Journal of Biomedical Optics

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Abstract. In order to understand the so-called "social brain," we need to monitor social interactions in face-to-face paradigms. Near-infrared spectroscopy (NIRS) is a promising technique to achieve this goal. We investigate the neuronal underpinnings of sharing a task in a proper social context. We record cortical activity by means of NIRS, while participants perform a joint Simon task. Different from other hemodynamic techniques, NIRS allows us to have both participants sit comfortably close to each other in a realistic and ecological environment. We found higher activation in the sensorimotor cortex while processing compatible trials as compared to incompatible ones referring to one's own action alternative. Strikingly, when the participant was not responding because it was the turn of the other member of the pair, the inferior parietal was activated. This study provides twofold findings: first, they suggest that the joint Simon effect relies more on shared attentional mechanisms than a proper mapping of the other's motor response. Second, they highlight the invaluable contribution NIRS can afford to social neuroscience in order to preserve ecological and naturalistic settings. [DOI: 10.1117/1.JBO.18.2.025005]

Keywords: near infrared spectroscopy; social neuroscience; social Simon effect.

Paper 12634RRR received Sep. 24, 2012; revised manuscript received Jan. 29, 2013; accepted for publication Jan. 30, 2013; published online Feb. 15, 2013.

1 Introduction

Interest in bridging neuroscience and social psychology has seen a significant increase. Much of this interest has centred on brain localization—the attempt to relate social events to locations of brain activity. Social neuroscience, however, uses a rather unsocial environment.[1] Indeed, the brain activity of observers is often measured in isolation while viewing a variety of stimuli. The only social aspect is that employed stimuli involve other human beings.

This caveat of social neuroscience is mostly related to the technique employed, such as functional magnetic resonance imaging (fMRI), which suffers from several limitations. In this context, the most problematic limitation is that a proper and realistic social context is difficult to achieve. Due to this limitation, most previous studies have necessarily been conducted in an unusual and unrealistic way, such as using pictures shown on a computer screen. A functional brain imaging methodology that enables monitoring of brain activation in a more natural setting might well offer more informative data from more realistic social interactive situations, which is impossible with fMRI because of its methodological constraints.

In this study, we try to overtake these problems by measuring the cortical activity of individuals while they are engaged in a well-known social task, namely the social or interactive Simon, by means of near-infrared spectroscopy (NIRS).[2,3]

The Simon effect is observed when people carry out spatially defined responses to non-spatial stimulus features, the location of which varies randomly. For instance, imagine that you are requested to press a left key in response to a green stimulus randomly presented on the left or right half of a display and a right key in response to a blue stimulus also randomly presented on the left or right half of the same display. Even though the stimulus location is irrelevant for the task, you will nevertheless be faster and more accurate if the green stimulus appears on the left side and the blue stimulus on the right one than if the green stimulus appears on the right or the blue stimulus on the left.[4] That is spatial stimulus–response compatibility facilitates task performance. This phenomenon is known as the Simon effect. Usually, this effect disappears when participants respond to only one of the two stimuli, making the task a go/no-go task. Most accounts of the Simon effect are based on the assumption that it arises from a conflict between the spatial code of the stimulus and that of the response.[5,6] Accordingly, responses are assumed to be automatically activated if the stimulus corresponds spatially to the correct response, and thus it facilitates task performance, whereas a lack of correspondence between stimulus-response pair leads to response competition. At the theoretical level, the theory of event coding might account for this competition. This theory claims that perceptual representations (e.g., of things we can see) and motor representations (e.g., of hand actions) are linked, as the same representation (a common code) is shared by both perception and action.[5] Thus, the simultaneous recruitment of two incompatible representations accounts for higher mean reaction time (RT) for incompatible trials as compared to compatible ones.

At the neuronal level, the Simon effect is thought to originate in posterior parietal structures,[7,8] which host attentional orienting and oculomotor mechanisms.[9]

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0091-3286/2013/$25.00 © 2013 SPIE

This is not the whole story, though: the simultaneous recruitment of a common representational medium does occur not only when acting and perceiving in isolation but also when acting and perceiving in social context.[10–12] This claim receives its strongest support from studies on the social version of the classical Simon task. In this version, pairs of participants share a Simon task: one participant presses a key in response to one color, and the other participant presses another key in response to the other color, so that each participant actually performs a go/no-go task. This version of the task has been shown to produce a full-blown Simon effect: people perform better if the stimulus appears on the same side as the response key they operate. According to Sebanz and colleagues[10–12] this kind of social Simon effect suggests that each participant represents the stimulus-response rules and action plans of both agents involved. Thus, people may represent stimulus events irrespective of their intended target and may represent an action irrespective of who is carrying it out.

