009). Such a fast start of the next turn is not possible just as a reaction to the end of the previous turn. Answering in a conversation is much more complex than, for example, reacting to a heard vowel [a:] with a button press that takes about 180 ms, or reacting to the vowel by repeating it which takes about 210 ms (Fry, 1975). Taking a turn in the conversation requires comprehending the partner's speech, covertly preparing an answer and initiating a motor response to vocalize it.

It has been claimed that the smooth turn-taking in a conversation relies on mutual entrainment of brain oscillations between the conversation partners. Wilson and Wilson (2005) argue that the likelihood that a speaker (or a listener) will initiate the next syllable constantly oscillates, so that when the current speaker has the lowest likelihood to initiate the next syllable, the listener has the highest likelihood to do so. The authors argue that, considering the length of the syllables in speech (100–150 ms) and the typical length of pauses between turns (80–180 ms), the candidate brain oscillations could fall approximately between 5 and 12 Hz (Wilson & Wilson, 2005).

While no overall correlation has been found between the breathing rhythms of interaction partners in dyadic conversation (Warner *et al.*, 1983; Rochet-Capellan & Fuchs, 2014), the breathing rhythm of the listener becomes more similar to the breathing rhythm of the speaker when the turn change approaches (McFarland, 2001). This finding supports some kind of entrainment between the interaction partners.

People are able to predict turn changes in pre-recorded conversation when they hear the content of the speech but the intonation contour is completely removed; if they hear the prosodic changes, but the speech content is unintelligible, the predictions about turn changes are not reliable (Ruiter *et al.*, 2006). However, these findings do not imply that the non-verbal cues are unimportant, since the subjects were able to distinguish the sound excerpts taken from the middle of a turn from the sound excerpts taken from the turn end, but only when the pieces contain disagreement (Stephens & Beattie, 1986). However, people were not able to distinguish the same middle-turn and turn-ending utterances when these phrases were given to them in a written form.

Besides the speech itself, people use their gaze to signal a turn change: for example, at the end of a turn they briefly engage in gaze contact, after (or dur-

ing) which the previous listener starts speaking (Novick *et al.*, 1996). Turn-taking-like communication patterns have an effect on the reactions of infants: when an adult responds to a child in a manner that resembles turn-taking with the infant, the child produces more syllabic (speech-like) sounds than when the adult answers at random moments (Bloom *et al.*, 1987). The turns of conversation partners overlap less when people can see each other, compared with an audio-only conversation, indicating that the amount of available cues improves the turn-taking accuracy (Neiberg & Gustafson, 2011).

2.3.3 Sensorimotor activity during speaking and listening

Speaking is a complex process that, as sensorimotor activity, involves control of articulation, vocalization, and breathing. Murphy and colleagues (1997) compared brain activity (measured by positron emission tomography (PET)) while people *(i)* repeated aloud a sentence vs. vocalized the sentence without moving their mouth or tongue and *(ii)* mouthed the sentence without making a sound vs. thought the same sentence silently. By subtracting between the conditions it was possible to find that the brain areas related to articulation only included bilateral sensorimotor cortices and cerebellum, in addition to right-lateralized thalamus/caudate. Further comparison between brain activity while *(iii)* saying the sentence aloud vs. mouthing it silently, and *(iv)* vocalizing the sentence without articulation vs. thinking it silently, revealed brain regions related to control of breathing during speaking, vocalization, and hearing self-generated speech. These areas included sensorimotor cortex, thalamus, cerebellum, supplementary motor area and superior temporal cortex.

Although clinical studies underline the crucial role of the left hemisphere in speech production (Vargha-Khadem *et al.*, 1985), it is also known that aphasic patients with left-hemisphere lesions are able to produce non-propositonal speech, such as counting numbers or reciting the names of the months (Levy & Trevarthen, 1977). Brain-imaging studies have reported both bilateral activation and left-hemisphere dominance during speech production. Sensorimotor cortices were activated bilaterally while subjects repeated single vowels (Tarkka, 2001), words they just heard (Wise *et al.*, 1999), or a phrase (Murphy *et al.*, 1997). On Left-hemisphere dominance has been observed in subjects reading aloud single nouns (Salmelin *et al.*, 2000) or reciting the names of the months (Riecker *et al.*, 2000).

The role of motor cortex during listening has been less clear. Whereas motor-cortex activation has been reported during listening in some studies, the majority of studies using passive listening tasks did not indicate such activity (for a review see Scott *et al.*, 2009). One explanation of these differences is the variable task demand in different experiments: motor and premotor cortices are activated while listening to distorted or noisy speech (Davis & Johnsrude, 2003) or to foreign-language syllables (Wilson & Iacoboni, 2006). Participants' ability to discriminate stop consonants in noise (syllables 'pa', 'ta', 'ka') significantly decreased when the activity in their left premotor cortex was disrupted by repeated transcranial magnetic stimulation (Meister *et al.*, 2007). These findings indicate that the activation of motor cortex may be crucial in

challenging listening situations when the auditory input is unfamiliar, distorted, or noisy.

Motor cortex is also activated while the subjects are listening to words that represent motor actions, and this activation may follow somatotopic organization. For example, the word "lick" has been reported to activate the most ventral part of motor cortex (controlling tongue movements) and the word "kick" the most dorsal part of motor cortex controlling leg movements (Pulvermüller, 2005). However, this phenomenon is not unique for motor cortex, as words representing real objects that have clear visual representations activate brain areas related to visual processing (Kiehl *et al.*, 1999; Fiebach & Friederici, 2004).

Mu rhythm as an indicator of sensorimotor activity during speaking and listening

The term *mu rhythm* refers to rolandic cortical oscillations at frequencies around 10 and 20 Hz. These rhythms are dampened before and during movements (Chatrian *et al.*, 1959; Tiihonen *et al.*, 1989). Suppression of MEG mu rhythm has been demonstrated in humans e.g. during finger, toe, and mouth movements (Salmelin *et al.*, 1995). The direct relation between sensorimotor-cortex activation and the suppression of mu rhythm makes it an good marker for studying the involvement of these brain regions in various tasks.

Study P4 of this Thesis describes the modulation of mu rhythm during natural conversation. From previous studies we know that simple mouth movements (e.g. mouth opening) are usually related to bilateral suppression of the mu rhythm (Salmelin *et al.*, 1995). There are indications that the activation is different during production of speech vs. non-speech sounds (e.g. Salmelin & Sams, 2002), but the results are still controversial, partially due to various types of vocalizations used as speech vs. non-speech sounds.

Sensorimotor coordination is especially relevant during turn-taking in conversation. In P4, we also inspected the modulation of the mu rhythm at turn changes to see whether it would inform about how the listeners are able to switch to speaking so smoothly.

2.4   Magnetoencephalography in studying social cognition

Magnetoencephalography is a non-invasive brain imaging method that allows recording the brain's electromagnetic activity with sub-millisecond accuracy. The first magnetoencephalographic signals were recorded in 1968 in the USA (Cohen, 1968), and the first whole-scalp MEG recordings were made 25 years later in Finland (Ahonen *et al.*, 1993).

MEG is most sensitive to cortical currents tangential to the skull; only tangential currents produce magnetic fields outside an ideal sphere (Hämäläinen *et al.*, 1993) The main generators of the MEG signals are postsynaptic intracellular currents in the pyramidal neurons of the cortex (Hari, 1990). Tens of thousands of parallel neurons need to be active synchronously to produce signals that are large enough to be recorded outside the head. The spatial resolu-

tion of MEG can be 2–3 mm in the cortex when all assumptions of the source-estimation method are met (Hämäläinen *et al.*, 1993)

The excellent temporal resolution of MEG makes it suitable for following the sequences of rapidly evolving cortical processes related to sensory perception and motor actions (for a review, see Hari *et al.*, 2000), and to perception and production of language (for a review, see Salmelin, 2007). Moreover, MEG can reveal brain processing in naturalistic situations (e.g. during movie viewing, Lankinen *et al.*, 2014) or, as presented in this Thesis, during live interaction (P4).

MEG has had a significant role in pinpointing the cortical generators of various electric evoked responses (e.g. Hari *et al.*, 1980) and brain rhythms (for a review see Hari & Salmelin, 1997). MEG has been applied in both healthy and clinical populations; its clinical applications range from localizing epileptic foci (Paetau *et al.*, 1990) to following the progress of stroke rehabilitation (Roiha *et al.*, 2011; Laaksonen *et al.*, 2012). In temporal resolution, MEG and EEG significantly outperform methods such as fMRI and near-infrared spectroscopy that are both limited by the sluggish hemodynamic response that evolves over several seconds (Miezin *et al.*, 2000; Huppert *et al.*, 2006).

Although EEG has similar temporal resolution as MEG, the spatial resolution of MEG is better than that of EEG. The reasons for this difference are that (1) the tissues between the brain and the sensors do not significantly affect the magnetic field, whereas the electric field is considerably smeared by inhomogeneities in tissue conductivities (Hämäläinen *et al.*, 1993), and (2) MEG recordings give direct information about local magnetic fields whereas EEG recordings always represent voltage differences (potentials) between two recording sites. The ability to quite straightforwardly link/superimpose the estimated locations of MEG sources to a subject's own anatomical magnetic resonance images makes it possible to use MEG in pre-surgical mapping of functional brain areas (Mäkelä *et al.*, 2006).

2.4.1 Analysis of MEG data

The analysis of MEG data varies from averaging evoked response to estimating various inter-brain or intra-brain correlation metrics.

