A Direct Brain-to-Brain Interface in Humans

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Abstract

We describe, to our knowledge, the first direct brain-to-brain interface between two humans. The interface is noninvasive and combines electroencephalography (EEG) for recording brain signals with transcranial magnetic stimulation (TMS) for delivering information to the brain. We demonstrate our method using a visuomotor task in which two humans must cooperate through direct brain-to-brain communication to achieve a desired goal in a computer game. The brain-to-brain interface detects motor imagery in EEG signals recorded from one subject (the “sender”) and transmits this information over the internet to the motor cortex region of a second subject (the “receiver”). This allows the sender to cause a desired motor response in the receiver (a press on a touchpad) via TMS. We quantify the performance of the brain-to-brain interface in terms of the amount of information transmitted as well as the accuracies attained in (1) decoding the sender’s signals, (2) generating a motor response from the receiver upon stimulation, and (3) achieving the overall goal in the visuomotor task. Our results provide evidence for a rudimentary form of direct information transmission from one human brain to another using noninvasive means.

Introduction

Many of the greatest contemporary technological developments have centered on advancing human communication. From the telegraph to the Internet, the primary utility of these game-changing innovations has been to facilitate communication by increasing the range of audiences that an individual can reach. However, all current methods for communicating are inherently limited by the words and symbols available to the sender and understood by the receiver.

These constraints can sometimes be severe. A great deal of the information that is available to our brain is not introspectively available to our consciousness, and thus cannot be voluntarily put in linguistic form. For instance, knowledge about one's own fine motor control is completely opaque to the subject [1], and thus cannot be verbalized. As a consequence, a trained surgeon or a skilled violinist cannot simply "tell" a novice how to exactly position and move the fingers during the execution of critical hand movements. But even knowledge that is introspectively available can be difficult to verbalize. Brilliant teachers may struggle to express abstract scientific concepts in language [2], and everyone is familiar with the difficulty of putting one's own feelings into words. Even when knowledge can be expressed in words, one might face the hurdle of translating between the many existing spoken human languages. In all of these circumstances, can information that is available in the brain be transferred directly in the form of the neural code, bypassing language altogether? We explore this idea in the rest of this article.

The idea of direct brain-to-brain communication could potentially be achieved using a brain-to-brain interface (BBI) [3,4]. A BBI relies on two pillars: the capacity to read (or "decode") useful information from neural activity and the capacity to write (or "encode") digital information back into neural activity. In recent years, we have witnessed incredible progress in these two capabilities with the development of Brain-Computer Interfaces, or BCIs [5,6]. BCI researchers have demonstrated the possibility of decoding motor [7], visual [8] and even conceptual information [9] from neural activity via a range of recording techniques such as implanted electrodes [7], electrocorticography (ECoG, e.g., [10]), electroencephalography (EEG, e.g., [11]), functional MRI (e.g., [12]), and magnetoencephalography (MEG, e.g., [13]). A variety of stimulation techniques also exist that permit users to transform digital information into neural activity using implanted electrodes [14, 15], transcranial magnetic stimulation, (TMS, [16]) and focused ultrasound (FUS, [17]). Prominent examples of BCIs that use stimulation include the cochlear implant [14] and deep brain stimulators [15].

Given these advances in BCIs, two recent efforts have addressed the question of whether direct brain-to-brain communication is possible with the technology we have today. Pais-Vieira and colleagues [3] explored the possibility of directly connecting the brains of two awake and behaving rats. In their experiment, cortical microelectrode arrays recorded the neural activity of “encoder” rats performing either a motor task or a tactile stimulation task, and guided the stimulation of motor and sensory areas in the brains of “decoder” rats. Because the actions of “decoder” rats mimicked those of the original “encoder” rats, the authors concluded that information had to have been transferred between their brains. An alternative BBI was proposed by Yoo and colleagues [4], who successfully demonstrated the transmission of information from a human brain to a rat brain. In this case, visual evoked potentials in the human brain were recorded with EEG and translated into FUS-based stimulation of the part of motor cortex that controlled the tail of the anesthetized rat.

Both of these BBIs rely on stimulation technologies that are either invasive or experimental in humans, and thus are currently confined to animal models. In this paper, we demonstrate direct transmission of information from one brain to another using only non-invasive technologies that can be safely applied to humans. Specifically, we show that it is possible to use EEG to decode motor intentions from a “sender” brain, and TMS to deliver an equivalent motor command to the motor cortex of a “receiver” brain, allowing the receiver to perform the hand movement that was intended by the sender. To test the feasibility and applicability of this procedure, a task was designed that required cooperative information sharing between pairs of participants along the BBI. Preliminary results from a pilot study of our BBI were announced in an online report in August 2013 [18]. This article describes the BBI in detail and presents in-depth results from 6 human participants who played the role of either sender or receiver of information in the BBI.

Materials and Methods

Participants

Six participants (aged 21-38; see Table 1) took part in the experiment over the course of three months. All participants were recruited through word of mouth, were fully informed about the experimental procedure and its potential risks and benefits, and gave written consent prior to the beginning of the experiment. They were divided into three pairs, with one participant playing the role of the “sender” and one playing the role of the “receiver.” Participants were free to decide which role they wanted to play, and received monetary compensation that was independent of their role and proportional to the total amount of time devoted to the study. Both the experiment and its recruitment procedure were reviewed and approved by the Institutional Review Board of the University of Washington.

Experimental Task

During each experimental session, two participants had to carry out a specific task in the form of a series of consecutive trials of a computer game. The game was designed so that the two participants had to play cooperatively, and the required cooperation could only be achieved through direct brain-to-brain communication (Figure 1A). The goal of the game (Figure 1B) was to defend a city (which is located beyond the left visible part of the screen) from enemy rockets fired by a pirate ship on the lower right portion of the screen (represented by a skull-and-bones insignia). The rockets followed an arc trajectory, traversing the screen from the lower right (where the ship was located) to the upper left corner of the screen, beyond which the city was located. A cannon, located in the lower center portion of the screen, tracked the rocket as it crossed the screen. To defend the city, the subjects had to fire the cannon by pressing a touchpad. If the cannon was fired before the moving rocket reached the city, the rocket was destroyed and the city was saved. In 50% of the trials, a friendly "supply airplane" flew across the screen instead of a pirate rocket. In such trials, participants had to avoid firing the cannon to let the supply airplane enter the city.

