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Original article

From social behaviour to brain synchronization: Review and perspectives in hyperscanning

De la synchronisation comportementale à la synchronisation cérébrale : état de l'art et perspectives en hyperscanning

G. Dumas [a,b,c,1], F. Lachat [a,*,b,c,1], J. Martinerie [a,b,c], J. Nadel [d], N. George [a,b,c]

[a] *UMR-S975, centre de recherche de l'institut du cerveau et de la moelle épinière, université Pierre-et-Marie-Curie-Paris 6, Paris, France*
[b] *CNRS, UMR 7225, CRICM, hôpital de la Salpetriere, 47, boulevard de l'Hôpital, 75651 Paris cedex 13, France*
[c] *Inserm U 975, CRICM, Paris, France*
[d] *CNRS, USR 3246, centre émotion, pavillon Clérambault, hôpital de La Salpêtrière, Paris, France*

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Abstract

Recently, the neuroscience field took a particular interest in the use of a neuroimaging technique called 'hyperscanning'. This new technique consists in the simultaneous recording of the hemodynamic or neuroelectric activities of multiple subjects. Behind this small technical step lays a giant methodological leap. Groundbreaking insight in the understanding of social cognition shall be achieved if the right paradigms are implemented. A growing number of studies demonstrate the potential of this recent technique. In this paper, we will focus on current issues and future perspectives of brain studies using hyperscanning. We will also add to this review two studies initiated by Line Garnero. These studies will illustrate the promising possibilities offered by hyperscanning through two different key phenomena pertaining to social interaction: gesture imitation and joint attention.

Keywords: Hyperscanning; Synchronization; Spontaneous imitation; Joint attention; Gaze; EEG

Résumé

Récemment, un intérêt particulier a été porté à l'utilisation d'une technique de neuro-imagerie appelée *hyperscanning*. Cette nouvelle technique consiste en l'enregistrement simultané de l'activité hémodynamique ou neuroélectrique de plusieurs sujets. Derrière ce petit pas technique se cache un grand pas méthodologique. Il peut nous conduire à une meilleure compréhension de la cognition sociale si toutefois les bons paradigmes expérimentaux sont développés. Le nombre croissant d'études utilisant l'*hyperscanning* démontre le potentiel de cette technique. Dans cet article, nous traiterons à la fois de son récent historique mais surtout des futurs potentiels qu'elle ouvre. Nous illustrerons cela par deux réalisations en *hyperscanning* dont Line Garnero a été l'instigatrice. Ces réalisations serviront d'exemple pour montrer les possibilités prometteuses par l'*hyperscanning* au travers de deux phénomènes clés dans les interactions sociales : l'imitation gestuelle et les comportements de regard en attention conjointe.

Mots clés : Hyperscanning ; Synchronisation ; Imitation spontanée ; Attention conjointe ; Regard ; EEG

1. From behaviour synchronization...

"The most important things in human life come down to relationships with other people," says Michael Huerta (associate director of Neuroscience and Basic behavioural science at the National Institute of Mental Health). Our actions, feelings,

* Corresponding author.
E-mail address: fanny.lachat@upmc.fr (F. Lachat).
[1] Contributed equally to this work.

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and thoughts take place in a social world where communicating with others is an everyday challenge. Wilson and Wilson [1] theorised on a particular type of interindividual interaction: conversation. According to the authors, during conversation, several oscillators in the brain of the listener are led by some oscillators of the speaker's brain. In this oscillatory interplay, the two brains become synchronized. Even though the authors based their model on conversation properties, the idea of inter-brain synchronization can be generalized to any social situation, which generates coordination between partners. This paper especially takes interest in two phenomena that entail behaviour synchronization: gesture imitation and gaze following.

