Brain to Brain Interface

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Abstract—*This paper concentrates on the Brain to Brain interface. Scientists at the University of Washington have successfully completed what is believed to be the most complex human brain-to-brain communication experiment ever. It allowed two people located a mile apart to play a game of "20 Questions" using only their brainwaves, a nearly imperceptible flash of light, and an internet connection to communicate.[1] BBI is the combination of BCI(brain computer interface) and CBI(computer brain interface). The recent development of brain-computer interfaces (BCI) has provided an important element for the creation of brain-to-brain communication systems, and precise brain stimulation techniques are now available for the realization of non-invasive computer-brain interfaces (CBI). These technologies, BCI and CBI, can be combined to realize the vision of non-invasive, computer-mediated brain-to-brain (B2B) communication between subjects (hyperinteraction). Here we demonstrate the conscious transmission of information between human brains through the intact scalp and without intervention of motor or peripheral sensory systems. Pseudo-random binary streams encoding words were transmitted between the minds of emitter and receiver subjects separated by great distances, representing the realization of the first human brain-to-brain interface. In a series of experiments, we established internet-mediated B2B communication by combining a BCI based on voluntary motor imagery-controlled electroencephalographic (EEG) changes with a CBI inducing the conscious perception of phosphenes (light flashes) through neuronavigated, robotized transcranial magnetic stimulation (TMS), with special care taken to block sensory (tactile, visual or auditory) cues. Our results provide a critical proof-of-principle demonstration for the development of conscious B2B communication technologies. More fully developed, related implementations will open new research venues in cognitive, social and clinical neuroscience and the scientific study of consciousness. We envision that hyperinteraction technologies will eventually have a profound impact on the social structure of our civilization and raise important ethical issues.*

1. INTRODUCTION

The evolution of civilization points to a progressive increase of the interrelations between human minds, where by "mind" we mean a set of processes carried out by the brain. Until recently, the exchange of communication between minds or brains of different individuals has been supported and constrained by the sensorial and motor arsenals of our body. However, there is now the possibility of a new era in which brains will dialogue in a more direct way [2]. Previous attempts to realize this vision include demonstrations of bidirectional computer-brain communication [3]–[5] and

cortical-spinal communication [6] in the monkey, and hippocampus-to-hippocampus [7] or social communication [8] in the rat – all of invasive nature. Despite these and other significant advances with human subjects [9]–[10], invasive methods in humans remain severely limited in their practical usefulness. Pioneering research in the 60's using non-invasive means already demonstrated the voluntary control of alpha rhythm de-synchronization to send messages based on Morse code [11]. Over the last 15 years, technologies for non-invasive transmission of information from brains to computers have developed considerably, and today brain-computer interfaces embody a well-established, innovative field of study with many potential applications [12]–[16]. Recent work has demonstrated fully non-invasive human to rat B2B communication by combining motor imagery driven EEG in humans on the BCI side with ultrasound brain stimulation on the CBI-rat side [17]. However, the realization of non-invasive CBI in humans remains elusive, and adequate methodologies to provide computer-mediated non-invasive brain conscious interventions are lacking. Here we show how to link two human minds directly by integrating two neurotechnologies – BCI and CBI –, fulfilling three important conditions, namely a) being non-invasive, b) cortically based, and c) consciously driven (Fig. 1). In this framework we provide the first demonstration of non-invasive direct communication between human minds.
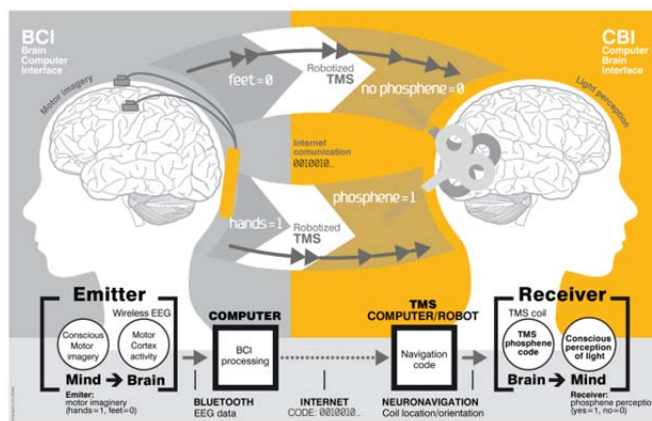