Brain-to-Brain Collaboration Between the Two Participants

The two participants were given different and complementary roles. One participant (henceforth, the "Sender") was able to see the game on a computer screen, but was not provided with any input device to control the cannon (Figure 2, Sender watching the game screen, which is not shown). The second participant (henceforth, the “Receiver”) could use his/her right hand to press a touchpad, but could not see the game. The two participants were located in separate buildings on the University of Washington’s campus. Specifically, the Sender side was stationed in the Neural Systems Laboratory (NSL) in the Computer Science & Engineering building while the Receiver side was stationed in the Cognition and Cortical Dynamics Laboratory (CCDL) in the Psychology building. The two participants could only communicate with each other through a brain-to-brain communication channel.

The brain-to-brain communication channel was built using two existing technologies: EEG for noninvasively recording brain signals from the scalp and TMS for noninvasively stimulating the brain (Figure 1A). During rocket trials, the sender conveyed the intent to fire the cannon by engaging in right hand motor imagery. Electrical brain activity from the Sender was recorded using EEG, and the resultant signal was used to control the vertical movement of a cursor (Figure 1B). When the cursor hit the “Fire" target (large circle) located at the top of the screen, the NSL computer transmitted a signal over the Internet to the CCDL computer. The two computers communicated using the standard hypertext transfer protocol (HTTP).

The CCDL computer was connected through a custom-made serial cable to a TMS machine. Whenever the CCDL computer received a fire command, a TMS pulse was delivered to a pre-selected region of the Receiver's brain. The stimulation caused a quick upward jerk of the Receiver's right hand, which was positioned above the touchpad. This up-down movement of the hand typically resulted in enough force to trigger a “click” event on the touchpad, causing the cannon in the computer game to be fired as requested by the Sender. In successful “supply airplane” trials, the Sender would rest and refrain from motor imagery, allowing the cursor to drift towards the bottom of the screen; in such trials, no signal was sent to the CCDL computer.

Procedure

Each experiment consisted of two experimental blocks and two control blocks (10 trials in each block for Pair 1, 16 trials in each block for Pairs 2 and 3), the order of which was randomized prior to the beginning of the experiment. Participants were told in advance of the presence of two conditions, but were not told to which condition each block belonged. Trials were separated by 2 seconds of set-up time plus a 20 second visual countdown. This large pause prevented two consecutive TMS pulses from being delivered less than 20 seconds apart, thus reducing the maximum amount of magnetic stimulation delivered to the Receiver to a level well below the strictest safety guidelines [19], and setting the upper limit of information throughput to 0.05 bits per second. During the experimental blocks, the non-invasive brain-to-brain channel was fully operational. However, during the control blocks the brain-to-brain channel was made non-operational by changing the coil position so that the TMS pulse could not cause the desired movement of the right hand.

EEG Procedure

Participants playing the role of the Sender came in for two consecutive sessions: a training session and the BBI experimental session. During both sessions, electrical signals were recorded at a frequency of 512 Hz from the Sender's scalp via a 64-channel Ag/AgCl electrode cap (actiCAP, Brain Products GmBH, Gilching, Germany) and amplified using gUSBamps (Guger Technologies, Austria). A Laplacian spatial filter [6] was used to reduce artifacts common to nearby electrodes and emphasize local activity. Signal processing and data storage were managed through the BCI2000 software package.

Changes in the "mu" band (typically 8-12 Hz) have long been linked to motor imagery signals and used in BCIs (for an introduction, see [5,6]). During the training session, subjects learned to control the vertical movement of a 1-D cursor by imagining right hand movement. The power in a low frequency band (the "mu" band) was computed across the electrodes and the electrode most correlated with the subject's motor imagery during an initial training period was selected as the control electrode for the task. The computer translated the power in the mu band to vertical movement of a cursor (Figure 1B). Specifically, the decrease in power that accompanied right hand motor imagery was mapped to upward movement of the cursor, while a lack of suppression in the mu band caused downward cursor movement (see Figure 3 for an example).

During the experimental session, a monitor displayed both the cursor window and the cannon game (Figure 1B). Depending on the type of projectile in each trial, the Sender modulated activity in the mu band to guide the cursor to either the “Fire” target at the top of the screen or towards the bottom of the screen.

TMS Procedure

Participants playing the role of the Receiver came in for two consecutive sessions. During the first session, as part of informed consent, they were asked to complete a TMS safety screening questionnaire, aimed at identifying potential conditions (such as family history of seizures or frequent migraines) that might represent potential risk factors for adverse side effects of TMS. One participant was rejected for failing the safety questionnaire.

Participants who passed the safety questionnaire underwent a TMS parameter estimation session, whereby the appropriate stimulation site and intensity was identified. The procedure worked as follows. The participant was asked to wear a tight-fitting swim cap, where the location of the inion and the vertex were identified using the 10-20 system procedure [6]. A 4x4 grid of dots were marked on the up and to the left of the vertex, each dot placed at a distance of 1cm from its neighbors. Each dot was then stimulated in sequence, using a 70mm MagStim circle coil connected to a Super Rapid^2 magnetic stimulator (MagStim, UK). This search procedure continued until an ideal position was found to stimulate the motor region that controls the *extensor carpi radialis*. Notice that, because this muscle *extends* the wrist, it produces an *upward* movement of the hand.

The circle coil was always placed so that it was flush against the head, the current was flowing in clock-wise direction ("B" side), and the coil handle pointed horizontally and leftwards from the participant's head (Figure 4). The threshold was estimated as the minimum amount of power that was needed to solicit a consistent upward response of the hand. Once identified, the coil position and the stimulation intensity were marked on the cap, and the cap was put in a sealed envelope to be re-used in the experimental session. The parameter estimation session lasted between 10 and 30 minutes. The stimulation parameters for the three participants who played the role of receivers are given in Figure 4.

