Exploring the Connected Brain by fNIRS: Human-to-Human Interactions Engineering

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Abstract. Functional Near Infrared Spectroscopy (fNIRS) is a relatively new neuroimaging technique adequate and useful for exploring neural activity in social contexts involving human interactions. Compared to functional Magnetic Resonance Imaging (fMRI), fNIRS is easy-to-use safe, noninvasive, silent, relatively low cost and portable, and applicable to subjects of all ages, thus resulting in a good option for ecological studies involving humans in their real-life context. Moreover, by using hyperscanning technique, fNIRS allows recording the hemodynamic cerebral activity of two interacting subjects in an ecological context or during a shared performance. Thus, moving from a simple analysis about each subject's neural response during joint actions towards more complex computations makes possible to investigate brain synchrony, that is the *if* and *how* one's brain activity is related to that of another interacting partner simultaneously recorded. Here, we discuss how connectivity analyses, with respect to both time and frequency domain procedures, permitted to deepen some aspects of inter-brain synchrony in relation to emotional closeness, and to highlight how concurrent, cooperative actions can lead to interpersonal synchrony and bond construction.

Introduction

In the last twenty years, the use of Functional Near Infrared Spectroscopy (fNIRS) has widely expanded in the social and cognitive neuroscience field, because of the several advantages that this neuroscientific tool can provide if compared to other brain imaging techniques. Indeed, fNIRS is a noninvasive, easy-to-use, stable and reliable neuroimaging technique that allows the measurement of brain tissue concentration modifications of oxygenated (O2Hb) and deoxygenated (HHb) hemoglobin following changes in regional cerebral blood flow, due to neuronal activation. Its basic physical principle relies on the Near Infrared light spectrum property, that is shined into the head (650–1,000 nm) by emitting diode and it is relatively absorbed and reflected by the brain tissue, within this NIR optical window. On the other hand, fNIRS uses detector diodes to measure the light reflected by the cortical surface. These flexible optics fibers bring the light to source and from detector tissues and are generally adaptable for any head position and location. If diodes are located to the standard source-detector distance of three centimeters, they can give the chance to obtain ad adequate depth of light penetration [see 2]. In addition, fNIRS device is suitable for multimodal imaging recording given that these optical elements do not interfere with electromagnetic fields or with electric implanted therapeutic devices.

Because of its specific features, fNIRS has been extensively used within the field of social neuroscience, ranging from the study of cognition, towards more complex emotional and interpersonal mechanisms. Considering social neuroscience as a potential field of application, in fact, the main strength features of fNIRS include its portability and low sensitivity to body movements, its safety of use and the chance to integrate it with other neuroscientific measures, making it suitable for monitoring cortical hemodynamics in a variety of experimental and ecological conditions, specifically in interactive tasks [1] or motor [2]. Moreover, these advantages have made this technique particularly adequate for investigating brain function in a variety of specific healthy and clinical populations such as children and adults' functional organization and their social brain functioning since it does not impose closed, tight or noisy environment, and can be also applied at the bedside or while moving. Previously it has also been demonstrated to be a promising tool to investigate psychiatric or neurodegenerative diseases [3–5]). To get more in detail, fNIRS allows a better temporal resolution recording but has a lower spatial resolution than fMRI; on the other hand, it has a higher tolerance to motion artifact and it gives the chance to monitor O2Hb and not only HHb, as provided by fMRI. It is also suitable for long-time continuous monitoring, and it is more participant-friendly than fMRI, given that all participants are eligible for its application, of all ages, without particular exclusion criteria. These advantages are specifically useful for ecological task, mainly because it is not easy to reproduce real-life situations within an fMRI or a PET scanner. These contexts, in fact, introduce many requirements about spontaneous movement, sounds, experimental timing, etc. This way, the task becomes very unlikely and there is the risk of unreliable behaviors and response by the subjects. This is particularly important when considering the ecological validity of an experiment and data disclosure.