Fig. 1

2. MATERIALS AND METHODS

Human Subjects

Four healthy participants (age range 28–50) were recruited, and their informed written consent was obtained. Of the four subjects, one was assigned to the BCI branch (the *emitter* - Subject 1) and the other three to the CBI branch of the experiments (i.e., as *receivers* - Subjects 2, 3 and 4).

Ethics Statement

The Ethics Committee of the University of Barcelona, following the Ethical Principles for Medical Research Involving Human Subjects of the WMA Declaration of Helsinki, approved this study. The TMS part of the experiments was conducted according to TMS safety guidelines[18]. The individuals in this manuscript gave their written informed consent (as outlined in the PLOS consent form) to publish these case details.

Methods Summary

The computer-mediated brain-to-brain transmission from Thiruvananthapuram (Kerala state, India) (BCI side) to Strasbourg, France (CBI) was realized using internet-linked EEG and TMS technologies respectively. On the CBI side, three information *receiver* subjects were stimulated with biphasic TMS pulses at a subject-specific occipital cortex site. The intensity of pulses was adjusted for each subject so that a) one particular orientation of the TMS-induced electric field produced phosphenes [19] (representing the "active direction" and coding the bit value "1"), and b) the orthogonal direction did not produce phosphenes (representing the "silent direction" and coding the bit value "0"). Subjects reported verbally whether or not they perceived phosphenes on stimulation. A fourth subject acted as *emitter* of information using a BCI system based on motor imagery (of moving feet or hands) to select two kinds of states in EEG spectral power in the motor cortex (coding for the bit values of "0" and "1"). We ensured that receiver subjects were not relying on peripheral nervous system (PNS) cues (visual, tactile and auditory sensations produced by the TMS device) to decode the information by blocking sensory cues: we used a force sensor on the coil to maintain a constant contact pressure on the scalp, implemented a coil rotation information encoding strategy (as opposed to one relying on coil location), and had subjects wear eye mask and earplugs. We verified the effectiveness of these means in series of *d-prime* control experiments [20]–[22] comparing pairs of stimuli delivered either with the same or different orientations of the coil. Finally, as performance measures for the BCI, CBI and B2B system we analyzed error transmission rates and transmission speed (bits per minute).

3. BRAIN-COMPUTER INTERFACE

The BCI communication subsystem used in our experiments converted conscious voluntary motor imagery into brain activity changes that could be captured non-invasively as physical signals conveying information. To monitor EEG activity related with motor imagery tasks we used a wireless (500 S/s, 24 bit) EEG recording system [23] (Starstim tCS/EEG system, by Neuroelectrics, http://www.neuroelectrics.com). Eight Ag/AgCl electrodes were placed at F3, F4, T7, C3, Cz, C4, T8 and Fz scalp sites (10–20 EEG positioning system) and electrically referenced to a clip electrode placed in the right ear lobe. A spatial filter was applied to the electrodes of interest (C3, Cz and C4) by referencing them to the average potential of their neighboring electrodes. To transform EEG signals into binary information we used the BCI-2000 platform [24] implementing the detection of anatomically localized changes in EEG related with voluntary motor imagery. The emitter subject was sequentially shown on the screen a representation of the bits to be transmitted (the message). Each bit was represented either by a target cue in the downright part of the screen (bit value 0) or in the upright part (bit value 1) (Figs. 1 and 2). If the bit to be transmitted was a 1 (0), the emitter was to encode it through motor imagery of the hands (feet). These motor imagery tasks controlled the vertical movement of a ball appearing on the screen from the left with a constant horizontal speed. If the ball hit the displayed target on the right of the screen, the transmitted bit was then correctly encoded. Whatever will be the outcome the BCI encoded bits were then automatically sent via email to the CBI subsystem. Following a training period, the emitter subject was able to regularly achieve an accuracy of well over 90% in BCI encoding.
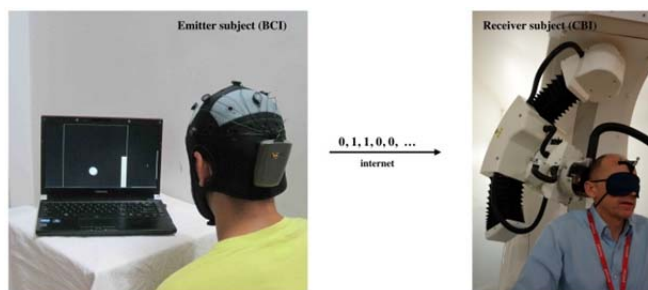