During the experimental session, the returning participant wore the same cap while sitting on a BrainSight (Rogue Resolutions, Montreal, CA) anatomical chair designed for TMS. The participant's head was accommodated on a neck rest (Figure 5A) and kept in position by an adjustable arm equipped with padded forehead prongs (Figure 5B). The participants left arm was accommodated on the chair's armrest. The chair's right armrest was removed, and the participants' right arm was placed on an adjustable table, so that the four non-opposable fingers of the right hand rested on a wireless Logitech T650 touchpad (Logitech, Morges, Switzerland) connected to the CCDL computer. Note that, because the TMS pulse causes an upward jerk of the hand, the touchpad is actually pressed during the downward part of the moment, when the hand falls back in position. Before the experiment, the TMS coil (Figure 5C) was mounted on a Manfrotto (Cassola, Italy) dual rod articulated arm (Figure 5D) connected to the left swinging arm of the Brainsight chair.

To keep the Receiver subjects blind to the course of the experiment, the TMS room was set up so that they were facing a blank wall with their back to the experimenter and experimental devices, including the TMS computer and the TMS device. In addition, participants were required to wear a pair of Bose (Framingham, MA) QuiteComfort 20/20i noise cancellation earphones. Before the beginning of the experiment, participants were instructed to bring either music or an audiobook of their choice to be played through the earphones. As a result, the TMS participants were not given any visual or acoustic cues about the experiment. At the beginning of each new experimental block, the TMS experimenter moved the TMS coil away from the participant's head, and changed the position of the coil according to the experimental condition. During experimental blocks, the coil was placed in the exact same position determined during the parameter estimation session. During the control blocks, the position of the coil was changed so that, with the same power output, it could not trigger a hand response. Specifically, the coil was simply rotated 180 degrees on the axis of its handle, so that its electrical current was flowing in counter-clockwise fashion ("A" side facing up). None of the participants could distinguish between the two coil positions.

Results

Overall Accuracy in the Experimental Task

Because our task was designed so that it could be carried out successfully only if participants cooperated though the BBI, one way to gauge the efficacy of our BBI was to examine each pair's accuracy during the game, and specifically to compare the pair's accuracy during the experimental and the control blocks. Overall, the three pairs of subjects correctly identified and destroyed 83.3%, 25.0%, and 37.5% of the rockets respectively during the experimental blocks, and 0% of the rockets during the control blocks (see Table 2). The difference between conditions indicates that the BBI was crucial in enabling the two participants to collaborate. Figure 3 shows an example of a successful BBI trial by Pair 1.

The percentage of rockets that were identified and destroyed provides only a partial measure of the participants' behavior. Each experimental trial can be categorized as a "true positive" (a rocket correctly destroyed), a "false positive" (supply airplane that was mistakenly destroyed), a "false negative" (a rocket that was not destroyed), or a "true negative rejection" (supply airplane that was allowed to fly by). Therefore, the collaboration between the two subjects in the three pairs can be quantified using signal detection theory, and in particular, by calculating the area under the corresponding Receiver Operating Characteristic (ROC) curve [20]. Because the ROC curve plots the proportion of true positives against the proportion of false positives, optimal performance corresponds to an area of 1, and chance performance corresponds to an area of 0.5. The results of ROC analysis for the BBI interface are visually represented in the first row of Figure 6. In each plot, the red line represents the ROC curve for the experimental condition, and the grey line represents the ROC curve for the control condition. From the ROC curves, it is apparent that Pairs 1 and 3 were overall successful in cooperatively playing the game (i.e., the area under the red ROC curve was larger than 0.5, and larger than the area under the grey ROC curve), while Pair 2 was not (the grey and red curves have approximately the same areas) due to poor discriminability of the Sender's EEG signals as discussed below.

Behavioral and EEG Data for the Senders

Because of the cooperative nature of the task, the overall performance of the pair is constrained by the performance of both the sender and the receiver. Thus, poor performance of the pair might not accurately reflect the efficacy of the BBI per se, but only of one of the two participants. For this reason, we estimated the ROC curves for each sender and receiver separately. In the case of the sender, the ground truth is represented by the object on the screen (supply plane or rocket) and the response by the participant's success in moving the vertical cursor to the target. Thus, moving the cursor upward in response to a rocket represents a true positive, while moving the cursor upward in response to a plane a false positive. In the case of the receiver, the ground truth is the TMS pulse, and the desired motor response is the corresponding touchpad press. Thus, a touchpad press in response to a TMS pulse is a true positive whereas a press without a TMS pulse is a false positive.

When the ROC curves for the Sender and the Receiver are plotted separately (Figure 6, middle and bottom rows), it becomes apparent that Pair 2's poor performance was due to the Sender's failure to consistently move the cursor upward to the "Fire" target during rocket trials. This is confirmed by an inspection of the task-related EEG activity of the three senders as summarized in Figure 7. Each panel in the figure plots the power of a Sender's brain activity in the subject-specific mu control band during the 2.5 seconds before the cursor hit the target and a "Fire" command was sent to the TMS machine (rocket trials are plotted in red while airplane trials are plotted in blue). Notice how, in the 2.5 seconds preceding a response, the EEG activity for rocket versus airplane trials are well separated for the Senders in Pair 1 (top panel) and Pair 3 (bottom panel). This separation is indicative of the Sender's capacity to control the cursor's position by engaging in motor imagery and successfully reducing mu band activity during the rocket trials. In contrast, EEG activity was essentially identical for rocket versus airplane trials in the case of Pair 2 (middle panel), suggesting that the Sender, though successful in completing the initial training session, was unable to properly control the cursor during the BBI experiment, resulting in poor overall BBI performance for Pair 2.

Behavioral Data for the Receivers

The performance of the three receivers was close to optimal in all the experimental blocks (Figure 6, third row). Thus, even when a Sender's EEG signals could not successfully discriminate between planes and rockets (as in the case of Pair 2), the BBI system worked properly, and the two subjects could still collaborate on the task (albeit with low accuracy).