In this Thesis, evoked responses and changes in brain oscillations were analysed. The term *evoked response* refers to EEG or MEG responses evoked in the human brain by a certain type of stimulus. To obtain the evoked response, the stimuli are presented repeatedly and single responses averaged time-locked to stimulus presentation. The averaging reduces uncorrelated noise and enables studying the precise time course of the brain activity related e.g. to certain type of sensory processing. One way to model the underlying generators is to use equivalent current dipoles that model the location, strength, and direction of the source currents (Hämäläinen *et al.*, 1993).

Analysis of the brain's intrinsic oscillations is also used both in EEG and MEG research. The most known human brain rhythm is the posterior alpha that emerges in the parieto-occipital cortex particularly when the subject's eyes

are closed and diminishes or disappears when the eyes are open again (Berger, 1929). Further studies have shown that modality-specific rhythms are characteristic to several brain areas (Hari & Salmelin, 1997), e.g. sensorimotor cortex exhibits 10- and 20-Hz oscillations that are strongest at rest and diminish during movement preparation and execution—this sensorimotor mu rhythm is in the focus of P4 in this Thesis.

3. Aims

The goal of the Thesis was to improve understanding about how the human brain processes different types of social information (either during observation or during interaction). The specific research questions were to

- investigate whether the brain responds to subtle facial movements such as eye blinks (P1), and whether these responses can also be seen in a natural situation where the eye blinks are embedded in other auditory and visual information (P2);

- create an experimental setup that enables studying behaviour and brain activity during live interaction (P3);

- assess how brain rhythms are modulated during natural conversation (P4).

4. Materials and Methods

4.1 Participants

Altogether 44 volunteers took part in the experiments (see Table 1 for the number of participants, their gender and age in each publication). All subjects, except one in P1, were right handed. All had normal hearing and normal or corrected-to-normal vision. All experiments had prior approval by the Ethics Committee of the Hospital District of Helsinki and Uusimaa. The subjects gave their written consent before the experiments.

Table 1. Participant characteristics in each publication: number (N), gender (female/male) and age (range and mean in years).

Publication	N	Female/Male	Mean age (Range)
P1	11	5/6	26 (21–55)
P2	13	8/5	24 (19–30)
P3	2	1/1	44 (31–57)
P4	18	6/12	28 (21–49)

4.2 Stimuli

Figure 1 shows the frames of blink and bar videos that were used in P1. A video of a person blinking her eyes and a control video (black bars moving with the same characteristic as the eyelids in the blink video) were shown at normal speed (length 2.7 s) and in slow motion (length 7.1 s). All these stimuli were presented to the subjects 102 times.

In P2, the participants saw a video of a person looking at the camera and telling a story (with and without sound), or heard the same story with a still frame of the video on screen.

In P3, 50-ms tone beeps (frequency 500 Hz) were presented to both subjects at the same time. In P4, the participants had a free conversation (mean length 7 min) on a given topic (holidays or hobbies).
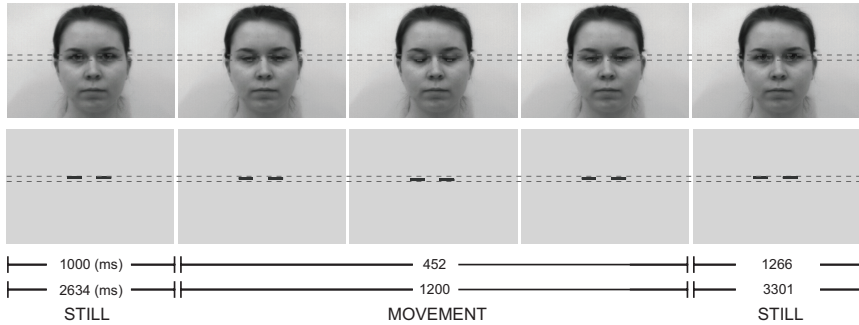
Figure 1. Example frames from video stimuli: blink (*above)* and black bars (*below*). The time lines below the video frames mark the length of still and movement phases in the videos. Figure modified from Fig. 1 of P1.

4.3 MEG measurements

Magnetoencephalographic brain responses were measured with 306-channel whole-scalp neuromagnetometers (Elekta Neuromag™ in Aalto University and Neuromag Vectorview system in BioMag Laboratory in Helsinki University Hospital; both manufactured by Elekta Oy, Helsinki, Finland) in a magnetically shielded room. All experiments (P1–P4) took place in the MEG core of Aalto NeuroImaging and experiments in P3–P4 occurred simultaneously between the Aalto and BioMag Laboratories. The two MEG laboratories are 5 km apart.

The neuromagnetometers comprise 102 sensor units, each with one magnetometer and two orthogonal planar gradiometers; the sensors are arranged in a helmet-shaped array that covers the scalp of the subject. Magnetometers are sensitive both to nearby and far-away sources whereas planar gradiometers are sensitive to sources just underneath them.

Prior to the experiments, four (or five, depending on the coil system) head-position-indicator coils were attached to the subject's scalp, and head coordinates were registered with a 3D-digitizer by identifying the locations of the indicator coils with respect to three anatomical landmarks (nasion and two preauricular points). At the start of each block in the experiments, the position of the participant's head in the MEG helmet was determined by feeding weak currents to the indicator coils, and then registering the corresponding signals with the MEG sensors.

Both vertical and horizontal electro-oculograms (EOGs) were recorded in all experiments: vertical EOG between two electrodes above and below the left eye of the subject and horizontal EOG between two electrodes attached to the left and right eye canthi. EOG recordings were used to remove artifacts induced by blinking or excessive eye movements from the MEG data (in P1–P3 the contaminated epochs were rejected from the analysis; in P4, the artifacts were removed using independent component analysis).

Data presented in the current thesis were sampled at 600 Hz (P1; band-pass filter 0.03–200 Hz) or 1000 Hz (P2–P4; band-pass filter 0.1–330 Hz in P2 and P4, and 0.03–330 Hz in P3).

4.3.1 Analysis of MEG data

In all studies, MEG data were first pre-processed with the signal-space separation method (P3; Taulu *et al.*, 2004) or temporal signal-space separation method (P1, P2, P4; Taulu & Simola, 2006; Taulu & Hari, 2009) to remove artifacts caused by external sources. In P1–P3, the epochs contaminated by blink-artefacts were rejected from further analysis.

In P4, where the focus was on brain oscillations instead of evoked responses, independent component analysis was used as an additional measure to remove artifacts (Vigário *et al.*, 2000) induced by eye movement, blinking, muscle activity and electric activity of the heart.

In P1 and P2, we averaged the brain responses with respect to the eye blinks seen on video; in P3, the brain signals were averaged with respect to sound onsets.

In P1 and P2, vector sums (square roots of the sums of the squared signals) were calculated over the two orthogonal planar gradiometer channels in each MEG sensor. Vector sums no longer contain polarity information, which minimizes the effect of source orientations and therefore increases the robustness of evoked-response analysis. In P1, areal averages of the vector sums were calculated for three (left, central, right) parieto-occipital regions. In P2, the source waveform with the clearest evoked response was picked from each subject for further analysis. Before the amplitude measurements, the evoked responses were low-pass-filtered at 30 Hz.

In P2 and P3, the sources of the observed brain responses were modelled as equivalent current dipoles fitted at the peak of the evoked responses. In P1, source modelling was attempted but was found unreliable because the long-lasting signals formed complex, non-dipolar field patterns.

In P4, the MEG data collected during the conversation task were first divided into speaking and listening periods (according to the audio recording synchronized with MEG). Thereafter, the power spectra (0–50 Hz; based on the average of fast Fourier transforms of 1-s long hanning-windowed segments) for each subject were calculated separately for both periods. Since MEG gradiometers from the same pair are sensitive to the magnetic field gradients in orthogonal directions, the two spectra from each planar gradiometer pair were averaged. In addition, time–frequency representations (TFRs) of MEG signals were calculated at the turn changes (from −5 to 5 s from the turn start, from 1 to 40 Hz with frequency steps of 1 Hz, 7-cycle wavelets shifted in 20-ms steps). Thereafter, 10- and 20-Hz bands were extracted from the TFRs to study the modulations of the mu rhythm in relation to turn taking.

4.4 Behavioural measures

4.4.1 Open questions and questionnaires

In P1, subjects were asked to freely describe whether the bar motion had resembled anything in particular. In P2, subjects answered open questions about the content of the story the speaker in the video was telling; the aim was to promote the subjects' attention to the stimuli.

In P2, the participants filled the Interpersonal Reactivity Index (IRI; Davis, 1980) that has four subscales. The *Perspective Taking* subscale measures the tendency to put oneself in the situation of another person, the *Empathic Concern* subscale assesses the tendency to feel compassion for others who are in a trouble, the *Fantasy* subscale indicates a tendency to imagine oneself in the place of fictional characters, and the *Personal Distress* subscale measures the tendency to experience distress or anxiety in response to distress in others.

4.4.2 Eye tracking

In P2, eye tracking was used to assess where the participants were looking while watching the video of a speaking person. The subject's eye gaze was measured with an MEG-compatible remote eye tracker EyeLink 1000 (SR Research, Ottawa, Canada) that was placed on a table ca. 80 cm from the subject's eyes. The eye tracker has an infrared light illuminator and a camera that measures the reflection from the subject's eye. Gaze position was recorded at 500 Hz with 0.5° spatial accuracy.

We focused especially on what proportion of the total viewing time the subjects spent fixated on the eyes and mouth of the speaker. We also examined the saccades they made after the speaker in the video had blinked.