Gesture imitation has been pointed out as a keystone of human social interaction because of the ability it gives us to know others as persons like ourselves [2,3]. Pragmatically, the matching of our own behaviour with that of others allows us to detect contingencies in our social world. This enables us to synchronize with others, copy them, and learn in which context particular behaviours have to be used [4,5]. Growing evidence at the developmental [6], psychological, and neuroscientific levels indicates that perception and action are in fact intertwined processes. The recent discovery of mirror neurons provides a direct demonstration of this overlap between perception and action networks. Furthermore this discovery also puts in light the major role of this overlap in motor imitation. However, imitation is only related to morphological similarities of gestures. Thus it is not the only component of motor social interaction. Behavioural synchrony complements imitation during interindividual interaction by providing a temporal coherence between the interacting partners. Developmental studies have demonstrated a very early ability to detect interactive synchrony in humans: the introduction of a delay in the loop of interaction between a baby and his/her mother leads to a breakdown of the ongoing communication [7,8].

These results suggest an intrinsic human capacity for perceiving and producing events in synchrony with other individuals. Immediate imitation is an almost perfect example of interactive synchrony [6]. It was suggested that the dynamics of neuronal coupling plays a role in the emergence of such synchrony, providing a neural substrate for interpersonal exchanges and synchronizations among individuals at the behavioural level [1]. The modelling approach further suggests that the phenomenon of turn-taking may emerge from the synchrony itself [9,10].

Thus, spontaneous gestural imitation is an ideal case for the study of behavioural synchrony and its neuronal correlates. It possesses all the features of social interaction and leads to phases of behavioural synchronies. Furthermore, it is mainly a motor interaction. In comparison with a verbal interaction, the hypothesized underlying interindividual neural synchronization should be easier to detect.

Other types of interindividual interactions may generate such neural synchronizations. For instance, gaze following is a key example of behavioural synchronization in everyday life. Interestingly, it is easier for humans than other species to follow the eye direction of their conspecifics. Indeed, the human eyes have evolved to allow perceiving clearly the contrast between the (white) sclera and the (darker) iris. This facilitates the detection of someone's eyes and more importantly it makes it easier and faster to identify the direction of the gaze of seen fellows [11,12]. Gaze direction subtends referential communication and synchronisation during interindividual exchanges. For example, during conversation, gaze contributes to speech understanding as well as to the organization of turn-taking with eye contact enabling the converses to be coordinated and synchronized [13].

Furthermore, eye direction perception is a core process of joint attention, which is a fulcrum of social cognition. Joint attention results from the alignment of an observer's attention with that of a seen fellow, enabling both persons to attend to the same external object [14–16]. This behavioural synchronization is crucial to social interaction as it subtends the understanding of others' attentional focus and intention. Joint attention is proposed to be one of the precursors of Theory Of Mind (TOM) [17]. TOM is the skill to attribute mental states to others and to understand that their believes, emotions, intentions, desires might differ from our owns. This ability is essential for understanding others and for adaptive communication and interaction with others. We believe that engaging in joint attention processes prompt coordinated actions between the participants, which might lead to interindividual neural synchronizations.

In sum, both gestural imitation and joint attention involve another partner with whom a non-verbal, interpersonal communication is established. They provide good ecological paradigms for the study of human social interaction. Combined with the use of a new neuroimaging technique called hyperscanning, they also open the way for the investigation of interindividual neural synchronizations that might accompany behavioural synchronies. This brain-to-brain synchronization emerges from the sensorimotor couplings created through the social interactions.

2. . . .to brain synchronization

Almost nothing is known about the brain activities of two individuals while those individuals are engaged in a social interaction. Recently, a new technique made possible for researchers to record at the same time two persons engaging in an interpersonal exchange. This technique is called hyperscanning and has been applied with fMRI and EEG. Hyperscanning is a very powerful method as it makes possible to perform within- as well as between-brain analyses.

The hyperscanning story starts with an uncanny use of the technique. Indeed, this technique was first applied to parapsychology issues [18,19]. The main purpose of these studies was to investigate telepathy, namely the brain information transmission between isolated participants. The conclusions were highly suspicious. In a small number of cases, the brain activity of one person was reported to correlate with that of a partner localised in another room without any communication device linking the two participants. Many commentaries questioned these idiosyncratic results. They pointed out that the positive results obtained were most likely attributable to some dynamical similarity between the two brains engaged in the same perceptual context rather than to an effective transmission of information.