In contrast to the senders, the receivers' performance was at a minimum during the control condition (corresponding to 0% of rockets correctly identified: see Table 2), reflecting the expected lack of response when the brain-to-brain channel was blocked. Notice that while the receivers' performance varied as a function of the experimental condition (as evidenced by the difference between red and grey curves in the bottom row of Figure 6), the performance of the senders was unaffected by this manipulation, reflecting the fact that the manipulation of the BBI control condition did not affect their behavior. This fact rules out the possibility that the apparent drop in performance during the control condition was due to the Sender not responding.

Finally, it is worth noting the extremely low rates of false positives across the receivers' responses (only one response was recorded in the absence of TMS stimulation), as well as the complete lack of touchpad presses during the control blocks. These facts lend support to our statement that the Receiver could receive information only through the BBI. If the Receiver was responding based on an arbitrary strategy, or responding to some environmental cue (e.g., residual noise of the TMS pulse), then at least *some* false positives would be expected, at least at the beginning of the control blocks.

Measures of BBI Efficacy

A more specific measure of the efficacy of the BBI is the degree to which a behavioral response of the Receiver can be ascribed to a pulse that was sent by the Sender, rather than to chance or response guessing. This measure can be computed by creating two binary vectors S and R for each block, each element of which corresponds to a single trial. Of these two vectors, S represents the Sender's performance, and contains 1s if the Sender delivered a "Fire" command to the Receiver, and 0s if no "Fire" command was sent. The Receiver's vector R, on the other hand, contains 1s if the Receiver pressed the touchpad during the trial, and 0s if the touchpad was not pressed. The efficacy of the BBI is proportional to the extent to which R is explained by S, which in turn can be measured by the slope coefficient β in a linear regression model $R = \alpha + \beta * S$. Note that, if the Receiver responds randomly, then the two vectors are completely uncorrelated, and $\beta = 0$. On the other hand, when the two vectors are identical and perfectly correlated, then $\beta = 1$.

Figure 8 visually depicts the S and R vectors across all pairs of participants and all blocks, as well as the values of β for each block (blue dashed line). In all six experimental blocks, the value of β was significantly greater than zero, ranging from $\beta = 0.4$ (Pair 3, second experimental block, $F(1,14) = 6.42$, $p = 0.02$) to $\beta = 1$ (Pair 3, first experimental block). Also, $\beta = 0$ in all six control blocks. Thus, by establishing that the effect of the sender's pulses on the receivers' responses is greater than expected by chance, we are also implicitly establishing that the effect is significantly greater in the experimental conditions than in the control conditions, as would be expected from a working BBI system.

Finally, it is useful to calculate the amount of information that was effectively transmitted between a Sender and a Receiver. This can be estimated by calculating the mutual information [21] between the Sender and Receiver response vectors, i.e. $I(S, R)$ (see Figure 8, red line, and Table 3). Because the value of $I(S, R)$ ranges between 0 and 1 and is expressed in bits, the total amount of information transferred during a block can be estimated by multiplying $I(S, R)$ by the number of trials within that block. The results of these calculations, given in Table 3, show that no information was transferred during the control blocks, while between 4 and 13 bits were transferred from one brain to the other during each experimental block.

Discussion and Conclusion

Our results show that information extracted from one brain using EEG can be transmitted noninvasively to another brain using TMS, ultimately allowing two humans to cooperatively perform a task using only a direct brain-to-brain interface (BBI) as a channel of communication. To the best of our knowledge, this is the first demonstration of a working BBI in humans.

We believe that our results are noteworthy on at least three fronts. First, they show that current technology is sufficient to develop devices for rudimentary brain-to-brain information transmission in humans. Such devices, which have been a long-cherished dream of science fiction writers, have the potential to not only revolutionize how humans communicate and collaborate, but also open a new avenue for investigating brain function. Second, our results show that working BBIs can be built out of non-invasive technologies. Because non-invasive technologies are currently simpler and safer for humans than invasive, surgically implanted devices, they have a potentially wider range of applicability, and could be used to develop BBIs in humans for a diverse array of tasks compared to animal BBIs. Third, by demonstrating a proof-of-concept BBI in humans, our results highlight the need for accelerating discussions between ethicists, neuroscientists, and regulatory agencies on the ethical, moral, and societal implications of BBIs whose future capabilities may go well beyond the rudimentary type of information transmission we have demonstrated here.

In comparison to invasive tools for stimulation [14,15], non-invasive technologies, such as TMS or transcranial current stimulation (tCS: [22]) are currently more limited in both the number of available stimulation sites and the spatial resolution of stimulation targets. Thus, the development of BBIs that can truly replace or augment current means of human communication depends on significantly improving these technologies, or developing alternatives (such as focused ultrasound (FUS): [3, 17]). However, current established technologies like TMS or tCS could still be used in interesting ways beyond what we have demonstrated here. For example, rather than focusing on the transfer of motor intention information, TMS could theoretically be applied to almost any area of the cortex that is close to the skull. We are thus exploring extensions of our BBI, including a BBI for transfer of visual information via stimulation of the occipital lobe, which is known to induce visual percepts localized in the visual field [23]. In contrast to motor information, visual information can be consciously processed by the receiver, thus potentially increasing the amount of collaboration possible between the two subjects.

Because the neural underpinnings of sensorimotor information are much better understood than those of conceptual and abstract information [24, 25], BBIs in the near future will likely be limited to transmitting visual, auditory, or motor information. In the long term, the development of more powerful BBIs will be predicated on understanding how abstract thoughts and complex cognitive information are encoded within distributed patterns of neural activity in the human brain. We see this as both a challenge and an opportunity for future research.

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Tables

Table 1: Participant demographics.

