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Teams on the same wavelength perform better: Inter-brain phase synchronization constitutes a neural substrate for social facilitation

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ABSTRACT

Working together feels easier with some people than with others. We asked participants to perform a visual search task either alone or with a partner while simultaneously measuring each participant's EEG. Local phase synchronization and inter-brain phase synchronization were generally higher when subjects jointly attended to a visual search task than when they attended to the same task individually. Some participants searched the visual display more efficiently and made faster decisions when working as a team, whereas other dyads did not benefit from working together. These inter-team differences in behavioral performance gain in the visual search task were reliably associated with inter-team differences in local and inter-brain phase synchronization. Our results suggest that phase synchronization constitutes a neural correlate of social facilitation, and may help to explain why some teams perform better than others.

Introduction

Teamwork is a prominent feature of today's western working cultures in fields as diverse as science, healthcare, or business (Hall and Weaver, 2001; Hoegl and Gemuenden, 2001; Wuchty et al., 2007). In economics and organizational psychology much research has sought to capture the characteristics of good teamwork, to measure teamwork quality and to identify beneficial aspects of team composition (Ancona and Caldwell, 1992; Bell, 2007; Keller, 2001). Most of the empirical work in these fields did not consider neural mechanisms that facilitate teamwork, but has relied instead on interview protocols and measures of work quality. Delineating the neural mechanisms relevant for teamwork would advance our mechanistic understanding of team dynamics, including the question why working together feels easier with some people than with others.

Social neuroscience, in turn, has often focused on single individuals in 'passive' social contexts, such as observing pictures of social encounters, and has paid relatively little attention to the study of teams or groups. In recent years, however, 'hyperscanning' techniques (Montague et al., 2002), which refer to the simultaneous assessment of the brain activity of more than one person, have helped neuroscientists to study the inter-personal dynamics of neural processes. Experiments using this technique have given rise to a body of research examining the neural processes observed in socially interacting individuals (Babiloni et al., 2007; Dumas et al., 2010; Lindenberger et al., 2009; Sänger et al., 2012, 2013). This move from 'one-body' neuroscience to 'two-body neuroscience' (Dumas et al., 2010) or 'second-person neuroscience' (Schilbach et al., 2013) was informed by theoretical concepts that emphasize the interactive nature of human cognition (Varela et al., 1992). According to these concepts, brain functions cannot be fully understood by observing neuronal subsystems or individuals in isolation; instead, the dynamic interactions among brain, behavior, and environment (Kelso, 1994; Thompson and Varela, 2001) need to be taken into account. In line with this assertion, studies of interacting individuals (Freundlieb et al., 2015; Lachat et al., 2012; Sebanz et al., 2006; Sebanz et al., 2003) have identified cognitive processes that would have gone unnoticed if individuals had been studied in isolation only. For example, Freundlieb et al. (2015)

Abbreviations: IPC, inter-brain phase coherence; mc-PLS, mean centered partial least squares; nr-PLS, non rotated partial least squares; *PLI*, phase locking index

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examined when participants adopted another's visuospatial perspective. Only if the other was perceived as an intentionally acting agent, participants consistently adopted their visuospatial perspective.

In addition to representing the partner's intention, neural mechanisms are likely to serve as a substrate for coordinated perception, action, or both. Hyperscanning studies have observed enhanced synchronization of neural processes in interactive paradigms, such as gesturing, finger tapping, guitar play, card play, or speech (for review, see Sänger et al. (2011)). It has been suggested that neural synchronization during joint action may go beyond similarities in perceptual input and motor output and also reflect the synchronization of cognitive processes. To substantiate this point, researchers have tried to extract 'functional relevance' from patterns of neural synchronization. For example synchronization between signal time courses across brains was observed to correlate with story comprehension in speaker-listener settings (Stephens et al., 2010). Similarly, neural synchronization across brains has been reported to reflect leader/follower roles of the participants (Jiang et al., 2015). Cui et al. (2012) reported increased interpersonal coherence in superior frontal cortex during cooperation but not during competition using near-infrared spectroscopy. Sänger et al. (2012) and Konvalinka et al. (2014) were able to distinguish leader/follower roles based on stronger phase locking and stronger frontal alpha suppression in leaders. These initial results fuel the hypothesis that inter-personal as well as intra-personal neural dynamics capture functional characteristics of social interaction.