A small number of studies used hyperscanning in the interest of investigating the brain activities of participants committed into social interaction. The first exploratory experiment of Montague et al. [20] paved the way for the use of hyperscanning. These authors recorded with fMRI the brain activities of two participants engaging through a video link in the game of "handy dandy", a guessing game in which a participant has to presume the location of an object hidden by the other participant. King-Casas et al. [21] used hyperscanning in participants playing a multiround trust game of economic exchange. The authors found that response magnitude correlated with the "intention of trust" in the caudate nucleus. They also found a temporal transfer of the intention of trust in cross- and within-brain correlations. This response timing was similar to a reward prediction but, for the first time, it was observed in the context of a social exchange. Babiloni et al. [22] were the first to use hyperscanning with EEG. They recorded the brain activities of participants playing prisoner's dilemma. They found that the most consistently activated region during this type of interaction was the medial prefrontal cortex. In 2009, the same group of authors [23] reported a similar study but this time, they found that the orbital frontal cortex was the region that was most involved in such competitive interaction. In another study, Babiloni et al. [24] made a quartet of participants play a card game and recorded the players' brain activities with EEG hyperscanning. They found that, before playing the card in response, the companion of the first player develops a brain activity in the right prefrontal and parietal areas, which is correlated with that of the first player. Babiloni et al. also reported a larger activity in prefrontal and anterior cingulate cortices for the player who starts the game as compared to the other players. Yun et al. [25] used the ultimatum game to probe decision making in two participants whose neural activities were recorded with EEG hyperscanning. The results demonstrated that "high frequency oscillations of frontocentral regions of the brain are closely related to the social interaction". They also proved that the information flow of these regions correlated with decision making in both participants. Lindenberg et al. [26] used EEG hyperscanning on pairs of guitar players. The authors demonstrated that coordinated actions, such as playing guitar or even just listening to a metronome, are preceded and come with between-brains oscillatory couplings. Tognoli et al. [27] used EEG hyperscanning in participants who were instructed to perform a rhythmic finger movement with or without the vision of the other participant's movement. The authors observed that when participant could see each other they coordinate their behaviour. More interestingly, they discovered a particular oscillatory component (phi complex) that either favored independent movement (phi1) or to the contrary favored behavioural synchronization (phi2). Anders et al. [28] were interested in the facial communication of affects between love partners. They found that the sender's and the receiver's brains activate the same neural regions during the communication of emotion. The receiver's neural activations can be predicted from those of the sender. The authors also found a temporal succession of the flow of affective information from the sender's brain to the receiver's brain. Moreover, they showed a progressive tuning of this flow while the experiment was in progress. This is a neurophysiological illustration of the social resonance found in behavioural studies [29,30] and raises new questions on how such neurobehavioural resonance emerges.

These studies have used hyperscanning to solve different questions, but their common denominator is the investigation of neuronal activities in participants involved in social interaction.

It is important to note that other studies did not use hyperscanning *per se* as they did not record simultaneously two participants. Nevertheless, these studies used neuroimaging across multiple participants and look at relationships between their brain activities. In an fMRI study, Hasson et al. [31] recorded the brain activities of participants watching the same part of a movie. Even though they recorded isolated participants, they found a strong functional and anatomical similarity across the individuals who were immersed in the same natural settings. In another fMRI study, Schippers et al. [32] recorded separately the brain responses of the guesser and the gesturer during a social game, namely a game of charade. They found that the guesser's the brain regions involved in mentalizing and mirroring are temporally synchronized with the gesturers' brain. Stephens et al. [33] scanned the brain of a speaker reciting a monologue. Then, they scanned the brain of a participant listening to the speaker's monologue. The authors found temporal and spatial coupling between the speaker's and the listener's brains during the monologue. The three above-mentioned studies could not catch up the emergent properties of a mutual and live interaction between subjects since they did not record the subjects simultaneously. Moreover, there was no real social presence involved. By contrast, rather than giving access to the activities of each actor individually, hyperscanning – which involves recording the activities of multiple individual's brains simultaneously – makes possible the investigation of the effects of actions on several actors at the same time. This opens an avenue to the study of interbrain relationships. Moreover, hyperscanning paradigms lead to more ecological procedures: participants are immersed in a common environmental setting and real-time reciprocal interactions can be achieved in a laboratory context [34].

With these concerns in mind, we built up hyperscanning paradigms where the electrical brain activities of two participants were recorded at the same time while these participants were involved in a reciprocal social interaction.