Pair	**Role**	**Age**	**Gender**
Pair 1	Sender	21	M
	Receiver	30	M
Pair 2	Sender	23	M
	Receiver	27	M
Pair 3	Sender	27	M
	Receiver	38	M

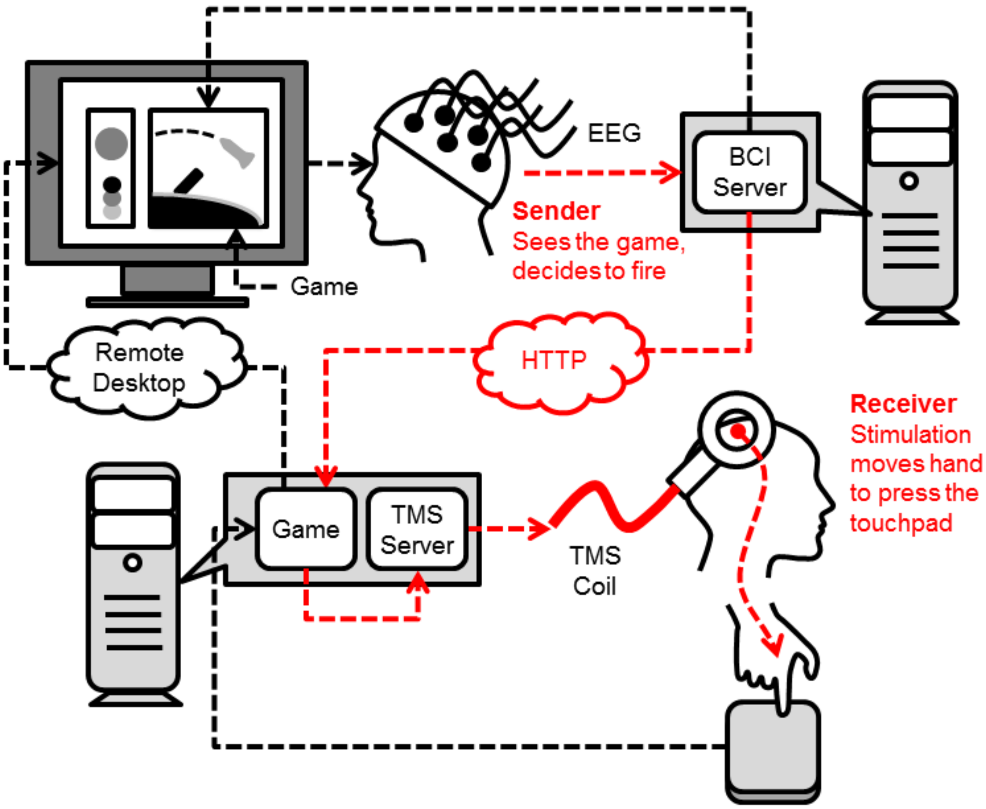
Table 2: Percentage of rockets correctly identified by pair.

	Condition	Pair 1	Pair 2	Pair 3
% Rockets Identified	Experimental	83.33%	25.00%	37.50%
	Control	0.00%	0.00%	0.00%

Table 3: Mutual information between Sender and Receiver response vectors across the different conditions and pairs of participants. Values in parenthesis indicate the total number of bits transferred during the corresponding block.

	Experimental Blocks		**Control Blocks**	
	First	**Second**	**First**	**Second**
Pair 1	0.39 (3.95)	0.45 (4.46)	0.00 (0.00)	0.00 (0.00)
Pair 2	0.65 (10.44)	0.64 (8.70)	0.00 (0.00)	0.00 (0.00)
Pair 3	0.81 (12.98)	0.24 (3.84)	0.00 (0.00)	0.00 (0.00)

Figures



A

B

Figure 1. Experimental Set-Up. (A) Schematic diagram of set-up. Brain signals from one participant (the "Sender") were recorded using EEG. When imagined hand movements were detected by the computer, a "Fire" command was transmitted over the internet to the TMS machine, which caused an upward movement of the right hand of a second participant (the "Receiver"), resulting in a press by the hand on a touchpad. This press triggered the firing of the cannon in the game seen by the Sender. Red lines mark the part of the architecture that corresponds to the direct brain-to-brain interface. (B) Screen shot from the game. In 50% of the trials, the pirate ship on the right side (skull-and-bones) shoots a

rocket towards a city on the left. The Sender engages in motor imagery to move the white cursor on the left to hit the blue circular target in order to destroy the rocket before it reaches the city. In the other 50% of the trials, a supply airplane moves from the right to the left side of the screen (not shown). The Sender rests in this case and refrains from imagery in order to avoid hitting the target.

Figure 2. EEG Set-Up. EEG signals being recorded from a subject (the "Sender") as the subject watches the computer game (the game screen is to the left and not shown in the picture). The larger screen displays EEG signals processed by the BCI2000 software. The smaller laptop screen placed further away is from the live Skype session and shows a “Receiver” subject in the TMS lab across the University of Washington campus. (Image from the pilot study referred to in the text).

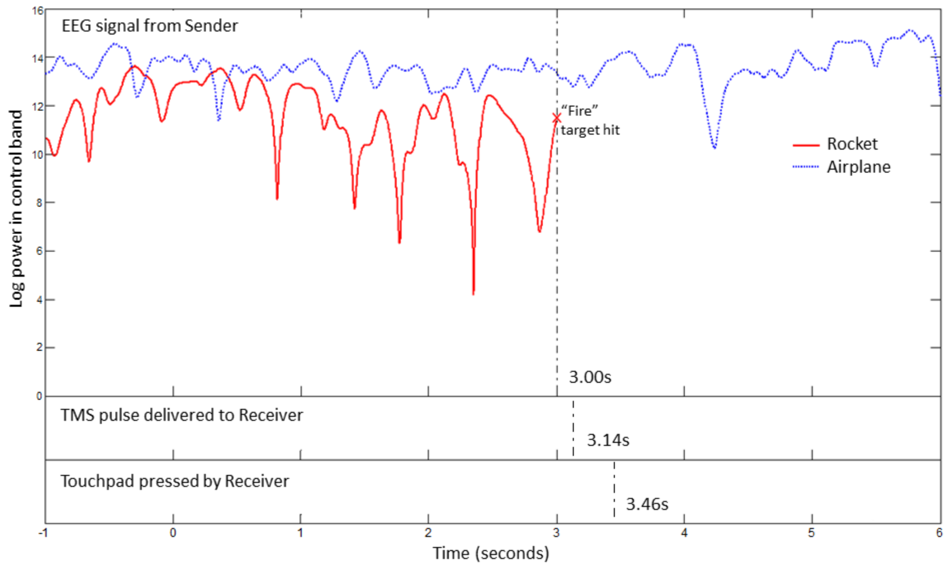


Figure 3: EEG Traces during the Two Trial Types and Timing of Information Transfer from Sender to Receiver during a Rocket Trial. EEG signal during one rocket trial (red trace) and one airplane trial (blue trace) from the Sender in Pair 1 is shown, demonstrating suppression of power in the mu control band (11-13 Hz) during motor imagery. Dashed vertical lines mark timestamps of key events in the transfer of information in the BBI from Sender to Receiver during a single rocket trial.