5. Results

5.1 Publication 1: The viewer's brain responds to other person's eye blinks

Background. Behavioural studies have shown that eye blinking can give information about the mental state of others: people blink less e.g. during cognitively demanding tasks (Oh, et al., 2012). Eye-blinking behaviour also affects the ways in which others judge an actor so that people who blink very often are perceived as nervous or careless (Omori & Miyata, 2001). Very little is known about how eye blinks of others affect the brain activity of the viewer. An EEG study using simulated eye blinks (a sequence of photos of open–closed–open eyes) demonstrated that observed eye blinks evoke a response with several deflections peaking at 100–600 ms after the start of the blink (Brefczynski-Lewis *et al.*, 2011). Our aim was to find out how brain responds to natural eye blinks and whether the brain responses to slow-motion eye blinks are weaker and slower, as would be expected, based on previous results about brain responses to stimuli moving with different speed (Heinrich, 2007).

Methods. The participants watched video clips of the face of a subject who was blinking her eyes every few seconds and, as a control, black bars that moved on a grey background with the same speed and amplitude as the eyelids in the blink clip (see the example frames of the stimuli in Figure 1, p. 26). The blink video was recorded with a high-speed camera at 500 fps and bar video at 30 fps. Both types of stimuli were shown at normal speed (blink/bar movement duration 452 ms) and in slow motion (blink/bar movement length 1200 ms) and repeated 102 times each. Normal and slow-motion bar-stimuli were always shown before the blink stimuli to avoid the effect the blinking eyes might have on watching similarly moving bars. Participants' brain responses were measured with MEG.

Results. Figure 2 shows that brain responses to both eye blinks and bar stimuli peaked in the occipital cortex about 200 ms after stimulus onset. The strengths and latencies of brain responses to eye blinks did not change when the stimuli were slowed down, whereas the responses bars were 24% weaker ($F(1,10) = 18.2$; $p = 0.002$) and peaked on average 33 ms later ($F(1,10) = 8.6$; $p = 0.015$) to slow-motion than normal-speed stimuli).

Discussion. During typical face-to-face interaction, the eye blinks of other persons are rarely noticed, but we now showed that the brain of an observer clearly responds to such stimuli. Furthermore, the responses to slow-motion eye blinks remained equally fast and strong even when the stimuli were considerably slowed down. This result contrasts with previous findings showing

that brain responses to more slowly moving stimuli rise more slowly and are weaker (Heinrich, 2007); in the present study, this slower, weaker behaviour was seen in response to the control bar stimuli but not the eye blink stimuli.

These findings may relate to the social significance of eye blinks for the viewer. Previous studies have shown that healthy viewers tend to synchronize their blinking with a speaker on a video, whereas people with ASD do not (Nakano *et al.*, 2011). Slow-motion blinks may be even more salient than normal eye blinks, because the unusually slowly moving eyelids make the blinker look drowsy or odd, thereby catching the viewer's attention. On the other hand, we know that attention enhances cortical responses in visual discrimination (Spitzer *et al.*, 1988) and spatial-attention tasks (Kanwisher & Wojciulik, 2000). The effect of eye-blink saliency on brain responses needs further investigation in natural situations.
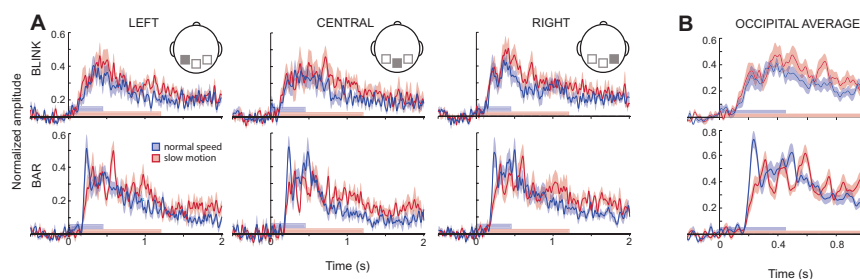

Figure 2. Mean (± SEM; shadowed areas) responses across subjects to observed eye blinks (*top row*) and bars (*bottom row*), presented at normal speed (*blue*) and in slow motion (*red*). **A**. Evoked responses separately in left, central and right parieto-occipital cortex (see the schematic head). The bars on the horizontal axis mark the duration of the normal-speed and slow-motion videos **B**. Same responses averaged over the three regions. Figure modified from Figs. 2 and 3 of P1.

5.2 Publication 2: Brain responds to other person's eye blinks also in a natural situation—the more empathetic the viewer, the stronger the responses

Background. In P1, we showed that the brain of the viewer responds to eye blinks that the viewer is seeing. The aim of the current experiment was to extend these results by asking whether the brain responds to eye blinks also in a natural situation in the presence of additional visual and/or auditory information that might mask the eye blinks or direct the viewers' attention elsewhere.

Methods. The participants now watched a video of a woman telling a story (cropped still-frames of the video in Fig. 3A) while their MEG signals were measured. The video was first shown without sound (visual only, VIS), then with sound (audiovisual, AUDVIS), and finally the audio story was presented with a still frame of the video on screen (auditory only, AUD). Before the experiments, the subjects filled an IRI (Davis, 1980) questionnaire that measures participants' tendencies to easily empathize with others or feel stress in social situations. Subjects' eye movements were tracked during the MEG recording.

To see how much the subjects looked at the eyes and mouth of the speaker, we defined regions of interest (ROIs; 220 pixels x 70 pixels in size) around the speaker's eye and mouth areas. The saccades that the subjects made were counted (in 40-ms time windows) with respect to the start of blinks in the video. We separated the saccades that ended in the eye-ROI of the speaker from the saccades that ended elsewhere on the screen.

Results. Figure 3A shows that the viewers mainly gazed at the speaker's eye region (mean ± SEM 60 ± 6 % of the total fixation time during VIS, 60 ± 5% during AUDVIS, and 61 ± 7% during AUD). The speaker's blinks affected the eye movements of the viewers (Fig. 3B): the viewer's saccades were during VIS and AUDVIS conditions suppressed around 180 ms after the speaker's blink had started. The number of saccades returned to the baseline level (or higher, seen as a "rebound") at about 340 ms.
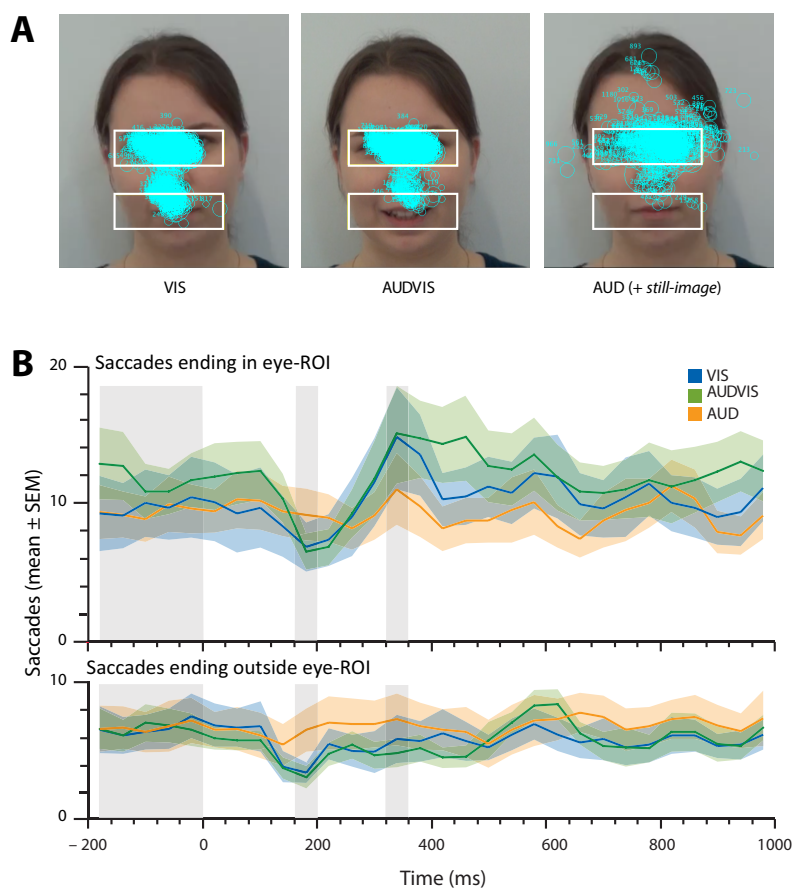
Figure 3. A. Fixation patterns from an individual subject during visual-only (VIS), audiovisual (AUDVIS) and auditory-only (AUD) condition. White boxes on the video frames mark the ROIs for eye and mouth area. **B.** Mean (± SEM) number of saccades ending in the eye region of the speaker (*above*) and elsewhere on the screen (*below*) during VIS (*blue*), AUDVIS (*green*) and AUD (*yellow*) conditions. Grey bands on the graphs mark the baseline (*left*), suppression (*middle*), and "rebound" (*right*) periods examined in the statistical analysis. Figure modified from Figs. 1 and 2 of P2.
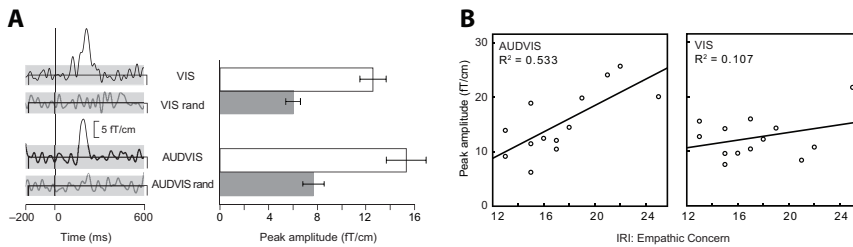
Figure 4. A. Brain responses to observed eye blinks (from an individual subject) during visual (VIS) and audiovisual (AUDVIS) conditions, and when the same data were averaged with no relation to eye blinks (VIS rand, and AUDVIS rand, respectively). Shaded areas indicate the baseline ± 3 SD levels. The bar graph on the right shows mean (± SEM) peak amplitudes of responses from the same conditions. **B**. Peak amplitudes of brain responses to observed eye blinks as a function of individual Empathic Concern scores from the Interpersonal Reactivity Index for all 13 subjects. Figure modified from Figs. 3 and 4 in P2.