So far, the majority of studies in the field of hyperscanning research ha focused on joint action. The settings explored range from highly restricted tasks such as finger tapping (Konvalinka et al., 2014) to ecologically valid tasks such as guitar duet play (Lindenberger et al., 2009; Müller et al., 2013; Sänger et al., 2012, 2013) or conversation (Jiang et al., 2015). A major critique to many of the hyperscanning studies mentioned has been the lack of a proper control condition, namely, a condition that is missing the social interactive aspect but keeps most aspects of perceptual input and motor output constant relative to the social condition. Here, we propose a paradigm that includes such a control condition by investigating an essential aspect of joint action that does not involve motor output: joint attention. Joint attention has been found to play a crucial role in social interaction (Tomasello, 1995) and particularly joint action (Sebanz et al., 2006). Joint attention entails that "two individuals know that they are attending to something in common" (Tomasello, 1995, p.106), and can be seen as providing "a basic mechanism for sharing representations of objects and events" (Sebanz et al., 2006, p.70). Hence, it constitutes a core feature of joint action, and of teamwork in general.

Joint action typically requires joint attention, but the inverse is not necessarily true, that is, there can be joint attention without joint action, such as when people are jointly looking at a photo. Also, the very same object (e.g., photo) can also be attended to alone. Thus, comparing joint attention to individual attention makes possible what hyperscanning studies have generally failed to achieve, namely, to compare two conditions, in the absence of synchronized motor activity, that vary on the social dimension without varying the perceptual setup.

The aim of the present study was to assess whether synchronization in inter-brain dynamics reflects a modulation of cognitive processes by social facilitation or merely the presence of a common driver, such as shared perceptual input. Social facilitation subsumes changes in behavioral performance associated with the passive or active presence of another person (Allport, 1920; Zajonc, 1965). For this purpose, we chose to investigate differences between individual and joint attention. We embedded individual and joint attention in a visual search task, which was carried out either individually or in dyadic teams. This setup enabled us to first analyze differences in neural dynamics between individual and joint attention and to then relate these neural differences to behavioral performance differences between individual work and teamwork. This teamwork went beyond the period of initial joint attention studied in the first step and includes the coordination of a joint response. The current study thus explores joint attention as an important aspect of teamwork in two ways: first by analyzing intra- and inter-brain neural dynamics of joint attention and second by relating them to behavioral team performance proficiency (see Fig. 2).

To investigate the performance benefits of joint attention, we used an adaptation of Miller's Race Model Inequality (RMI; (Miller, 1982; Ulrich et al., 2007)) to separate the collaborative benefit of teamwork from the benefit that would be expected under the assumption of processing independence. Miller's RMI was originally developed to test whether two target signals were processed in one mind as a race between independent activations (with the faster signal determining the response on each occasion) or whether the signals were co-activated (signal activations were combined prior to the response decision). We apply the same logic and method here, testing whether responses by two-person teams reflect a race between independently processing individuals (with the faster person eliciting the valid response) or whether teams collaborated prior to the response (i.e., shared the task and exchanged information).

It should be kept in mind that team performance has both benefits and costs. On the one hand, cognition can be made more efficient when collaborators divide the cognitive load of the task (Houtkamp and Roelfsema, 2009). On the other hand, coordinating joint performance through speech or gesture requires effort and time (Brennan et al., 2008). Our measure of team performance captures some mix of these benefits and costs and reflects the overall collaborative benefit/cost for each team. If inter-brain dynamics indeed reflect the synchronization of cognitive processes, they should vary with the degree (and potentially the benefit) of social interaction, and might correlate (positively) with behavioral team performance. Thus, the present study was guided by two specific hypotheses: (a) Inter-brain synchronization will be greater in a social context than in a comparable setting that does not engage joint attention; (b) between-pair differences in inter-brain neural dynamics will correlate with between-pair differences in task performance.

Material and methods

Participants and data analysis

Research participants

Fifty-two healthy individuals participated in the study, forming a total of 26 non-overlapping pairs, 13 male-male pairs and 13 female-female pairs. The age of the participants ranged from 18 to 30 years (mean age = 25.2, SD = 3.43). One male pair had to be excluded from the analysis due to a technical problem, thus 25 pairs (13 female, 12 male) were retained in the EEG data analysis. Four pairs (three female, one male) had to be excluded from behavioral data analysis due to technical problems with data recording. Thus 21 pairs (10 female, 11 male) were included in the behavioral analyses, and the brain-behavior regression analyses. Participants were randomly assigned to pairs and did not know each other prior to the experimental session. At the beginning of each experimental session, participants filled out questionnaires that assessed personality (NEO Five-Factor-Inventory, Costa and McCrae, 1992) and interpersonal values (Circumplex scales of interpersonal values, Locke, 2000). While being prepared for the EEG session the two participants were placed in front of each other and asked to talk to get to know one other. All pairs talked about study subjects and hobbies/interests for ca. 10 min, after which the experimenter asked them to stop talking and to enter the EEG cabin. All pairs took part in another EEG-experiment before starting the visual search task. All participants volunteered for the experiment, and gave their written informed consent prior to their inclusion in the study. The Ethics Committee of the Max Planck Institute for Human Development approved the study. The study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.