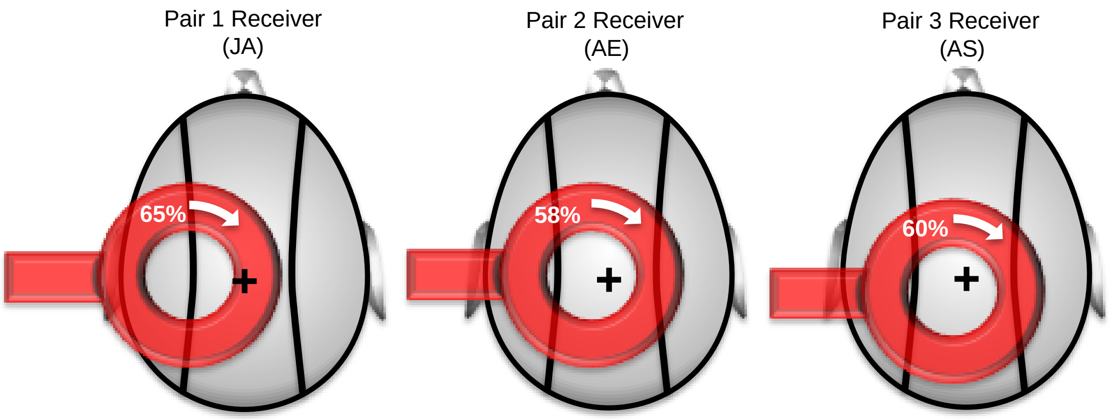


Figure 4. Stimulation Parameters for the Three Receivers. The figure represents the approximate position of the TMS circle coil (in red) on the head of the three participants. The "+" sign represents the location of the vertex. The white arrow shows the direction of the inducing current in the coil; the numbers represent the percentages of stimulator output used for each Receiver during the experiment.

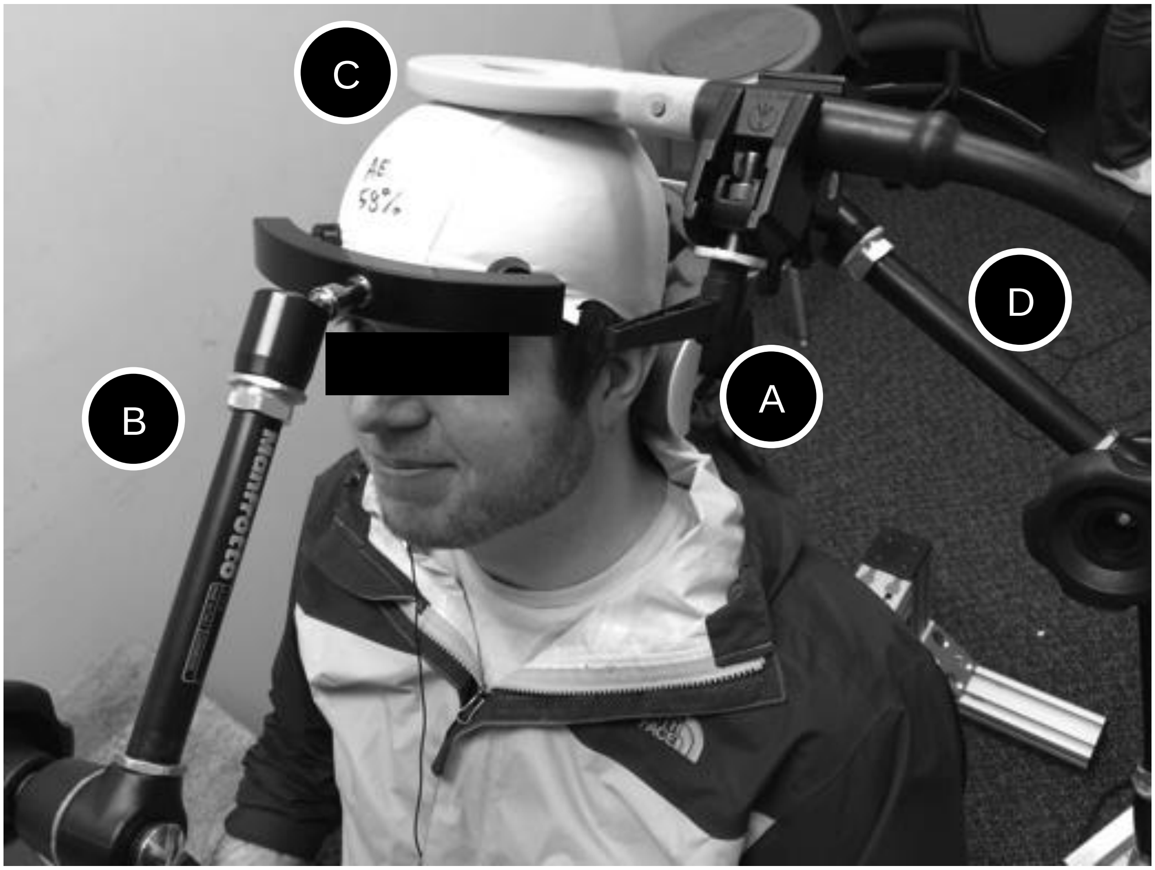


Figure 5. TMS Set-Up. During the experiment, the receiver was accommodated on a BrainSight chair, with the back of the head resting against a neckrest (A) and kept in place by an adjustable arm with padded forehead prongs (B). A 70mm circle TMS coil (C) was kept in place by an articulated arm (D). During the experiment, the receiver wore noise-cancellation earphones while listening to a selection of music or to an audiobook of his/her own choice.