Fig. 2

4. COMPUTER-BRAIN INTERFACE

For the CBI subsystem, we relied on biphasic TMS pulses to encode information. For each receiver subject, we identified first a TMS phosphene-producing hotspot in the right visual occipital cortex (approximately 2 cm anterior and 2 cm right from inion, the precise location depending on the subject), which was used for the *active* condition (to encode the bit value '1'). We achieved the required high precision in

relocation and reorientation of the TMS target by using a neuronavigated [25]–[28], robotized TMS system (Axilum Robotics TMS-Robot, http://www.axilumrobotics.com, piloted by Localite 2.8 Neuronavigation system using the MagVenture MagPro R30 TMS Stimulator with a "butterfly" coil of type Cool-B65-RO). Subjects went through a familiarization period in which we administered several TMS pulses to the chosen right occipital cortex site using various rotations of the coil, and identified the intensity of TMS pulses (range 57–90% of maximum intensity of the coil) that optimally discriminated *active* (i.e., producing phosphenes) from *silent* (not producing phosphenes) orientations (Fig. 3). Subjects described the sensations of light produced by TMS pulses of the active orientation as having a strong, clear and reliable nature, and located at the bottom of the visual field contralateral to the stimulation site [29]. They were instructed to report verbally the presence of phosphenes immediately after TMS pulse delivery. TMS pulses were administered by the robotized TMS system controlled by a researcher sitting away from the visual field of the subject, or directly programmed into the neuronavigation computer by the BCI message sequence received via email (Fig 2). Sequences of two or three redundant TMS pulses were delivered with an inter-stimulus interval of 2 seconds.

Our first robotized CBI experiments (subject 1) used a position-dependent encoding with the TMS hotspot representing the active condition (bit $=1$) and another scalp location (displaced about 2 cm from the first) representing the silent condition (bit=0). This strategy was used for CBI transmissions of 60 bit messages with a low error rate. An associated first B2B experiment (Barcelona to Strasbourg) – carried out offline (i.e., with the BCI and CBI branches of transmission separated in time by buffering the data after BCI transmission) – resulted in a 15% transmission error rate (5% in the BCI segment and 11% in the CBI one). However, we identified the possibility that the receiver subject at the CBI end was being cued on the (active or silent) stimulation condition by PNS sensory inputs (tactile, auditory or visual) related to the repositioning of the coil at different scalp sites. In order to rule this out, we implemented a series of measures on the next experiments – including the final B2B transmissions described below. First, to avoid contact related cues and taking advantage of the anisotropic response of the visual cortex to TMS [30], we adopted the strategy of encoding bits through rotation of the TMS coil: the location and "active" orientation of the coil (producing phosphenes in most trials) were chosen with the condition that a 90° rotation of the coil on the same location did not produce phosphenes (Fig. 2). The robot was programmed to move the coil away from the scalp after the delivery of each triad of TMS pulses. A force sensor on the coil surface was used to maintain a constant contact force with the scalp in all conditions. The cable holder on the robot was adjusted to keep the coil's cable at a good distance from the subject's shoulders and back, preventing contact during coil rotation. Second, to avoid