As regards the neuronal underpinnings of the social Simon effect, to date only two studies are available: one using EEG,[12] the other fMRI.[13] In the EEG study, pairs of participants shared a Simon task: one participant pressed the left key in response to one color, and the other participant pressed the right key in response to the other color, so that each participant was performing a go/no-go task. Results showed that stimuli referring to the other's action elicited an electrophysiological response, recorded from frontal electrodes, similar to that elicited by stimuli referring to one's own action. Moreover, P300 component had higher amplitude in the group condition as compared to the single condition. According to the authors, these findings suggest that individuals acting in a social context form shared action representations. In the fMRI study, participants in the scanner performed the go/no-go task together with a confederate who was sitting next to the scanner and whose actions were visible in the lower part of a display. Results showed increased activation in ventral premotor cortex when participants acted upon stimuli referring to their own action alternative in the co-acting condition. Also, this condition was associated with increased orbitofrontal activation.

The above reported studies provide evidence that, while acting in social context, each participant represents the stimulus-response rules of both agents involved. Nevertheless, they do not help us to disentangle whether the social Simon effect originates at the level of parietal structures, as the standard Simon effect, or the level of sensorimotor cortex often activated during social tasks, likely via mirror mechanisms.[14–16] Indeed, both studies have intrinsic caveats, which are mostly related to the employed techniques. On the one hand, from the EEG study it is not possible to draw clear-cut conclusions about the cortical regions involved during the task. It is well known that EEG has a spatial resolution far from being accurate due to the distortion of the electric field while passing through the scalp.[17] On the other hand, in the fMRI study, the participant being scanned could see the co-actor's hand projected on the display, but they cannot surely share a common space, as it occurs in everyday social interaction, thus making the experimental context largely artificial and far away from realistic social interactions. This becomes particularly relevant if one considers Guagnano and colleagues' report.[18] They submitted participants to a social Simon task with a co-actor who sat either within or beyond their peripersonal space. Results showed that social Simon occurred provided that the co-actor sat within the participants' peripersonal space. The authors claimed that the major role of the co-actor in the social Simon task might be to provide a spatial reference frame that allows coding of one's own action as left or right relative to the other person—just as one's own action alternatives provide a reference frame for relative response coding.[19] A confederate sitting too far away (in the actor's extrapersonal space) cannot provide the reference point for the spatial coding of the actor's response.

The aim of the present study is to highlight the valuable contribution that NIRS can provide in studying social cognition. To this aim, we recorded cortical hemodynamic, from the left parietal and sensorimotor cortices, by means of NIRS, while 12 pairs of participants performed a social Simon task.

Two hypotheses were assumed: if the social Simon effect originates, as the standard Simon effect, at the level of attentional orienting and oculomotor mechanisms,[8,9,20] then higher activation should be found while processing no-go trials in parietal structures. On the other hand, if it originates from an actual mapping of the response of the other subject, then higher activation should be found in the sensorimotor cortex.

2 Method

2.1 *Participants*

Twenty-four participants (12 male and 12 female), recruited at the University of Chieti-Pescara, took part in this study after having given written informed consent. All were right-handed. They had normal or corrected-to-normal visual acuity and were naïve as to the purposes of the experiment. The experimental protocol was approved by the ethics committee of the University of Chieti-Pescara.

2.2 *Procedure*

The experiment was conducted in a dimly lit room where participants sat side-by-side in front of a monitor (see Fig. 1). They were required to respond to digital photographs of a right hand with the index finger pointing to the left or to the right half of the screen. On the index finger there was a blue or green ring. Visual stimuli were presented on the central axes of the display, and the ring always appeared at the same location. Picture size was

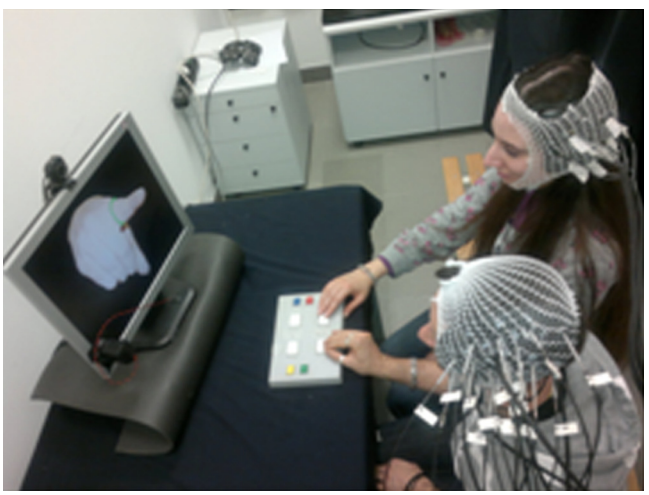

Fig. 1 Experimental setting in the social Simon task. Hemodynamic activity was recorded from one subject during the experiment. Nevertheless, both the participants of each pair wore the fitting cup with probes and detectors.