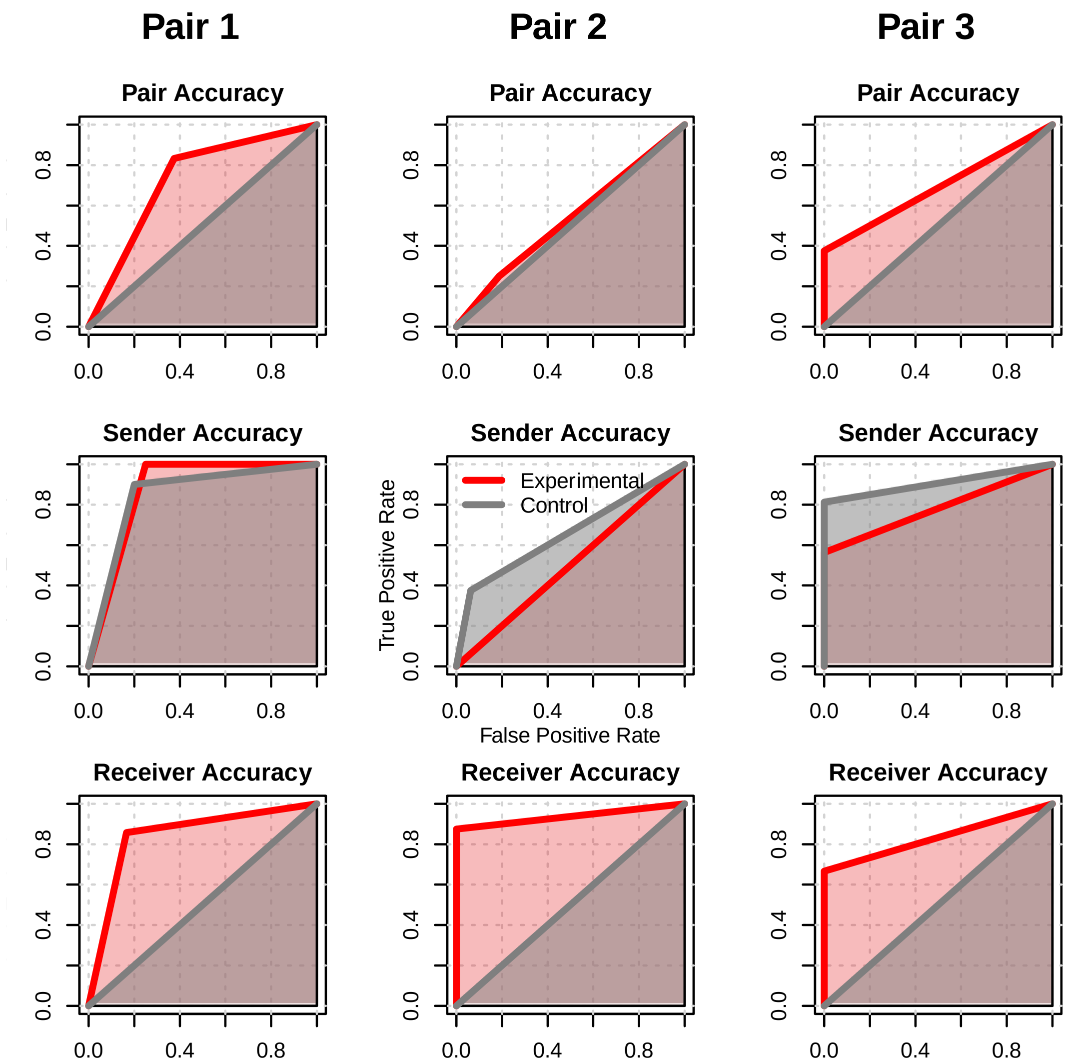


Figure 6. BBI Accuracy. ROC curves for each of the three pairs of subjects (columns), presented in terms of overall pair accuracy in the game (top panels), accuracy of the Sender (middle panels), and accuracy of the Receiver (bottom panels). Red lines and areas represent the experimental conditions, while grey lines and areas represent the control conditions.