identification of coil orientation from auditory information, subjects wore earplugs and the robot moved the coil between each pair or triads of TMS pulses towards a parking site located approximately 1 cm away from the scalp with an intermediate rotation of 45°. This forced the robot to realize a movement of similar duration and with equal noise levels for all bit transmission events, irrespective of coil orientation. Lastly, we blocked visual cues on stimulation configuration by having subjects close their eyes and wear an eye mask.

To assess the effectiveness of these measures, we carried out a series of control studies using the sensitivity index (or *d-prime*) statistic [20]–[22]. The first control studied TMS noise induced auditory cueing and had subjects (2 and 3) wear an eye mask and earplugs and receive a sequence of 32 balanced pairs of three TMS stimuli randomly interspersed over silent and active conditions. We mimicked the contact of the coil but eliminated the production of phosphenes by interposing, between coil and scalp, a single piece of foam slightly displacing ($\sim$1 cm) the center of the coil orthogonally away from the head. After the administration of each pair (of triads) of stimuli, subjects were asked if they were delivered with the equal or different orientations. Then, we performed a second control experiment to evaluate cues from (tactile) skin contact, based on another sequence of 32 balanced pairs, without foam on the coil but setting a null intensity in the magnetic stimulator. Results from these tests indicated with high confidence that, after correct blinding of auditory, visual or tactile cues, the subjects were unable to distinguish coil orientations in the absence of actual phosphene-inducing TMS pulses (Subject 2: d'=0.0 in the auditory task, d'=−0.1 in the skin contact task; Subject 3: d'=0.6 in the auditory task, d'=0.1 in the skin task).

5. CONCLUSION

The final round of experiments targeted the demonstration of online brain-to-brain transmission of information between remotely located subjects. On March 28th, 2014, 140 bits were encoded by the BCI emitter in Thiruvananthapuram and automatically sent via email to Strasbourg, where the CBI receiver (subject 3) was located. There, a program parsed incoming emails to navigate the robot and deliver TMS pulses precisely over the selected site and with the appropriate coil orientation. A similar transmission with receiver subject 2 took place on April 7th, 2014. In both cases, the transmitted pseudo-random sequences carried encrypted messages encoding a word – "*hola*" ("*hello*" in Catalan or Spanish) in the first transmission, "*ciao*" ("hello" or "goodbye" in Italian) in the second. Words were encoded using a 5-bit Bacon cipher [31] (employing 20 bits) and replicated for redundancy 7 times (for a total of 140 bits). The resulting bit streams were then randomized using random cyphers selected to produce balanced pseudo-random sequences of 0's and 1's (for subject blinding and proper statistical analysis purposes in addition to providing word-coding). On reception, de-cyphering and

majority voting from the copies of the word were used to decode the message.

In these experiments, the individual BCI and CBI segments as well as the complete B2B link provided transmission of pseudo-random information with excellent integrity. In the first experiment the transmission error rates were of 6%, 5% and 11% for the BCI, CBI and the combined B2B components respectively, and in the second, error rates were of 2%, 1% and 4% respectively. We note that the probability of transmission of lists of 140 items having occurred with the low observed error rates or less by chance is negligible ($p<10^{-22}$). For example, the probability of guessing correctly 140 random, balanced bits with an error rate of 20% (28 errors out of 140) or less is extremely low, this being equivalent to obtaining 112 heads or more after 140 tosses of a fair coin ($p<10^{-13}$).

BCI and CBI transmission rates were of 3 and 2 bits per minute respectively. The overall B2B transmission speed was of 2 bits per minute (limited by the CBI branch). The encoded words were transmitted with full integrity by all links – BCI, CBI and B2B.

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