Indeed, a new research perspective tried to maximize the abovementioned fNIRS advantage towards the implementation of ecological conditions related to some constructs coming from a social/affective neuroscientific perspective, involving social closeness in human interactions. More specifically, the study of how people are connected to each other, in which way, and how this can be measured (and applied) by fNIRS. This kind of research aimed at disclosing "connectedness" was previously conducted by using the fMRI scanner [e.g. 7], not without several methodological and technical issues. In the present study, we propose fNIRS as a good alternative candidate to explore and understand interpersonal coordination and connectedness, from a human-to-human (H2H), towards a brain-to-brain (B2B) approach in real-time and in an ecological setting.

Experimental Setting and Materials

fNIRS allows recording the hemodynamic activity of two individuals in a natural interaction context or during a shared task performance using hyperscanning technique. It consists of the simultaneous recording of two interacting subjects' cerebral activity, representing an optimal technique for understanding the joint strategy of two interacting brains [7]. Paradigms used to explore interpersonal dynamics and to investigate the hemodynamic responses of two individuals involved in a social interaction typically focus on the structures that coordinate the performance of a joint task. This can be computerized or face-to-face, but, for both cases, it requires individuals to coordinate intentionally or spontaneously to achieve a shared result and a common goal. The ability to sustain reciprocal relationships results, indeed, to be regulated by perceptual -motor processes, but also by cognitive and affective mechanisms that coordinate the carrying out of joint actions [8].

Hyper Tasks – Dual Analysis - BRAIN+BRAIN (B+B). At this regard, two recent studies by Balconi and colleagues [9, 10] used a new paradigm to observe the different mental representations during a competitive and cooperative scenario in which the participants coupled in dyads had to compete or cooperate with their partner while carrying out a continuous attention task. Specifically, the game consisted of an attention task that required the recognition of target stimuli among non-targets. This procedure was designed to guarantee the perfect synchronization of activities. After each test, composed of three stimuli, the subjects received feedback in the form of two arrows at the top (high collaboration rate); a dash (average performance); or two arrows at the bottom (low collaboration rate). The task intended to reinforce the emotional bond of individuals in the cooperative situation and to discourage the formation of an emotional bond in the couples of subjects in the competitive condition. Also, some personality components related to approach or avoidance attitudes have been considered [11].

Specifically, from the results of the present studies it was possible to conclude that a cooperative condition induces a positive self-representation in term of ranking and a better way to face the task, as also reinforced by self-perception and cognitive outcomes. Accordingly, a significant increased activity emerged over the left prefrontal cortex (PFC) during cooperative than competitive contexts (see Table 1 for main results).

Table 1. Dual Brain analyses and results on neurophysiological fNIRS data.

	Analysis	**Results**
Balconi and Vanutelli (2017) [9]	ANOVA for O2Hb and HHb *d* dependent measures	HHb did not reveal significant effects O2Hb: general increased activity was found in post-feedback condition than in pre-feedback in the case of negative feedback the right Dorsolateral Prefrontal Cortex (DLPFC) activity was higher in post-feedback condition more for negative than for positive feedback in the case of negative feedback right DLPFC activity in post-feedback condition was increased than right DLPFC in pre-feedback condition the left DLPFC activity in post-feedback condition was increased than left DLPFC in prefeedback condition in the case of positive feedback
Balconi and Vanutelli (2017) [10]	ANOVA for O2Hb and HHb *d* dependent measures	HHb no significant effects O2Hb: increased left frontocentral activity for the postfeedback compared to the prefeedback condition
	Pearson correlation as similarity measure for each dyad in pre-post feedback condition	significant Pearson coefficients were found in five dyads in the prefeedback condition for both left and right hemisphere. 14 dyads were matched in postfeedback for left and 10 for right hemisphere during postfeedback the left hemisphere showed higher coefficient values than the right hemisphere the left hemisphere registered increased Pearson values in the postfeedback compared to the prefeedback condition