about 10×8 visual degrees, in horizontal and vertical direction. The task was distributed between two individuals. Each person responded to only one of the two colors by pushing a single button with the right index finger, regardless of the pointing direction. For example, when one participant's task was to respond to green, the co-actor responded to blue. This gave rise to four experimental conditions namely: (1) go compatible; (2) go incompatible; (3) no-go compatible; (4) no-go incompatible, where the go compatible trial refers to the condition in which the finger pointed toward the person who should respond; go incompatible trials refer to the condition in which the finger pointed away from the person who should respond. The very same stimuli were coded as no-go compatible and no-go incompatible for the co-actor, respectively. That is, if the finger pointed away from the participant and it was not her turn to respond, this trial was coded as no-go compatible. On the other hand, if the finger pointed toward the participant and it was not her turn to respond, this trial was coded as no-go incompatible.

Each stimulus was presented for 1000 ms followed by a fixation cross lasting between 1000 and 1500 ms. Participants completed one block of 200 trials, 50 trials per condition, presented in pseudo-random order. The sequence of trials was the same for all subjects. Stimulus presentation and data collection were controlled by a custom software (developed by Gaspare Galati at the Department of Psychology, Sapienza Università di Roma, Italy[21]), implemented in MATLAB (The MathWorks Inc., Natick, Massachusetts) using Cogent 2000 (developed at FIL and ICN, UCL, London, United Kingdom), and Cogent Graphics (developed by John Romaya at the LON, Wellcome Department of Imaging Neuroscience, UCL, London, United Kingdom).

2.3 *Functional Near-Infrared Spectroscopy Measurement*

To investigate cortical hemodynamic, we used a commercial frequency-domain brain imaging system (Imagent, ISS Inc.). The Imagent system is equipped with 32 sources (32 laser diodes, 16 at 690 nm, 16 at 830 nm) modulated at 110 MHz and four photomultiplier tube (PMT) detectors. The sources were time-multiplexed during measures (switch mode 32, sampling frequency: 5.787 Hz, one light source on at a time for 10 ms). The light power emitted by the diodes at the fiber end was <4 mW/cm^2, within the ANSI standard limits and permitting safe measurements. The light emitted by the diodes was injected into the scalp through 400 μm core diameter silica optic fibers. The detectors were four 3-mm diameter fiber optic bundles connected to the PMTs. The current feeding into the PMTs was modulated at 110 MHz + 5 KHz, generating a 5 KHz heterodyne detection. The output current of PMTs, sampled at 40 KHz, was processed by fast Fourier transform (FFT). Average intensity, modulated intensity, and phase delay with respect to a reference signal were automatically recorded. However, in this study we were interested only in standard hemodynamic responses for which the only average intensity (DC signal) is required.

Changes in oxy-hemoglobin (oxy-Hb) and deoxy-hemoglobin (deoxy-Hb) were evaluated by the average intensity changes at the two wavelengths. The 20 optodes (16 injection points and four detection points) were arranged to form a 24-channel (source-detector couple) optical pad, with an emitter-detector distance set to 3.0 cm. This inter-fiber distance allows measuring hemodynamic processes occurring at a depth of 1 to 2 cm below the scalp, that is at the surface of the cerebral cortex.[22]

The optodes configuration permitted us to measure hemoglobin (Hb) changes over an area of roughly 100 cm^2 and was placed on the participant's sensorimotor and parietal regions (Fig. 3). In order to have the recording pad positioned in the same position in all the participants, we first collected the volumetric T1-wieghted structural MRI data for each participant, then we identified on the individual's brain structural image two points of reference, namely the ventral premotor cortex and the temporo-parietal junction. The left ventral premotor cortex was defined as the portion of precentral gyrus below the intersection of the inferior frontal sulcus with the precentral sulcus (mean Talairach coordinates: $x = -48.9 \pm 3$, $y = 0.9 \pm 3.7$, $z = 22.2 \pm 2.6$).[23] The left temporo-parietal junction was defined as the posterior branch of the superior temporal sulcus (mean Talairach coordinates: $x = -54.2 \pm 2.9$, $y = -46.1 \pm 4$, $z = 6.8 \pm 3.2$).[24]