Responses were evident in the viewers' occipital cortex at about 250 ms after the start of the speaker's blink. The latencies and peak amplitudes did not differ between VIS and AUDVIS conditions (Fig. 4A). During AUDVIS, but not during VIS, the response strength correlated positively (Spearman's correlation = 0.73; p = 0.005) with the Empathic Concern score from the IRI questionnaire (Fig. 4B).

Discussion. This study showed that other person's eye blinks elicit clear responses in the viewers' parieto-occipital cortex, even when embedded within rich auditory and visual information. The response strength correlated positively with the empathic concern levels of the viewers, but only in the audio-visual condition—most likely because the speaker's story created a social context that enforced empathy-related modulations of brain activity. This interpretation is in line with a previous finding (Regenbogen *et al.*, 2012) that when a speaker's facial expressions, prosody or speech content did not match the emotion that the speaker was experiencing (through experimental manipulations), emotion recognition was poorest when the facial expression was manipulated. However, the observer's own emotional responses (reflecting empathy) reduced most when the speech content was manipulated (Regenbogen *et al.*, 2012). It is also possible that during audio-visual presentation the less-empathic viewers might have concentrated more on the speaker's voice, especially because they had already seen the same video without sound.

Thus the brain of a viewer reacts to tiny facial movements (eye blinks), even when they are embedded within more salient auditory and visual information. The results also suggest that the reactivity to other person's facial gestures is associated with the empathy of the viewer.

5.3 Publication 3: A dual-MEG system for studying live interaction between two subjects

Background. Some types of social interaction, such as conversation, cannot be studied without allowing people to communicate in real time. To study brain activity in such a situation, we developed the first-in-the-world dual-MEG system suitable for two-person studies.

Method. The dual-MEG system comprises two MEG laboratories, 5 km apart, where two subjects are studied simultaneously. Figure 5 illustrates the setup: the two participants communicated via a landline telephone connection, using earphones and microphones. MEG and audio data (MEG data sampled at 1 kHz and audio data at 22 kHz) were recorded and stored at both sites locally and later synchronized by means of a digital timing signal recorded in all datasets. The timing signals were generated by audio-recording computers whose real-time clocks were synchronized using the Network Time Protocol (NTP).
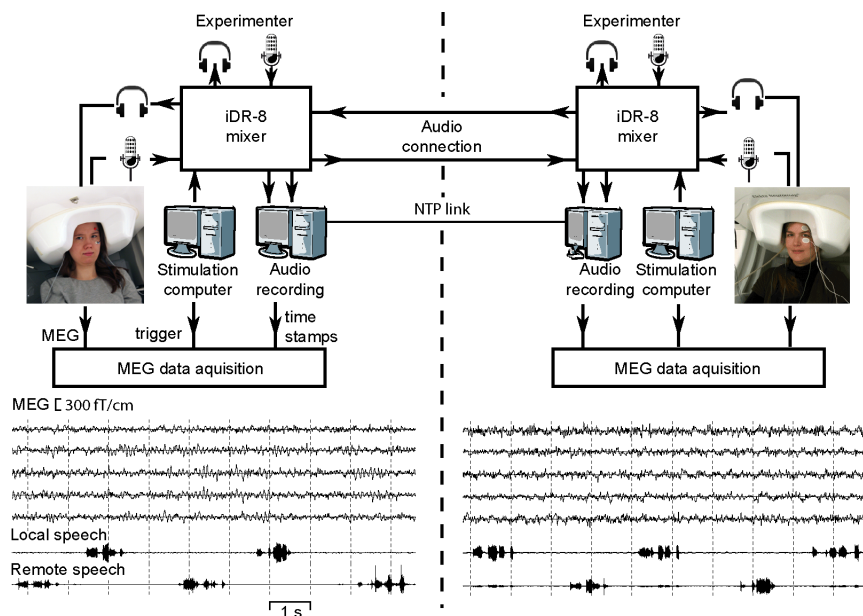

Figure 5. A schema of the dual-MEG measurement system where two persons are able to communicate via audio connection while their brain activity is measured with MEG. Lower panels show data samples from 5 MEG channels, and the two bottom-most lines indicate the speech recordings. Figure modified from Fig. 1 from P3.

To test the performance of the system, auditory evoked fields were recorded simultaneously from both subjects. The stimuli (500-Hz 50-ms tones, including 10-ms rise and fall times) were generated either in one or the other laboratory and were delivered to the other laboratory over the telephone connection. The tones were presented in two blocks (120 tones in each block) from each site. Sound loudness was adjusted to a comfortable hearing level for both subjects. The triggers of the sounds were recorded locally and later synchronized with the data set of the other measurement site. An 8-ms shift of the triggers was necessary for the remote data set to take into account the audio mixer and phone line delay. In this test measurement, only one dyad of subjects was studied.

Results. Figure 6 shows the auditory evoked responses of both participants to sounds delivered locally (black traces) and over the audio connection

(red traces). The responses peak at around 100 ms to both local and remotely presented sounds and are similar in amplitude and well replicable for both participants.
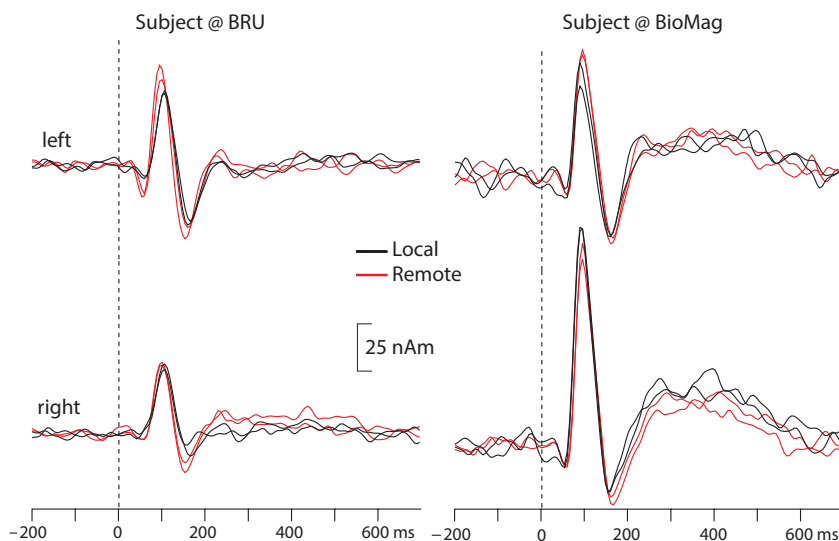

Figure 6. Source waveforms of the averaged auditory evoked responses (separately from left and right hemispheres) from two participants who listened to 50-ms tone beeps (500 Hz) that were either presented locally (*black traces*) and remotely via the audio-link (*red traces*). The passband was 0.03–40 Hz and about 110 single responses were averaged for each trace. Fig. 2 from P3.

Discussion. The recordings of auditory evoked responses in the dual-MEG setting indicated (in addition to all the technical tests made; cf. P3) that the new communication system and the data synchronization methods worked reliably, demonstrating the feasibility of this setup. This work formed a methodological basis for further real-time social interaction experiments with MEG.

5.4   Publication 4: Sensorimotor activation is left-hemisphere dominant during speaking in natural conversation, and listeners predict their turns a few seconds in advance

Background. Activity of the sensorimotor cortex during speaking and listening has been previously studied by asking the subjects to produce verbal utterances and non-verbal mouth movements. While simple mouth movements (e.g. opening the mouth) are usually related to bilateral involvement of the sensorimotor cortex (Salmelin *et al.*, 1995), as indexed by rebounds of the 20-Hz MEG oscillation, the results regarding hemispheric lateralization of motor-cortex activity during speaking have been divergent. Several studies have reported bilateral activation in sensorimotor cortices during the production of speech sounds (Murphy *et al.*, 1997; Wise *et al.*, 1999; Tarkka, 2001). Yet activation was found to be left-hemisphere dominant e.g. when the subjects were

reciting the names of the months (Riecker *et al.*, 2000; fMRI). The aim of the current study was to investigate sensorimotor activation during natural conversation by probing the modulation of the sensorimotor mu rhythm during speaking and listening phases of the conversation.

Methods. We studied 9 pairs of subjects who were engaged in a conversation while their brain signals were measured simultaneously with the dual-MEG setup that we developed in P3. Figure 7 illustrates the analysis approach in which the data of both subjects were first divided into speaking and listening periods in the conversation (the periods where the speech of the partners overlapped, were discarded). Subsequently, we calculated the spectra of brain responses (1–50 Hz) separately for speaking and listening phases and especially concentrated on comparing the differences in the rolandic mu rhythm at 7–13 (~10 Hz) and 15–25 Hz (~20 Hz) frequency bands.