Hyper Tasks - Connectivity Analysis – BRAINxBRAIN (BxB). Although the abovementioned studies significantly improved the neuroscientific research assessing social/intimate exchange, the advantage of an ecological setting for this topic lies in the opportunity to move from a simple analysis about each subject’s neural response during joint actions and its association with the behavioral output, towards more complex computations [12]. In detail, it is possible to investigate if and how one's brain activity is related to that of another interacting partner simultaneously recorded (synchrony analysis – BRAINXBRAIN). However, as already suggested by Crivelli and Balconi [13], in the attempt to address such research questions, important concerns have been raised in relation to the best statistical approach to calculate specific indices expressing the strength of such relationship. Accordingly, a variety of methods have been implemented to analyze and interpret concurrent data and calculate inter-brain synchrony, or functional connectivity. More specifically, this can be defined as the relation between the neural activities coming from different brain areas or, in our case, from the brain areas of different, separated, brains. Making a step back to a classical definition of interpersonal coordination, it can be described as "the degree to which the behaviors in an interaction are non-random, patterned or synchronized in both timing [and] form" ([14], p.403). Thus, when dealing with the neurophysiological data underlying such joint behaviors, the passage of time is of main interest. Indeed, when calculating inter-brain connectivity, the main goal is to establish the presence of a consistency in the time course of two (or more) time series [8,13,15]. Such synchrony is assessed with different techniques according to the methodology. For what concerns fNIRS in detail, it is worth distinguishing between time-domain (A) and frequency-domain (B) analyses.

Time-domain data. In the case of time-domain protocols, correlational indices are usually computed to assess time consistency between two biological events, data point per data point (functional hyperconnectivity). Here, different correlational indices have been used. One exemplificative study assessing bond construction was performed by Balconi and colleagues [8]. By using the same joint attentive tasks as described in the previous paragraph, they explored connectivity patterns during cooperative interactions. Different steps of analyses were performed: I) the first one was meant to generally explore the brain areas involved across the task by considering each brain individually, while the second (II) and third (III) steps were aimed at assessing intra and inter-brain connectivity, respectively. Finally, a fourth (IV) step was introduced to compute a new coefficient.

I) When analyzing results in the first phase, a higher brain activity was found before receiving the social feedback over the left premotor cortex (PMC). These areas are usually involved in movement planning and in the use of rules during performance. Also, it is sensitive to the temporal features during action selection. Such finding is consistent with the nature of the task where subjects had to put higher initial efforts to learn possible response strategies in a way to synchronize motor responses.

II) Then, intra and inter-brain connectivity was explored by applying partial correlation indices, which is a measure of the linear dependence of a pair of random variables [8]. The partial correlation coefficient Π_{ij} was computed to obtain functional connectivity indices, obtained by normalizing the inverse of the covariance matrix $\Gamma = \Sigma^{-1}$:

$\Gamma = (\Gamma_{ij})$ Σ^{-1} inverse of the covariance matrix

It quantifies the relationship between two signals (i, j) independently from the other. For what concerns intra -brain connectivity, results showed higher values before the social feedback between premotor and attentive areas dedicated to visual search and the allocation of spatial attention for salience detection. The interplay between these regions is particularly relevant in the first part of the task where the detection of visual stimuli must be accompanied by pertinent and corresponding motor responses but must also be synchronized with another person's behavior. This analysis was applied to the data, as showing in the following table (Table 2).