Coordinates in Talairach space[25] of these sites were estimated by means of the SofTaxic Navigator system. Thus, the recording pad was positioned according to these cortical sites on an individual basis. For each subject, the location of all the emitters and detectors, as well as the nasion, the preauricolar points and the inion (reference landmark points) were digitized using a Polhemus system (SPACE FASTRAK). The digitized image of the source and detector locations were spatially aligned with the MRI data using the reference points as landmarks after conversion to MNI space coordinates. The alignment was performed using the NIRS-SPM software package.[26] A hemodynamic signal was recorded from only one participant of each pair. Nevertheless, both the participants of each pair wore the fitting cup with probes and detectors. Because of technical limitations (length of real fibers), all the recorded participants were seated on the left side.

2.4 *NIRS Data Analysis*

Fast Fourier transform of the signals, recorded from the 24 channels at the two different wavelengths, was performed to compute the alternating current (AC), direct current (DC) components, and the phase shift of the optical measurement. Changes of hemoglobin concentration were assessed using the modified Lambert-Beer law on the DC signal.[27] We assumed the differential pathlength factor at the 830 and 690 nm wavelengths as 5 and 5.5, respectively.[28] In addition to the physiological noise (e.g., heart rate, Mayer wave), we considered motion artifacts, mainly due to head motion. After visual inspection, motion artifacts were defined and recognized according to what was proposed by Huppert and colleagues.[29–31] These algorithms provide reliable identification of motion artifacts based on changes in signal amplitude and/or standard deviation. In particular, if the standard deviation increases or the peak-to-peak amplitude exceeds given thresholds (20 times standard deviations and 50% of the amplitude, respectively), both within a predefined time window (1 s), then data from the beginning of that window to a given time length (see below) are defined as motion. Signal rapid variations, which are classified as artifact in one channel, are then marked as motion in all channels, based on the reasonable assumption that motion artifacts affect multiple channels.

In order to recognize and remove motion artifacts, we smoothed oxy-Hb and deoxy-Hb data over a 30 s time window (i.e., longer than the canonical hemodynamic response function (HRF) time duration), thus getting the carrier component of the

signal. Then we subtracted this carrier component to the original data. The motion artifacts are recognized on the resulting signal. The time window to be removed for each recognized artifact was estimated also on the basis of the analysis of correlation properties between oxy-Hb and deoxy-Hb data.[32] Removed data were replaced by the average values of the signal 1 s before and 1 s after the removed time window. All the trials affected by motion artifacts were entirely removed. On average, we identified and removed 8 ± 4 trials out of 50 trials per condition.

Then, single-subject analysis was performed by using an NIRS-SPM software package.[26] Correction for auto-regressive processes was performed by adopting the precoloring method[33] implemented into NIRS-SPM. In this method the intrinsic temporal correlations are swamped by an imposed temporal correlation structure by smoothing the data with a temporal filter that will attenuate high-frequency components; hence this is a "low-pass filter." To meet this goal, we used the canonical HRF. Such function, already implemented in NIRS-SPM, is a typical blood oxygen level dependent (BOLD) impulse response characterized by two gamma functions, one modeling the peak and one modeling the undershoot. The HRF is parameterized by an onset delay of 0 s, peak delay of 6 s, peak dispersion of 1, undershoot delay of 16 s, undershoot dispersion of 1 and a peak: undershoot amplitude ratio of 6.[34] Possible significant activations in response to the stimuli were assessed by means of GLM method[35]: the four experimental conditions were supposed as events. These covariates were convolved with the HRF, and compared to the hemoglobin concentration changes in each channel, to yield appropriate predictors (beta values). T-statistics of the different stimulation contrasts were then performed on beta-values.[35] Cortical maps of activation referred to the MNI space were then obtained through discrete Gaussian random field interpolation of the t-scores.[26] Group analysis was performed into the MNI space for the intersection region of each subject's cortical area covered by the optodes. Moreover, we performed false discovery rate method for multiple comparison correction in order to establish the significant activation threshold for each GLM contrast of the group analysis.[36]

3 Results

3.1 *Behavioral Results*

Error rate was 0.4%. Error trials were excluded from behavioral and fNIRS data analyses. Mean RT of the correct responses was calculated for each condition; responses longer than two standard deviations from the individual mean were treated as outliers and not considered (4.6% of the data set).