We also studied the time–frequency representations of the subjects' brain activity at the turn changes in the conversation (in ~10- and ~20-Hz bands, from −5 s to 5 s around the turn start of the subject). One MEG sensor unit over the left rolandic cortex, where the modulation was best visible, was selected for analysis from each subject (separately for ~10- and ~20-Hz bands).
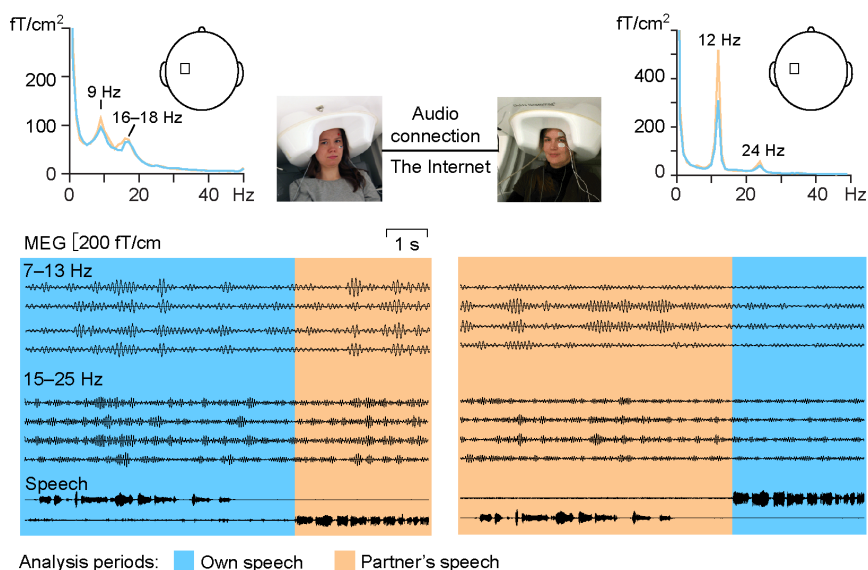
Figure 7. Dual-MEG setup for measuring brain activity simultaneously from two subjects having a conversation via an Internet-based audio connection. **Above**: Power spectra from one planar gradiometer over the left rolandic cortex; *blue lines* show the activity during participant's own speech and *orange lines* during partner's speech. **Below**: MEG data from 4 planar gradiometers over the left rolandic cortex filtered at 7–13 and 15–25 Hz, respectively. Two lowermost lines show the speech signals of the participant in question (*above*), and the speech of the partner (*below*). Fig. 1 from P4.

Results. Figure 8 shows that both the ~10 and ~20 Hz oscillations in the rolandic cortex were suppressed during speaking compared with listening periods.

As an additional observation, we noted that the ~10-Hz mu rhythm increased transiently (for 0.6 ± 0.1 s) in the listeners' brains around 2.3 s (for 8 subjects) or 1 s (for 4 subjects) before the start of their next turn. The pauses between turns lasted on average 567 ± 32 ms, and the increase in ~10-Hz activity occurred while the partner was still speaking. The ~20-Hz activity did not show any systematic modulations in relation to turn changes.
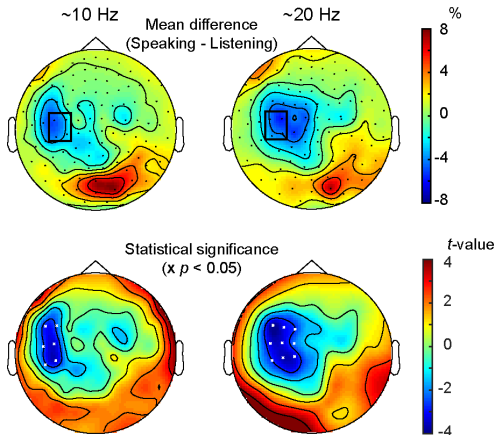

Figure 8. *Above:* Mean difference (group average) in ~10 Hz (*left*) and ~20 Hz activity (*right*) between speaking and listening periods in the conversation; *warm colours* mark an increase, and *blue colours* a decrease in the activation during speaking compared with listening periods. *Below:* Statistical significance map (*t*-values) between speaking and listening conditions in the same frequency bands. *White crosses* mark the sensors where the difference was statistically significant ($p < 0.05$).

Discussion. The suppression of the mu rhythm during speaking compared with listening phases of the conversation is in line with previous results showing that mu rhythm is dampened during motor action (for a review, see Hari & Salmelin, 1997; Cheyne, 2013).

It has also been found that comprehending isolated speech, such as phonemes or single words, is mainly related to bilateral activation of temporal cortices, whereas processing of connected speech (e.g. sentences) is related to left-lateralized frontotemporal activation (Peelle, 2012). Thus, the left-hemisphere dominant sensorimotor involvement during speaking in conversation could reflect increased linguistic demands in free conversation compared with uttering isolated speech sounds (single vowels, words, repeated phrases).

The observations of the transient increases of ~10-Hz mu rhythm in the listener's brain a few seconds before the turn change are completely novel. We hypothesise that they may be related with brief inhalations that listeners do when they expect their turn to start soon. Speech rhythm is related to the rhythm of breathing: whereas the inhalation and exhalation phases are rather balanced during rest, during speaking, short (around 0.5 s) inhalation phases are followed by a longer exhalation phase that can last several seconds, depending on the length of a particular utterance (Rochet-Capellan & Fuchs, 2014).

No overall correlation has been found between the breathing rhythms of speakers and listeners in conversation (Warner *et al.*, 1983; Rochet-Capellan & Fuchs, 2014), but the listener's breathing rhythm becomes more similar to the speaker's breathing rhythm (that is, the exhalation phase lengthens) when the

turn change is approaching (McFarland, 2001). Most turns are taken just after an inhalation, and listeners tend to match their breathing rhythm with the partner so that they inhale during the last part of the partner's exhalation phase (Rochet-Capellan & Fuchs, 2014).

In rats, brief inspirations during sniffing are related to the increased gamma oscillations in the olfactory bulb (Manabe & Mori, 2013) and in medullary regions that provide input to facial motoneurons (Moore *et al.*, 2013). We cannot confirm at present whether the transient enhancements of the sensorimotor 10-Hz rhythm before turn-taking could reflect the inhalations of a listener preparing for their own turn, as we did not monitor respiration. Thus, further studies are needed to address our hypothesis deriving from these interaction studies.

In summary, the results of P4 showed that the activation of the speaker's sensorimotor cortex is left-hemisphere dominant during natural conversation. This finding could be related to the linguistic demands of natural speech. The transient changes in sensorimotor activity a few seconds before the turn takings might reflect the listeners' prediction of the turn end and preparation for starting their own turn.

6. Discussion

6.1   General discussion

The findings presented in this Thesis broaden our understanding about the brain correlates of social interaction. The results showed that the brain reacts even to other person's eye blinks that rarely catch our conscious attention but could still give relevant behavioural information about others during social interaction. The finding that the strength of brain responses to eye blinks was related to the empathy of the viewer demonstrates that different people process social information differently.

Brain activity during real social interaction indicated that the type of speech (unconnected vs. continuous spontaneous speech) used in previous experiments might have affected e.g. the lateralization of brain activity even at the level of sensorimotor cortex, further underlining the need to use naturalistic setups while studying the brain basis of social interaction.

In addition, changes in brain activity at turn changes in a conversation revealed increased 10-Hz mu rhythm in the listeners' brains a few seconds before the start of their own turns, possibly indicating that the listeners predicted the end of their partner's turn and prepared to start their own turn. Turn-taking analysis would not have been possible by studying only one person speaking or listening in isolation.

We have taken the first steps in studying the brain basis of social communication and our findings have revealed the importance of studying human brain activity in its likely default mode—social interaction (Hari *et al.*, 2015).

6.1.1   Observer's brain responds to minor events with potential social significance

The results of the studies presented in this Thesis show that even minor events such as eye blinks elicit responses in the observer's brain. These responses are more persistent than responses to other similarly moving stimuli, indicating that the potential social significance of such facial features modulates the brain activity of the viewer.

Moreover, the brain of the viewer responded to eye blinks of a speaker even when the viewer was asked to concentrate on the story the speaker was telling and, in such a situation, the strength of the brain responses to eye blinks correlated with the empathy of the viewer. What could explain such effects?

Without claiming that each single eye blink carries a significant message to the observer, one can say that the blinking behaviour of others can convey sig-

nificant information about those persons' mental states: people blink more when they are getting tired (Barbato *et al.*, 2000), and less during tasks with increased cognitive demand (Drew, 1951; Tanaka & Yamaoka, 1993), but also while they are telling a lie (Mann *et al.*, 2002; Leal & Vrij, 2008). Anxiety, on the other hand, is linked with increased blinking, and other people perceive frequent blinkers as nervous or even untrustworthy (Omori & Miyata, 2001). Also brain disorders such as Parkinson's disease and schizophrenia typically affect blinking frequency (Karson, 1983).

Blinking is just one example of the vast variety of facial movements that affect social communication. Similarly, gaze direction can give information about others' focus of interest (Frischen, 2007). Gaze shifts and mouth movements activate (in addition to visual cortex) STS and middle temporal visual area (V5) regions in the observer's brain (for reviews, see Puce & Perrett, 2003; Nummenmaa & Calder, 2009). Eyebrow-rising is also a strong ostensive signal, indicating that a person wants to initiate communication or that some relevant signal is going to follow (Frith, 2009). Such ostensive signals, including e.g. prolonged eye contact and calling someone's name, activate the medial prefrontal cortex and temporal poles, areas related to thinking about others' mental states (Frith & Frith, 2006; Frith, 2009).

A significant amount of information during social interaction is delivered through non-verbal messages. Therefore, studying the brain correlates of those signals will continue to be of interest in the future.