III) Considering inter-brain connectivity, instead, higher coefficients were found before the feedback between the premotor areas of the two participants. Thus, it would be possible to assume that such areas could be strongly connected during the first part of the experiment in a way to synchronize motor planning and behavior by representing others' actions. Thus, we could suggest that inter-brain connectivity emerged between areas devoted to motor programming and imagery to allow synchronicity with the help of imaginative processes. This connection was enhanced in the first half of the task and disappeared after the social feedback. Going forward to the post-feedback condition, increased connectivity was found between participants' dorsolateral prefrontal cortices (DLPFc). This result is of particular interest considering the role that DLPFc for social cognition with respect to emotional regulation. More specifically, its recruitment was associated with perspective taking and theory of mind, with the suppression of selfish behavior and the commitment to significant relationships [see 9 for further details]. Of course, considering the social-reinforcing nature of the external feedback, these mechanisms could be very useful during the second part of the task. In fact, after receiving a positive feedback about the synchronicity of the couple, increased connectivity emerged in areas related to empathy and bonding, which were not that connected before the social reinforce.

IV) Finally, a new coefficient was computed in order to calculate the effects related to inter-brain synchrony net to the effects related to intra-brain synchrony. It was named ConIndex, as the ratio between inter-brain and intra-brain connectivity ($\text{Inter}_{\text{con}}/\text{Intra}_{\text{con}}$) to directly compare the two connectivity levels, and its modulation was explored across the different blocks, furthermore, reinforcing the contribution of the DLPFc. This study represents a good example of the possible use of concurrent data, from simple to complex analyses. However, the limitation of such procedure lies in the fact that it can only be run between two signals at a time and cannot involve 3 or more sets of data [13, 16]. An alternative to simple correlational methods is Granger causality, a statistical procedure aimed at determining whether one-time series can predict another one. Thus, a relationship of dependency is actually present here, which is tested by measuring the capacity of an initial time series to predict the future values of another one. Accordingly, it can produce an index of effective hyperconnectivity [17]. This technique is usually better applied to neuroelectrical signals since the hemodynamic response is not uniform across different brain areas [12].

Table 2. Main results from functional connectivity analysis.

	Analysis	**Results**
Balconi, Pezard, Nandrino and Vanutelli (2017) [8]	ANOVA for O2Hb and HHb intra-brain indices	HHb did not reveal significant effects O2Hb: intra-brain connectivity was generally higher in DLPFC compared to other areas considered
	ANOVA applied to inter-brain indices for the dyads	increased inter-brain connectivity was observed in the post-feedback condition compared to pre-feedback condition inter-brain connectivity increased in post-feedback compared to pre-feedback in DLPFC
	ANOVA for ConIndex	an increased ConIndex was observed in post-feedback than the pre-feedback condition within the DLPFC (i.e. general increase in inter-brain connectivity compared to intra-brain connectivity in DLPFC for the post-feedback condition)

Frequency-domain data. On the other hand, for frequency-domain analyses, coherence measures have been proposed to explore the presence of a joint trend of different frequency components within the oscillating signals [13]. Also, in this case the analysis can be run only between two data series at a time. One example of such procedure is that of Pan and colleagues [18]. The experiment consisted of a cooperative task performed by different dyads grouped for intimacy: specifically, couples of lovers, friends and strangers completed the task. Results showed the presence of interpersonal brain synchronization only for lover dyads over the superior frontal gyrus. Such result was in line with the behavioral performance: in fact, response time differences within lover dyads were smaller and less variable than friend and stranger dyads. Thus, the authors interpreted such findings in the light of better lovers' cooperation thanks to the power of bonding to trigger a tuning experience.

Conclusion

The present work was aimed at illustrating the use of fNIRS in the social/affective neuroscientific research seeking to explore interpersonal connectedness considering a brain-to-brain (B2B) approach. Moving from a single-person to a second-person approach, more complex analyses have been discussed with respect to concurrent, joint hemodynamic data, with respect to both time and frequency domain procedures. We believe that it should be important for upcoming work to frame and interpret the meaning of the presence of such "hyperlinks" by adopting evidence-based theoretical models to understand and explain the co-modulation of the neural parameters. The potentiality of fNIRS-based hyperscanning techniques should anyhow be better framed in future studies translating H2H to B2B interactions.

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