To compare performance on compatible and incompatible trials, a paired-sample t-test was performed between these two conditions. The analysis yielded significant results ($t_{23} = -4.6$; $p < 0.001$, see Fig. 2). RTs were faster on compatible [mean (SD) = 376 (9.3) ms] than on incompatible [mean (SD) = 385 (9.4) ms] trials. This result suggests a full-blown social Simon effect, which means that a representation of the action alternative not actually under one's own control was activated as well as when it was under one's own control.[11]

3.2 *NIRS Results*

3.2.1 *Effects of compatibility on go trials*

The linear contrast go compatible versus go incompatible trials was run with the aim of revealing cortical regions sensitive to the stimulus-response compatibility while processing stimuli referring to one's own actions. Results showed higher activation in the sensorimotor cortex [$p < 0.05$, FDR corrected, see Fig. 3(a)]. The opposite contrast did not reveal any significant activation. Analysis on deoxy-hemoglobin did not reveal any significant group activation.

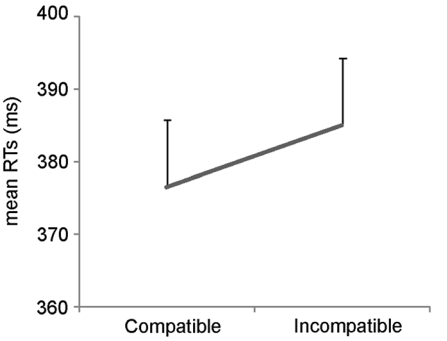

Fig. 2 Mean RT in the social Simon task. Error bars represent standard errors.

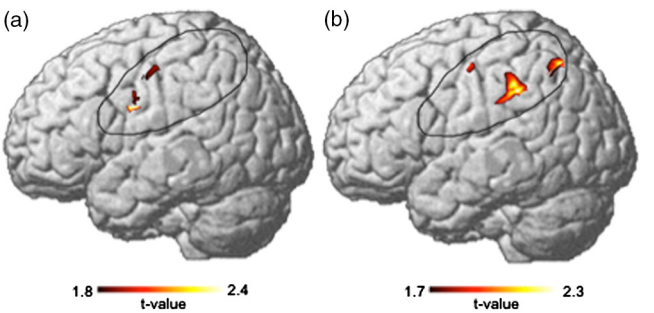

Fig. 3 Cortical activations (0.05 FDR corrected) contingent upon: (a) go compatible versus go incompatible trials; (b) no-go compatible versus no-go incompatible trials. Group activation data are rendered on the cortical surface of a "canonical" brain. The black line represents the recorded area.

3.2.2 *Effects of compatibility on no-go trials*

The linear contrast no-go compatible versus no-go incompatible trials was run with the aim of revealing cortical regions sensitive to the stimulus-response compatibility while processing stimuli referring to others' actions. Results showed higher activation in the left inferior parietal lobule [$p < 0.05$, FDR corrected, see Fig. 3(b)]. The opposite contrast did not reveal any significant activation. Analysis on deoxy-hemoglobin did not reveal any significant group activation. We do not report contrasts between go and no go trials because, as we do not have a "solo" condition, the activations merely due to motor response are not subtracted out.

4 Discussion

Although perception and action have been widely investigated on the assumption that they can be completely accounted for by focusing on single individuals, several cognitive neuroscientists, experimental and developmental psychologists, and philosophers have recently argued for the need to take a social perspective on perceptual, motor, and cognitive activities. Indeed, over the last few years, more and more theoretical and empirical papers have been devoted to finding out the neural and cognitive

processes underpinning basic social phenomena such as joint attention[37–39] and joint action[40–46] in development as well as in everyday adult life.

Currently the most commonly used brain imaging technique is fMRI,[47] which monitors brain activity by measuring BOLD responses. A major problem in utilizing this brain imaging technique to study the neural correlates of social phenomena is that the actual social dimension cannot be reproduced. Also, huge machinery dimensions, disturbing noise, together with the horizontal and unnatural position of the participant during scans' acquisition, constitute the most limiting factors in the use of the aforementioned technique. On the contrary NIRS, which measures tissue oxygenation, has several advantages compared to other imaging techniques. First, NIRS allows the participants to be almost totally free in their movements. Second, it enables brain activity measurement in a natural setting. Participants, indeed, can undergo NIRS examination in a comfortable position, without any noise. These characteristics of NIRS are considered to be particularly suitable for social interaction studies.