3. Ongoing programs

Our research group has always been participating in pioneering methodological trends in the neuroimaging community. In this line, Line Garnero initiated a collaborative reflection on how to set up a hyperscanning facility on the site of the Hôpital Pitié-Salpêtrière.

The idea of a hyperscanning facility emerged initially during meetings involving our neuroimaging group and psychologists from the "Centre émotion" (CNRS USR 3246). The evocation of the neural synchronization elicited a conceptual analogy with behavioural synchrony. This gave a starting point for collaborations between the two research groups. The initial objective was

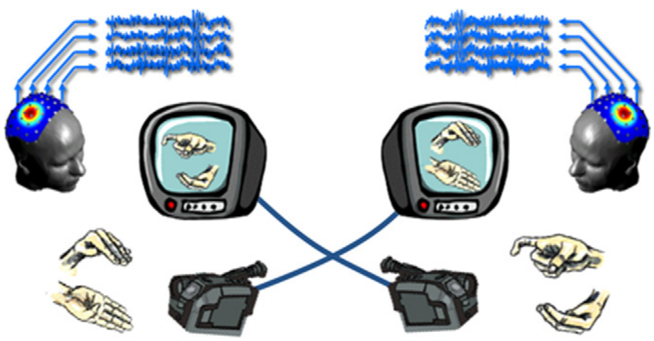

Fig. 1. Brain-to-brain communication experimental setup. Each participant sees the other through a dual-video system. The two EEG helmets are synchronized together and with the video cameras.

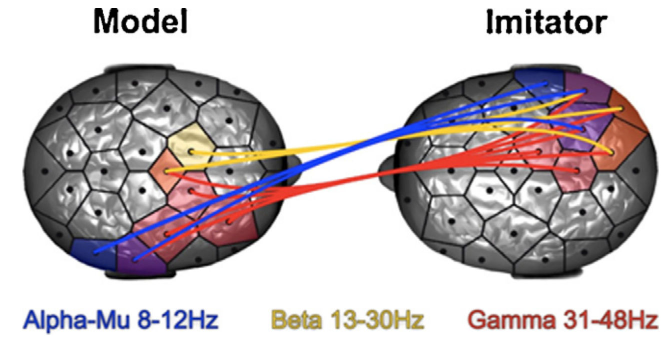

Fig. 2. Interbrain neural synchronizations during interactional synchrony. Adapted from Dumas et al. [32]. The links represent statistical increases of neural synchronization across the subjects when they are engaged in interactional synchrony. Notice the symmetric pattern in the low frequency band that become asymmetric in the highest ones.

to combine knowledge of the two fields toward the creation of an experimental paradigm in order to test the hypothetical link between behavioural and neural synchronization. Spontaneous gesture imitation was chosen as the basic task. Interestingly, the developmental psychologists' group had already developed a "behavioural hyperscanning setup" by simultaneously video recording two participants engaged in social interaction [7]. Two EEG helmets were added and synchronized to this setup in order to also record neuroelectric activity in both participants. This formed the initial hyperscanning facility. Later on, based on other previous reflections in our group regarding social attention driven by gaze [35], the idea grew up to use this hyperscanning facility for the study of joint attention. Thus, two studies have been conducted under the leadership of Line Garnero. Both of them aim at bridging the gap between neural and behavioural synchronization. They will also allow the comparison of the interindividual neural synchronizations in two different social contexts.

In the first study [36], the purpose of the experiment was mainly to test the existence of a neurodynamical phenomenon associated with the behavioural synchrony. In order to test this hypothesis, we recorded 22 participants paired by sex and age in 11 dyads, during spontaneous exchanges of intransitive bi-manual movements (Fig. 1).

We used a fined grain behavioural analysis thanks to a revised version of the ELAN software [37,38]. By a frame-by-frame analysis we were able to extract separately periods of imitation and behavioural synchrony: imitation was assessed when the two partners showed similar morphology and similar direction in their hand movements, behavioural synchrony was assessed when both participants started and ended their movements simultaneously (within the same video frame). This behavioural analysis showed first that participants prefer to imitate each other than to act separately. Moreover, even if they were not engaged in imitation – thus not executing the same movements – they were most of the time in behavioural synchrony.