6.1.2   Studying two persons in live interaction may reveal new aspects of human brain function

As already described in the Background, new methods for simultaneous recordings of brain activity of two interacting subjects have opened a new road for social neuroscience. The work in this Thesis was a part of a larger project to develop two-person neuroscience (Hari & Kujala, 2009) and especially a dual magnetoencephalography for studies of social interaction.

In this Thesis, we showed that it is technically feasible to study the brain activity of two persons sitting in different laboratories at the same time and hearing each other (or the same auditory stimuli) via landline connection (P3) or having a natural conversation via the Internet connection (P4).

The natural conversation in P4 indicated that the linguistic demands of speech (speaking spontaneously vs. uttering isolated words or phrases) could affect brain activity even at the level of the sensorimotor cortex. Analysing the brain activity at the turn changes revealed that listeners may predict their upcoming turn already a few seconds before the partner's turn ends, offering brain correlates to behavioural findings that the pauses during turn changes are so short that people have to be able to predict the turn change beforehand to be able to answer so quickly (Wilson & Wilson, 2005; Ruiter *et al.*, 2006).

Thus, although brain studies involving live communication are not a magic wand for revealing the brain basis of social interaction, they enable experimental situations that are more natural for the participants and thus reveal

aspects of brain processing that might otherwise not emerge. One may say that for an experiment such as P4, it is not necessary to measure the brain activity from two persons simultaneously. Whether one wants to measure brain and behavioural activity simultaneously from both (all) participants, or brain activity only from one and behavioural activity from both participants, depends on the question addressed. Since brains do not interact directly but people interact by behaving, the information exchanged during interaction has to be present in the behavioural signs (speech, facial expressions, body movements etc.). Still, recording brain activity only from one interaction partner at a time means losing the possibility to compare the brain activity of the two persons in the same situation, either in the same (in a synchronous task) or different roles.

6.2   Limitations of the experiments

The theoretical considerations for studying the brain basis of social interaction in one- vs. two-person-settings were already surveyed in the Background section.

Compromises are needed in data analysis: measuring brain activity during spontaneous interaction (such as P4 in this Thesis) means that each dyadic interaction is unique. Consequently, the data gathered are very variable. We decided to examine the data based on limited aspects of the interaction (speaking vs. listening, selecting only non-overlapping turn-taking events) to draw group-level conclusions. In this approach a significant amount of information present in the data were not utilized (e.g. the content of the speech). On the other hand, there was much variance in the data classified under the same label. For example, although the "predictability" of the turn end likely varies from turn to turn, we treated all non-overlapping turns as equal.

These compromises were made to extract brain-activity modulations that are linked to certain behavioural events during social interaction. Once such (potential) brain correlates of social interaction are found, it is possible to test how or which aspects of the environment affect these brain events.

In the experiments presented in this Thesis, the background and previous experiences of the participants were not taken into account. Still, it is known that such factors affect social behaviour. For example, when people have to evaluate the trustworthiness of strangers based on the face (of an avatar), they rate people who have facial features that are most typical in their environment as most trustworthy (Sofer *et al.*, 2015). Merely priming people with different aspects of their identity, such as Chinese or American roots of Chinese-American students, affects their behaviour in a cooperation game (Wong & Hong, 2005). In P2 presented in this Thesis, we found that the strength of the brain responses to eye blinks correlated positively with the empathy of the viewers. Thus, in future experiments, the personality characteristics and cultural backgrounds of the interacting subjects and whether they know each other should be taken into account, possibly as a part of the study design.

6.3 Future directions

The experiments in this Thesis revealed that the brain of the observer reacts even to minor facial movements in another person's face, and indicated, together with previous findings, that brain activity during real interaction might differ from the activity observed in restricted experimental settings, most likely because of the different cognitive demands in each situation.

In the future, interaction experiments could concentrate more on varying the task complexity in both verbal and non-verbal communication. For example, in addition to free communication, one could study persons who react in predefined ways (if your partner does A, you do B); such an approach could reveal differences in brain activity related to spontaneous vs. predictive or constrained behaviour.

More research is needed to determine how the human brain extracts information with possible social relevance, i.e. where is the line between social vs. non-social features. We know that people easily perceive inanimate objects with certain configurations ("eyes and mouth") as faces and interpret e.g. triangles moving with certain pattern as "chasing each other" (Heider & Simmel, 1944). We do not yet know the minimal features needed to induce the effect of a "social action or quality" and how these would be reflected in brain activity.

Better understanding of how social cues are processed in the brain would hopefully also help improve understanding about the brain basis of disorders in social communication and interaction. In addition to the well-known difficulties people with ASD have in understanding the mental states of others (even if their other cognitive skills are within normal range), people with schizophrenia also have problems understanding or explaining the behaviours of others and recognizing emotions from facial expressions (Brüne, 2005). Depression and anxiety are also associated with problems in social interaction as they considerably affect the way the patients perceive other people and how they act in social situations. For example, the severity of depression in patients and measures of depressiveness in the general population both correlate significantly with anxiety related to social encounters, fear of negative social evaluation, and the tendency to believe that other's see the respondent as inadequate (Gilbert, 2000). These few examples illustrate that disorders of social cognition and interaction concern a large part of the population. Better understanding of the brain basis of social interaction would therefore benefit everyone who wants to gain deeper knowledge about this fundamental aspect of human life.

References

Ahonen, A.I., Hämäläinen, M.S., Kajola, M.J., Knuutila, J.E.T., Laine, P.P., Lounasmaa, O. V, Parkkonen, L.T., Simola, J.T., & Tesche, C.D. (1993) 122-channel squid instrument for investigating the magnetic signals from the human brain. *Phys. Scr.*, T498A, 198–205.

Astolfi, L., Cincotti, F., Mattia, D., De Vico Fallani, F., Salinari, S., Marciani, M.G., Wilke, C., Doud, A., Yuan, H., He, B., & Babiloni, F. (2009) Estimation of the cortical activity from simultaneous multi-subject recordings during the prisoner's dilemma. In *Proceedings of the 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society: Engineering the Future of Biomedicine, EMBC 2009.* pp. 1937–1939.

Babiloni, F., Astolfi, L., Cincotti, F., Mattia, D., Tocci, A., Tarantino, A., Marciani, M.G., Salinari, S., Gao, S., Colosimo, A., & De Vico Fallani, F. (2007) Cortical activity and connectivity of human brain during the prisoner's dilemma: An EEG hyperscanning study. In *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings.* pp. 4953–4956.

Baess, P., Zhdanov, A., Mandel, A., Parkkonen, L., Hirvenkari, L., Mäkelä, J.P., Jousmäki, V., & Hari, R. (2012) MEG dual scanning: a procedure to study real-time auditory interaction between two persons. *Front. Hum. Neurosci.*, 6, 83.

Barbato, G., Ficca, G., Muscettola, G., Fichele, M., Beatrice, M., & Rinaldi, F. (2000) Diurnal variation in spontaneous eye-blink rate. *Psychiatry Res.*, 93, 145–151.

Baron-Cohen, S., Campbell, R., Karmiloff-Smith, a, Grant, J., & Walker, J. (1995) Are children with autism blind to the mentalistic significance of the eyes? *Br. J. Dev. Psychol.*, 13, 379–398.

Bentivoglio, A.R., Bressman, S.B., Cassetta, E., Carretta, D., Tonali, P., & Albanese, A. (1997) Analysis of blink rate patterns in normal subjects. *Mov. Disord.*, 12, 1028–1034.

Berger, H. (1929) Über das Elektrenkephalogramm des Menchen. *Arch. Psychiatr. Nervenkr.*, 87, 527–570.

Bloom, K., Russell, A., & Wassenberg, K. (1987) Turn taking affects the quality of infant vocalizations. *J. Child Lang.*, 14, 211–227.

Brefczynski-Lewis, J. a, Berrebi, M.E., McNeely, M.E., Prostko, A.L., & Puce, A. (2011) In the blink of an eye: neural responses elicited to viewing the eye blinks of another individual. *Front. Hum. Neurosci.*, 5, 68.

Brüne, M. (2005) Emotion recognition, "theory of mind," and social behavior in schizophrenia. *Psychiatry Res.*, 133, 135–147.

Carlson, M. & Earls, F. (1997) Psychological and neuroendocrinological sequelae of early social deprivation in Institutionalized children in Romania. *Ann. N. Y. Acad. Sci.*, 807, 419–428.

Chatrian, G.E., Petersen, M.C., & Lazarate, J.A. (1959) The blocking of the rolandic wicket rhythm and some central changes related to movement. *Electroencephalogr. Clin. Neurophysiol.*, 11, 497–510.

Cherry, E.C. (1953) Some experiments on the recognition of speech, with one and with two ears. *J. Acoust. Soc. Am.*, 25, 975–979.

Cheyne, D.O. (2013) MEG studies of sensorimotor rhythms: A review. *Exp. Neurol.*, 245, 27–39.

Cohen, D. (1968) Magnetoencephalography: evidence of magnetic fields produced by alpha-rhythm currents. *Science*, 161, 784–786.

Davis, M.H. (1980) A multidimensional approach to individual differences in empathy. *JSAS Cat. Sel. Doc. Psychol.*, 10, 85.

Davis, M.H. & Johnsrude, I.S. (2003) Hierarchical processing in spoken language comprehension. *J. Neurosi.,* 23, 3423–3431.

De Vico Fallani, F., Nicosia, V., Sinatra, R., Astolfi, L., Cincotti, F., Mattia, D., Wilke, C., Doud, A., Latora, V., He, B., & Babiloni, F. (2010) Defecting or not defecting: How to "read" human behavior during cooperative games by EEG measurements. *PLoS One*, 5, e14187.