In this study we investigated whether and to what extent the sensorimotor cortex and the parietal lobe are involved during social actions.[48,49]

Our study provides two main findings. First, higher activation was found in the sensorimotor cortex when participants acted upon compatible stimuli. Second, higher activation was found in the inferior parietal lobule when the co-participant acted upon compatible stimuli. As regards the first main finding, previous studies have shown a recruitment of sensorimotor and parietal cortices while performing a standard Simon task. For instance, Liu, Banich, Jacobson, and Tanabe[7] mapped the neural substrates of the Simon task with fMRI and reported that was more activation in the non-corresponding relative to the corresponding condition in the left posterior parietal cortex. In the same vein Rusconi and colleagues[8] investigated, by using repetitive transcranial magnetic stimulation (rTMS), the role of the posterior parietal cortex in the Simon effect. They found a causal involvement of this cortical region in the task, that is, interfering with the activity in this area vanished the Simon effect.

To us, the activation of sensorimotor structures in go trials and the activation of parietal structures in no-go trials is particularly striking as it helps us to shed light on the nature of the joint Simon effect. According to previous studies we might have expected higher activation in the ventral premotor cortex while processing others' actions; nevertheless, this was not the case. A possible explanation for this different result can be addressed. One could explain the difference on the basis of the different tasks employed. Indeed, while in previous studies the two participants simultaneously performed the required action, in our experiment participants never acted simultaneously. Thus, while in previous studies the production and the observation of a motor response co-occurred, in our task they are temporally segregated. In any case, our data suggest that the joint Simon effect does not occur at the level of sensorimotor cortex where the other's action is mapped; rather it seems to occur at the level of shared attentional orienting mechanisms, that is the parietal lobule. Our results are in line with a previous study by Egetemeir and colleagues.[48] They investigated brain activation during real-life joint-action tasks using functional near-infrared spectroscopy. Participants performed table-setting tasks, either alone or in cooperation with a partner. They found that joint action produced stronger activations, as compared to acting alone, in a number of areas including the inferior parietal lobule.[48] Similarly, Koehler and colleagues[49] measured brain activity while participants observed reaching, grasping, and displacing movements from different perspectives. They found that observation from an egocentric perspective led to a higher activation in the inferior parietal cortex than observation from an allocentric perspective.

Possibly one may argue that, as we do not have a condition in which participants performed the task alone to compare with the condition in which a pair acted together, our data should be interpreted with caution. Although we agree with this warning, based on previous evidence[12,13,46] and on our behavioral data, we believe that our activations are somehow related to a social phenomenon.

The existence of a mechanism allowing us to integrate our own and others' experiences has been suggested by neurophysiological, behavioral, and imaging studies in both humans and nonhuman primates. For instance, single cell recordings from monkeys' brains have shown that there are bimodal neurons located in the ventral intraparietal area (VIP) that respond not only to tactile or visual stimuli delivered within the peripersonal space of the monkey but also to visual stimuli presented within the peripersonal space of another individual facing it.[50] At the theoretical level, the integration of one's own experience with those of con-specific can be construed in terms of a shared we-centric space[51] conceived as providing "a powerful tool to detect and incorporate coherence, regularity, and predictability in the course of the interactions of the individual with the environment."

We processed both oxy- and deoxy-Hb. No deoxy-Hb activation survived to the group analysis. Diverging results between oxy-HB and deoxy-Hb are often interpreted as a lack of statistical power for the deoxy-Hb parameter. However, fNIRS studies on emotional modulation of brain activation[52–54] reported more robust results for deoxy-Hb compared to oxy-Hb. Even though our experiment immersed the subjects in a real and ecological social context, thanks to the physical presence of the co-actor, the associated potential emotional effects (e.g., embarrassment) could impact equally on all the experimental conditions, thus being nulled by the contrast analysis.

Summing up, we investigated the neural bases of a social interaction involving spatial proximity of two co-actors. Using NIRS, we were able to arrange an experimental setting closer to everyday life than previously done, which allowed us to shed new light on the role played by sensorimotor cortices during social interaction.

References

1. C. Keysers and L. S. McKay, "How to make social neuroscience social," *Psychol. Inquiry* **22**(3), 210–216 (2011).
2. M. Ferrari and V. Quaresima, "A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application," *NeuroImage* **63**(2), 921–935 (2012).
3. S. Cutini, S. B. Moro, and S. Bisconti, "Functional near infrared optical imaging in cognitive neuroscience: an introductory review," *J. Near Infrared Spectros.* **20**(1), 75–92 (2012).
4. J. Simon and A. Rudell, "Auditory S-R compatibility: the effect of an irrelevant cue on information processing," *J. Appl. Psychol.* **51**(3), 300–304 (1967).
5. B. Hommel et al., "The theory of event coding (TEC): a framework for perception and action planning," *Behav. Brain Sci.* **24**(5), 849–878; discussion 878–937, (2001).
6. S. Kornblum, T. Hasbroucq, and A. Osman, "Dimensional overlap: cognitive basis for stimulus-response compatibility—a model and taxonomy," *Psychol. Rev.* **97**(2), 253–270 (1990).