By the use of a non-linear measure called Phase Locking Value (PLV) [39], we were able to exhibit the emergence of an interindividual brain-web across several frequency bands when the participants were engaged in these synchronous exchanges (Fig. 2). These interbrain synchronizations were directly related to the sensorimotor information flowing through the two participants. Interestingly, this interbrain network was symmetric in the lowest frequency bands and became asymmetric for the highest frequency bands. This could reflect the different levels of information processing from the low-level coding of movements to the higher-level coding of the social roles (model/imitator).

The positive results of this experiment validated technically the hyperscanning facility and demonstrated the feasibility of detecting between-brains synchronization during social interaction. Furthermore, this is the first neuroimaging program to study real spontaneous and reciprocal interactions. This reveals the strong potential offered by scanning two brains at the same time because such real-time spontaneous interactions could not be reproduced artificially first for one subject and later on for the other participant, as it would have to be done in classical neuroimaging paradigms. It demonstrates the possibility to move paradigmatically from a one-body to a two-body neuroscience.

The second study used the same EEG hyperscanning setup adapted to a paradigm of joint attention. In this study, the two participants of each pair were in the same experimental room and faced each other. A pierced wooden board with four light-emitting diodes (LEDs) was placed in between them so that they could see each other trough the board hole as well as gaze at the LEDs. This setup enables us to record the brain activities of the two participants in three different stages of gaze communication: eye contact, joint attention (when both participants look at the same LED) or "anti-joint attention" (when each participant looks at a different LED) (Fig. 3).

We expect that joint attention and mutual gaze induce synchronization between parts of the brain both intra- and interindividually. We also assume that the brain synchronization between the partners will be more important during joint than anti-joint attention periods. To date, 16 couples of participants (32 participants for individual analyses) took part in the experiment. We are currently beginning the first stages of the analyses. First, we are going to evaluate the temporal dynamics of joint attention in the brain. Second, we aim at analysing the variations in brain synchronizations between the participants according to the different tasks. We expect that interbrain synchronization during joint relative to anti-joint attention conditions might occur in the gamma band, which is known to play a crucial

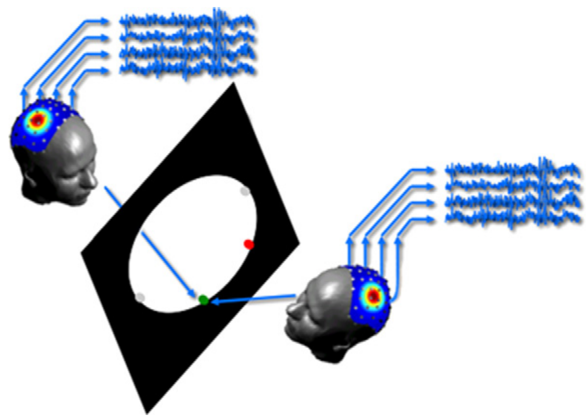

Fig. 3. Dual gaze experimental setup. Each participant seats face-to-face with the other; the wooden device is placed in between them. Both participants can see the LEDs attached to the border of the hole, and they can see each other through the hole. The participants move their eyes either to the same lighted up LEDs (joint attention, presented here) or to different LEDs (anti-joint attention).

role in gaze perception [40]. This innovative research program should help understanding the mechanism of joint attention in a real face-to-face situation while retaining the advantages of a laboratory-based task. We thus offer a new paradigm to shed light on the intra- and interbrain synchronization mechanisms occurring during joint attention.

4. Conclusion

More and more studies try to take a real look into ecological experimental settings. Some authors plead for cognitive ethology, meaning an observation of what happens in real life or at least creating situations that simulate the real world [41]. Scientific researches desperately need to get more and more real. Bringing the daily life into the lab is clearly a challenge for the next years [34] and more especially in the field of social neuroscience. In continuity with what was started under the direction of Line Garnero, our studies pursue this goal. These studies are compromises between the rigorous constraints of the scientific methods and the ecological needs of realistic tasks. We believe that they make a step further in the investigation of behaviour and brain synchronization during social interaction.

Conflict of interest statement

Nothing to declared.

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