Drew, G.C. (1951) Variations in reflex blink-rate during visual-motor tasks. *Q. J. Exp. Psychol.*, 3, 73–88.

Farroni, T., Csibra, G., Simion, F., & Johnson, M.H. (2002) Eye contact detection in humans from birth. *Proc. Natl. Acad. Sci. U. S. A.*, 99, 9602–9605.

Farroni, T., Mansfield, E.M., Lai, C., & Johnson, M.H. (2003) Infants perceiving and acting on the eyes: Tests of an evolutionary hypothesis. *J. Exp. Child Psychol.*, 85, 199–212.

Fiebach, C.J. & Friederici, A.D. (2004) Processing concrete words: fMRI evidence against a specific right-hemisphere involvement. *Neuropsychologia*, 42, 62–70.

Frischen, A. (2007) Gaze cueing of attention: visual attention, social cognition and individual differences. *Psychol. Bull.*, 133, 694–724.

Frith, C. (2009) Role of facial expressions in social interactions. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, 364, 3453–3458.

Frith, C. & Frith, U. (2006) The neural basis of mentalizing. *Neuron*, *50*, 531–534.

Frith, U. (2001) Mindblindness and the brain in autism. *Neuron*, 32, 969–979.

Fry, D.B. (1975) Simple reaction-times to speech and non-speech stimuli. *Cortex.*, 11, 355–360.

Fukuda, K. (1994) Analysis of eyeblink activity during discriminative tasks. *Percept. Mot. Skills*, 79, 1599–1608.

Gilbert, P. (2000) The relationship of shame, social anxiety and depression: the role of the evaluation of social rank. *Clin. Psychol. Psychother.*, 7, 174–189.

Gray, H.M., Ambady, N., Lowenthal, W.T., & Deldin, P. (2004) P300 as an index of attention to self-relevant stimuli. *J. Exp. Soc. Psychol.*, 40, 216–224.

Hämäläinen, M., Hari, R., Ilmoniemi, R.J., Knuutila, J., & Lounasmaa, O. V. (1993) Magnetoencephalography—theory, instrumentation, and applications to noninvasive studies of the working human brain. *Rev. Mod. Phys.*, 65, 413–497.

Hari, R. (1990) The neuromagnetic method in the study of human auditory cortex. In Grandori, F., Hoke, M., & Romani, G.L. (eds), *Advances in Audiology*. Krager, Basel, pp. 222–282.

Hari, R., Aittoniemi, K., Järvinen, M.L., Katila, T., & Varpula, T. (1980) Auditory evoked transient and sustained magnetic fields of the human brain localization of neural generators. *Exp. Brain Res.*, 40, 237–240.

Hari, R., Henriksson, L., Malinen, S., & Parkkonen, L. (2015) Centrality of Social Interaction in Human Brain Function. *Neuron*, 88, 181–193.

Hari, R. & Kujala, M. V (2009) Brain basis of human social interaction : From concepts to brain imaging. *Physiol. Rev.*, 89, 453–479.

Hari, R., Levänen, S., & Raij, T. (2000) Timing of human cortical functions during cognition: Role of MEG. *Trends Cogn. Sci.*, 4, 455–462.

Hari, R. & Salmelin, R. (1997) Human cortical oscillation: a neuromagnetic view through the skull. *Tins*, 20, 44–49.

Heider, F. & Simmel, M. (1944) An experimental study of apparent behaviour. *Am. J. Psychol.*, 57, 243–259.

Heinrich, S.P. (2007) A primer on motion visual evoked potentials. *Doc. Ophthalmol.*, 114, 83–105.

Hietanen, J.K., Leppänen, J.M., Peltola, M.J., Linna-aho, K., & Ruuhiala, H.J. (2008)

Seeing direct and averted gaze activates the approach-avoidance motivational brain systems. *Neuropsychologia*, 46, 2423–2430.

Hoffman, E.A. & Haxby, J.V. (2000) Distinct representations of eye gaze and identity in the distributed human neural system for face perception. *Nat. Neurosci.*, 3, 80–84.

Hoque, M.M., Hossain, Q.D., & Deb, K. (2014) Effects of robotic blinking behavior for making eye contact with humans. *Adv. Comput. Netw. Informatics*, 27, 621–628.

Howlin, P. (2000) Outcome in adult life for more able individuals with autism or Asperger syndrome. *Autism*, 4, 63–83.

Huppert, T.J., Hoge, R.D., Diamond, S.G., Franceschini, M. a., & Boas, D. a. (2006) A temporal comparison of BOLD, ASL, and NIRS hemodynamic responses to motor stimuli in adult humans. *Neuroimage*, 29, 368–382.

Kanwisher, N. & Wojciulik, E. (2000) Visual attention: insights from brain imaging. *Nat. Rev. Neurosci.*, 1, 91–100.

Karson, C.N. (1983) Spontaneous eye-blink rates and dopaminergic systems. *Brain*, 106 (Pt 3), 643–653.

Kiehl, K.A., Liddle, P.F., Smith, A.M., Mendrek, A., Forster, B.B., & Hare, R.D. (1999) Neural pathways involved in the processing of concrete and abstract words. *Hum. Brain Mapp.*, 7, 225–233.

Kobayashi, H. & Kohshima, S. (1997) Unique morphology of the human eye. *Nature*, 387, 767–768.

Krach, S., Müller-Pinzler, L., Westermann, S., & Paulus, F.M. (2013) Advancing the neuroscience of social emotions with social immersion. *Behav. Brain Sci.*, 36, 427–428.

Laaksonen, K., Kirveskari, E., Mäkela, J.P., Kaste, M., Mustanoja, S., Nummenmaa, L., Tatlisumak, T., & Forss, N. (2012) Effect of afferent input on motor cortex excitability during stroke recovery. *Clin. Neurophysiol.*, 123, 2429–2436.

Lankinen, K., Saari, J., Hari, R., & Koskinen, M. (2014) Intersubject consistency of cortical MEG signals during movie viewing. *Neuroimage*, 92, 217–224.

Leal, S. & Vrij, A. (2008) Blinking During and After Lying. *J. Nonverbal Behav.*, 32, 187–194.

Levy, J. & Trevarthen, C. (1977) Perceptual, semantic and phonetic aspects of elementary language processes in split-brain patients. *Brain*, 100, 105–118.

Lindenberger, U., Li, S.-C., Gruber, W., & Müller, V. (2009) Brains swinging in concert: cortical phase synchronization while playing guitar. *BMC Neurosci.*, 10, 22.

Mäkelä, J.P., Forss, N., Jääskeläinen, J., Kirveskari, E., Korvenoja, A., & Paetau, R. (2006) Magnetoencephalography in Neurosurgery. *Neurosurgery*, 59, 493–511.

Manabe, H. & Mori, K. (2013) Sniff rhythm-paced fast and slow gamma-oscillations in the olfactory bulb : relation to tufted and mitral cells and behavioral states. *J. Neurophysiol.*, 110, 1593–1599.

Mann, S., Vrij, A., & Bull, R. (2002) Suspects, lies, and videotape: An analysis of authentic high-stake liars. *Law Hum. Behav.*, 26, 365–376.

McFarland, D.H. (2001) Respiratory markers of conversational interaction. *J. Speech. Lang. Hear. Res.*, 44, 128–143.

Meister, I.G., Wilson, S.M., Deblieck, C., Wu, A.D., & Iacoboni, M. (2007) The Essential Role of Premotor Cortex in Speech Perception. *Curr. Biol.*, 17, 1692–1696.

Miezin, F.M., Maccotta, L., Ollinger, J.M., Petersen, S.E., & Buckner, R.L. (2000) Characterizing the hemodynamic response: effects of presentation rate, sampling procedure, and the possibility of ordering brain activity based on relative timing. *Neuroimage*, 11, 735–759.

Montague, P.R., Berns, G.S., Cohen, J.D., McClure, S.M., Pagnoni, G., Dhamala, M., Wiest, M.C., Karpov, I., King, R.D., Apple, N., & Fisher, R.E. (2002)

Hyperscanning: simultaneous fMRI during linked social interactions. *Neuroimage*, 16, 1159–1164.

Moore, J.D., Deschênes, M., Furuta, T., Huber, D., Smear, M.C., Demers, M., & Kleinfeld, D. (2013) Hierarchy of orofacial rhythms revealed through whisking and breathing. *Nature*, 497, 205–210.

Murphy, K., Corfield, D.R., Guz, a, Fink, G.R., Wise, R.J., Harrison, J., & Adams, L. (1997) Cerebral areas associated with motor control of speech in humans. *J. Appl. Physiol.*, 83, 1438–1447.

Nakano, T., Kato, N., & Kitazawa, S. (2011) Lack of eyeblink entrainments in autism spectrum disorders. *Neuropsychologia*, 49, 2784–2790.

Nakano, T. & Kitazawa, S. (2010) Eyeblink entrainment at breakpoints of speech. *Exp. Brain Res.*, 205, 577–581.

Nakano, T., Yamamoto, Y., Kitajo, K., Takahashi, T., & Kitazawa, S. (2009) Synchronization of spontaneous eyeblinks while viewing video stories. *Proc. Biol. Sci.*, 276, 3635–3644.

Neiberg, D. & Gustafson, J. (2011) Predicting speaker changes and listener responses with and without eye-contact. In *Interspeech 2011, 12th Annual Conference of the International Speech Communication Association*. pp. 1565–1568.