7. X. Liu et al., "Common and distinct neural substrates of attentional control in an integrated Simon and spatial Stroop task as assessed by event-related fMRI," *NeuroImage* **22**(3), 1097–1106 (2004).
8. E. Rusconi, M. Turatto, and C. Umiltà, "Two orienting mechanisms in posterior parietal lobule: an rTMS study of the Simon and SNARC effects," *Cognitive Neuropsychol.* **24**(4), 373–392 (2007).
9. M. Corbetta and G. L. Shulman, "Control of goal-directed and stimulus-driven attention in the brain," *Nat. Rev. Neurosci.* **3**(3), 201–215 (2002).
10. N. Sebanz, H. Bekkering, and G. Knoblich, "Joint action: bodies and minds moving together," *Trends Cogn. Sci.* **10**(2), 70–76 (2006).
11. N. Sebanz, G. Knoblich, and W. Prinz, "Representing others' actions: just like one's own?," *Cognition* **88**(3), B11–B21 (2003).
12. N. Sebanz et al., "Twin peaks: an ERP study of action planning and control in coacting individuals," *J. Cogn. Neurosci.* **18**(5), 859–870 (2006).
13. N. Sebanz et al., "Is it really my turn? An event-related fMRI study of task sharing," *Social Neurosci.* **2**(2), 81–95 (2007).
14. R. D. Newman-Norlund et al., "Anatomical substrates of cooperative joint-action in a continuous motor task: virtual lifting and balancing," *NeuroImage* **41**(1), 169–177 (2008).
15. R. D. Newman-Norlund et al., "Exploring the brain basis of joint action: co-ordination of actions, goals and intentions," *Soc. Neurosci.* **2**(1), 48–65 (2007).
16. R. D. Newman-Norlund et al., "The mirror neuron system is more active during complementary compared with imitative action," *Nat. Neurosci.* **10**(7), 817–818 (2007).
17. C. Babiloni et al., "Chapter 5 Fundamentals of Electroencefalography, Magnetoencefalography, and Functional Magnetic Resonance Imaging," in *International Review of Neurobiology*, R. Luca, I. Dario, and S. Leopold, Eds., pp. 67–80, Academic Press, New York (2009).
18. D. Guagnano, E. Rusconi, and C. A. Umiltà, "Sharing a task or sharing space? On the effect of the confederate in action coding in a detection task," *Cognition* **114**(3), 348–355 (2010).
19. B. Hommel, "The cognitive representation of action: automatic integration of perceived action effects," *Psycholog. Res.* **59**(3), 176–186 (1996).
20. C. Umiltà and R. Nicoletti, *An Integrated Model of the Simon Effect*, pp. 331–350, Elsevier, Amsterdam (1992).
21. G. Galati et al., "A selective representation of the meaning of actions in the auditory mirror system," *NeuroImage* **40**(3), 1274–1286 (2008).
22. O. Eiji et al., "Theoretical and experimental investigation of near-infrared light propagation in a model of the adult head," *Appl. Opt.* **36**(1), 21–31 (1997).
23. M. A. Mayka et al., "Three-dimensional locations and boundaries of motor and premotor cortices as defined by functional brain imaging: a meta-analysis," *NeuroImage* **31**(4), 1453 (2006).
24. F. Van Overwalle, "Social cognition and the brain: a meta-analysis," *Human Brain Mapping* **30**(3), 829 (2009).
25. J. Talairach and P. Tournoux, *Co-planar Stereotaxic Atlas of the Human Brain: 3-Dimensional Proportional System—An Approach to Cerebral Imaging*, Thieme Medical Publishers, New York (1988).
26. J. C. Ye et al., "NIRS-SPM: statistical parametric mapping for near-infrared spectroscopy," *NeuroImage* **44**(2), 428–447 (2009).
27. D. T. Delpy et al., "Estimation of optical pathlength through tissue from direct time of flight measurement," *Phys. Med. Biol.* **33**(12), 1433 (1988).
28. M. Essenpreis et al., "Wavelength dependence of the differential path-length factor and the log slope in time-resolved tissue spectroscopy," *Adv. Exp. Med. Biol.* **333**, 9–20 (1993).
29. T. J. Huppert et al., "HomER: a review of time-series analysis methods for near-infrared spectroscopy of the brain," *Appl. Opt.* **48**(10), D280–D298 (2009)