Novick, D.G., Hansen, B., & Ward, K. (1996) Coordinating turn-taking with gaze. *Proceeding Fourth Int. Conf. Spok. Lang. Process. ICSLP '96*, 3.

Nummenmaa, L. & Calder, A.J. (2009) Neural mechanisms of social attention. *Trends Cogn. Sci.*, 13, 135–143.

Oh, J., Jeong, S.-Y., & Jeong, J. (2012) The timing and temporal patterns of eye blinking are dynamically modulated by attention. *Hum. Mov. Sci.*, 31, 1353–1365.

Omori, Y. & Miyata, Y. (2001) Estimates of impressions based on frequency of blinking. *Soc. Behav. Pers.*, 29, 159–168.

Paetau, R., Kajola, M., & Hari, R. (1990) Magnetoencephalography in the study of epilepsy. *Neurophysiol. Clin.*, 20, 169–187.

Patterson, M.L., Churchill, M.E., Burger, G.K., & Powell, J.L. (1992) Verbal and nonverbal modality effects on impressions of political candidates: Analysis from the 1984 presidential debates. *Commun. Monogr.*, 59, 231–242.

Peelle, J.E. (2012) The hemispheric lateralization of speech processing depends on what "speech" is: a hierarchical perspective. *Front. Hum. Neurosci.*, 6, 309.

Perrett, D.I., Smith, P.A., Potter, D.D., Mistlin, A.J., Head, A.S., Milner, A.D., & Jeeves, M.A. (1985) Visual cells in the temporal cortex sensitive to face view and gaze direction. *Proc. R. Soc. Lond. B. Biol. Sci.*, 223, 293–317.

Puce, a, Allison, T., Bentin, S., Gore, J.C., & McCarthy, G. (1998) Temporal cortex activation in humans viewing eye and mouth movements. *J. Neurosci.*, 18, 2188–2199.

Puce, a, Smith, a, & Allison, T. (2000) Erps evoked by viewing facial movements. *Cogn. Neuropsychol.*, 17, 221–239.

Puce, A. & Perrett, D. (2003) Electrophysiology and brain imaging of biological motion. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, 358, 435–445.

Pulvermüller, F. (2005) Brain mechanisms linking language and action. *Nat. Rev. Neurosci.*, 6, 576–582.

Regenbogen, C., Schneider, D. a., Finkelmeyer, A., Kohn, N., Derntl, B., Kellermann, T., Gur, R.E., Schneider, F., & Habel, U. (2012) The differential contribution of facial expressions, prosody, and speech content to empathy. *Cogn. Emot.*, 26, 995–1014.

Riecker, A., Ackermann, H., Wildgruber, D., Dogil, G., & Grodd, W. (2000) Opposite hemispheric lateralization effects during speaking and singing at motor cortex, insula and cerebellum. *Neuroreport*, 11, 1997–2000.

Rochet-Capellan, A. & Fuchs, S. (2014) Take a breath and take the turn: how breathing

meets turns in spontaneous dialogue. *Philos. Trans. R. Soc. B Biol. Sci.*, 369, doi: 10.1098/rstb.2013.0399.

Roiha, K., Kirveskari, E., Kaste, M., Mustanoja, S., Mäkelä, J.P., Salonen, O., Tatlisumak, T., & Forss, N. (2011) Reorganization of the primary somatosensory cortex during stroke recovery. *Clin. Neurophysiol.*, 122, 339–345.

Ruiter, J.-P. de, Mitterer, H., & Enfield, N.J. (2006) Projecting the end of a speaker's turn: A cognitive cornerstone of conversation. *Language*, 82, 515–535.

Salmelin, R. (2007) Clinical neurophysiology of language: The MEG approach. *Clin. Neurophysiol.*, 118, 237–254.

Salmelin, R., Hámáaláinen, M., Kajola, M., & Hari, R. (1995) Functional segregation of movement-related rhythmic activity in the human brain. *Neuroimage*, 2, 237–243.

Salmelin, R. & Sams, M. (2002) Motor cortex involvement during verbal versus non-verbal lip and tongue movements. *Hum. Brain Mapp.*, 16, 81–91.

Salmelin, R., Schnitzler, A., Schmitz, F., & Freund, H.J. (2000) Single word reading in developmental stutterers and fluent speakers. *Brain*, 123, 1184–1202.

Sänger, J., Müller, V., & Lindenberger, U. (2012) Intra- and interbrain synchronization and network properties when playing guitar in duets. *Front. Hum. Neurosci.*, 6, 312.

Sänger, J., Müller, V., & Lindenberger, U. (2013) Directionality in hyperbrain networks discriminates between leaders and followers in guitar duets. *Front. Hum. Neurosci.*, 7, 234.

Schilbach, L., Timmermans, B., Reddy, V., Costall, A., Bente, G., Schlicht, T., & Vogeley, K. (2013) Toward a second-person neuroscience. *Behav. Brain Sci.*, 36, 393–414.

Scott, S.K., McGettigan, C., & Eisner, F. (2009) A little more conversation, a little less action--candidate roles for the motor cortex in speech perception. *Nat. Rev. Neurosci.*, 10, 295–302.

Sofer, C., Dotsch, R., Wigboldus, D.H.J., & Todorov, A. (2015) What Is Typical Is Good: The Influence of Face Typicality on Perceived Trustworthiness. *Psychol. Sci.*, 26, 39–47.

Sorjonen, M.-L. (2001) *Responding in Conversation: A Study of Response Particles in Finnish*, Pragmatics & Beyond New Series. John Benjamins Publishing Company, Amsterdam.

Spitzer, H., Desimone, R., & Moran, J. (1988) Increased Attention Enchances Both Behavioral and Neural Performance. *Science*, 240, 338–340.

Stephens, G.J., Silbert, L.J., & Hasson, U. (2010) Speaker-listener neural coupling underlies successful communication. *Proc. Natl. Acad. Sci. U. S. A.*, 107, 14425–14430.

Stephens, J. & Beattie, G. (1986) On Judging the Ends of Speaker Turns in Conversation. *J. Lang. Soc. Psychol.*, 5, 119–134.

Stivers, T., Enfield, N.J., Brown, P., Englert, C., Hayashi, M., Heinemann, T., Hoymann, G., Rossano, F., de Ruiter, J.P., Yoon, K.-E., & Levinson, S.C. (2009) Universals and cultural variation in turn-taking in conversation. *Proc. Natl. Acad. Sci. U. S. A.*, 106, 10587–10592.

Tanaka, Y. & Yamaoka, K. (1993) Blink activity and task difficulty. *Percept. Mot. Skills*, 77, 55–66.

Tarkka, I.M. (2001) Cerebral sources of electrical potentials related to human vocalization and mouth movement. *Neurosci. Lett.*, 298, 203–206.

Taulu, S. & Hari, R. (2009) Removal of magnetoencephalographic artifacts with temporal signal-space separation: demonstration with single-trial auditory-evoked responses. *Hum. Brain Mapp.*, 30, 1524–1534.

Taulu, S. & Simola, J. (2006) Spatiotemporal signal space separation method for rejecting nearby interference in MEG measurements. *Phys. Med. Biol.*, 51, 1–10.

Taulu, S., Simola, J., & Kajola, M. (2004) MEG recordings of DC fields using the signal space separation method (SSS). *Neurol. Clin. Neurophysiol.*, 2004, 35.

Tiihonen, J., Kajola, M., & Hari, R. (1989) Magnetic mu rhythm in man. *Neuroscience*, 32, 793–800.

Tomasello, M., Hare, B., Lehmann, H., & Call, J. (2007) Reliance on head versus eyes in the gaze following of great apes and human infants: the cooperative eye hypothesis. *J. Hum. Evol.*, 52, 314–320.

Vargha-Khadem, F., O'Gorman, A.M., & Watters, G. V (1985) Aphasia and handedness in relation to hemispheric side, age at injury and severity of cerebral lesion during childhood. *Brain*, 108, 677–696.

Vigário, R., Särelä, J., Jousmäki, V., Hämäläinen, M., & Oja, E. (2000) Independent component approach to the analysis of EEG and MEG recordings. *IEEE Trans. Biomed. Eng.*, 47, 589–593.

Warner, R.M., Waggener, T.B., & Kronauer, R.E. (1983) Synchronized cycles in ventilation and vocal activity during spontaneous conversational speech. *J. Appl. Physiol.*, 54, 1324–1334.

Watanabe, S., Kakigi, R., Miki, K., & Puce, A. (2006) Human MT/V5 activity on viewing eye gaze changes in others: A magnetoencephalographic study. *Brain Res.*, 1092, 152–160.

Wicker, B., Michel, F., Henaff, M.A., & Decety, J. (1998) Brain regions involved in the perception of gaze: a PET study. *Neuroimage*, 8, 221–227.

Wilson, M. & Wilson, T.P. (2005) An oscillator model of the timing of turn-taking. *Psychon. Bull. Rev.*, 12, 957–968.

Wilson, S.M. & Iacoboni, M. (2006) Neural responses to non-native phonemes varying in producibility: Evidence for the sensorimotor nature of speech perception. *Neuroimage*, 33, 316–325.

Wise, R.J.S., Greene, J., Buchel, C., & Scott, S.K. (1999) Brain regions involved in articulation 353, 1057–1061.

Wismer Fries, A.B., Shirtcliff, E.A., & Pollak, S.D. (2009) Neuroendocrine dysregulation following early social deprivation in children. *Dev. Psychobiol.*, 50, 588–599.

Wong, R.Y.-M. & Hong, Y.-Y. (2005) Dynamic influences of culture on cooperation in the prisoner's dilemma. *Psychol. Sci.*, 16, 429–434.

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