30. R. J. Cooper et al., "Transient haemodynamic events in neurologically compromised infants: a simultaneous EEG and diffuse optical imaging study," *NeuroImage* **55**(4), 1610–1616 (2011).
31. F. Scholkmann et al., "How to detect and reduce movement artifacts in near-infrared imaging using moving standard deviation and spline interpolation," *Physiol. Meas.* **31**(5), 649–662 (2010).
32. X. Cui, S. Bray, and A. L. Reiss, "Functional near infrared spectroscopy (NIRS) signal improvement based on negative correlation between oxygenated and deoxygenated hemoglobin dynamics," *NeuroImage* **49**(4), 3039–3046 (2010).
33. K. J. Worsley and K. J. Friston, "Analysis of fMRI time-series revisited—again," *NeuroImage* **2**(3), 173–181 (1995).
34. K. J. Friston et al., "Nonlinear event-related responses in fMRI," *Magnet. Resonance Med.* **39**(1), 41–52 (1998).
35. K. J. Friston et al., "Statistical parametric maps in functional imaging: a general linear approach," *Human Brain Mapp.* **2**(4), 189–210 (1994).
36. A. K. Singh and I. Dan, "Exploring the false discovery rate in multichannel NIRS," *NeuroImage* **33**(2), 542–549 (2006).
37. J. Campbell, *Reference and Consciousness*, pp. 1–280, Oxford University Press, Oxford, UK (2002).
38. N. Eilan, *Joint Attention, Communication and Mind*, pp. 1–33, Oxford University Press, Oxford, UK (2005).
39. J. Heal, *Joint Attention and Understanding the Mind*, pp. 34–44, Oxford University Press, Oxford, UK (2005).
40. M. Carpenter, "Just how joint is joint action in infancy?," *Top. Cogn. Sci.* **1**(2), 380–392 (2009).
41. G. Knoblich and J. S. Jordan, "The mirror system and joint action," *Adv. Conscious. Res.* **42**(1), 115–134 (2002).
42. G. Knoblich and J. S. Jordan, "Action coordination in groups and individuals: learning anticipatory control," *J. Exp. Psychol. Learn. Mem. Cogn.* **29**(5), 1006–1016 (2003).
43. E. Pacherie, *Action*, pp. 92–111, Cambridge University Press, Cambridge (2010).
44. D. Tollefsen, "Let's pretend! Children and joint action," *Philos. Soc. Sci* **35**(1), 75–97 (2005).
45. M. Tomasello et al., "Understanding and sharing intentions: the origins of cultural cognition," *Behav. Brain Sci.* **28**(5), 675–691; discussion 691-735, (2005).
46. S. Ondobaka et al., "Interplay between action and movement intentions during social interaction," *Psycholog. Sci.* **23**(1), 30–35 (2012).
47. C. deCharms, "Applications of real-time fMRI," *Nat. Rev. Neurosci.* **9**(9), 720–729 (2008).
48. J. Egetemeir et al., "Exploring the neural basis of real-life joint action: measuring brain activation during joint table setting with functional near-infrared spectroscopy (fNIRS)," *Frontiers Human Neurosci.* **5**(5), 1–9 (2011).
49. S. Koehler et al., "The human execution/observation matching system investigated with a complex everyday task: a functional near-infrared spectroscopy (fNIRS) study," *Neurosci. Lett.* **508**(2), 73–77 (2012).
50. H. Ishida et al., "Shared mapping of own and others' bodies in visuotactile bimodal area of monkey parietal cortex," *J. Cogn. Neurosci.* **22**(1), 83–96 (2009).
51. V. Gallese, "Intentional attunement: a neurophysiological perspective on social cognition and its disruption in autism," *Brain Res.* **1079**(1), 15–24 (2006).
52. L. Minati et al., "Emotional modulation of visual cortex activity: a functional near-infrared spectroscopy study," *Neuroreport* **20**(15), 1344–1350 (2009).
53. M. M. Plichta et al., "Auditory cortex activation is modulated by emotion: a functional near-infrared spectroscopy (fNIRS) study," *NeuroImage* **55**(3), 1200–1207 (2011).
54. F. B. Haeussinger et al., "Simulation of near-infrared light absorption considering individual head and prefrontal cortex anatomy: implications for optical neuroimaging," *PLoS ONE* **6**(10), e26377 (2011).