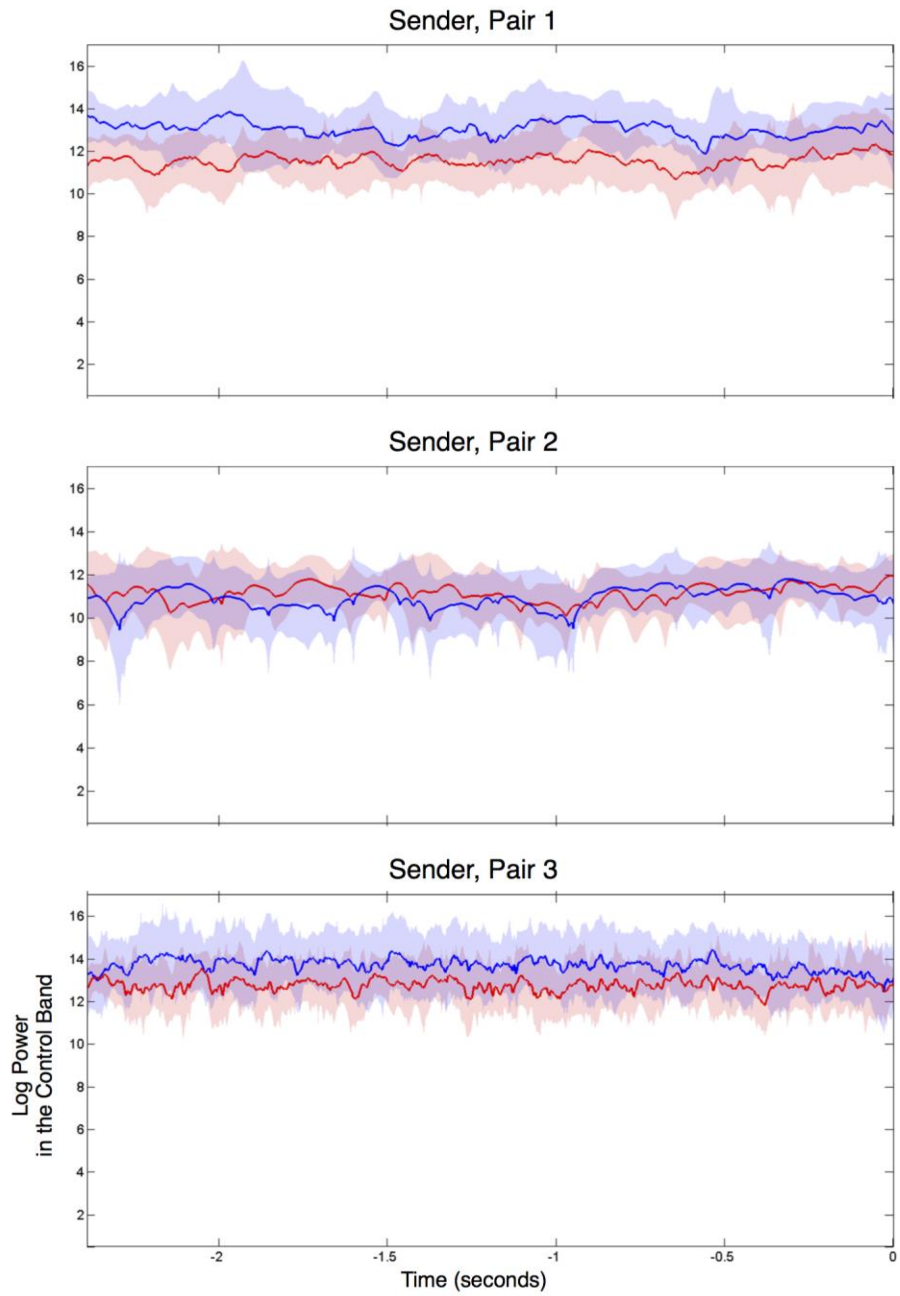


Figure 7: **Task-related EEG Activity for the Senders in the Three BBI Pairs.** Each panel shows the log power (mean +/- standard deviation) in the control band for a Sender during the final 2.5s of all rocket (red) and airplane (blue) trials. The control bands were as follows: Pair 1: 11-13 Hz; Pair 2: 18-20 Hz; Pair 3: 11-28 Hz. There is a clear separation in EEG control signals for the two types of trials for the Senders in Pairs 1 and 3, but not in Pair 2.

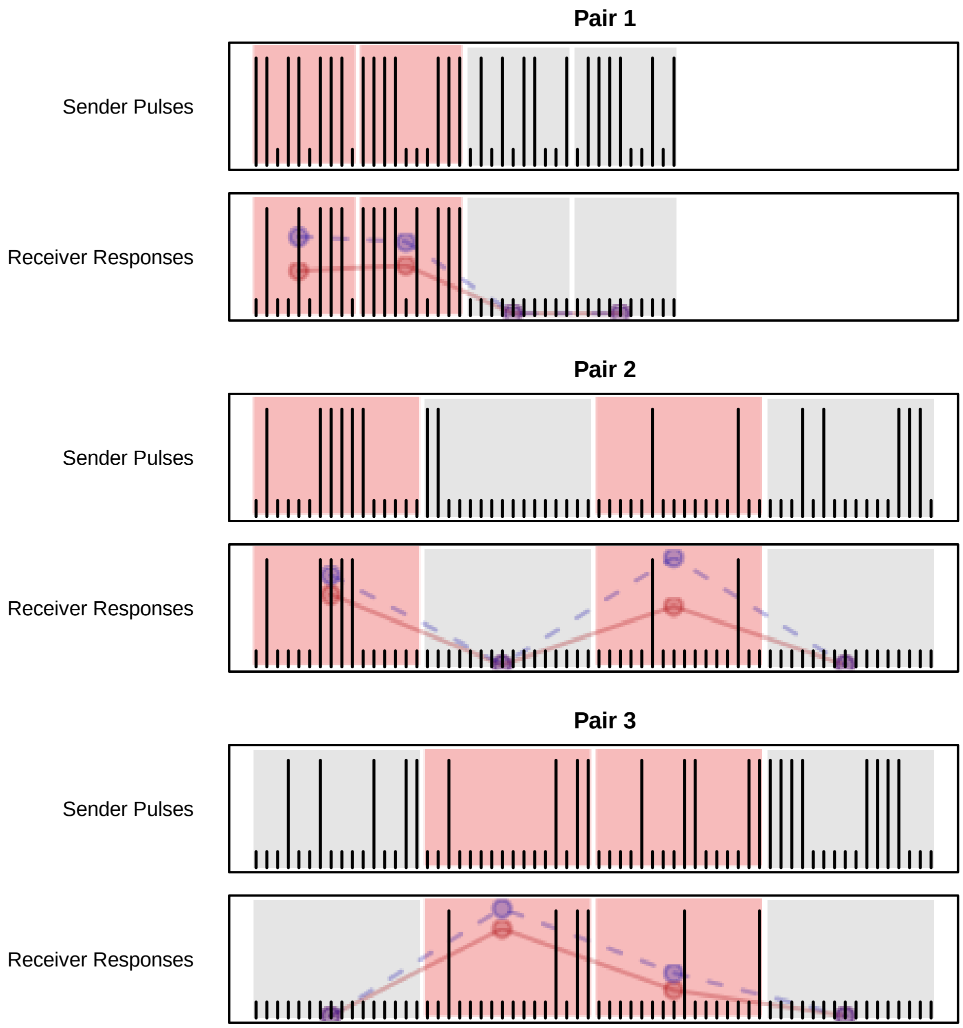


Figure 8: Response Vectors for the Sender and Receiver across Three Pairs. Each vertical tick represents a trial; long lines represent behavioral responses. Experimental blocks are marked by a red background; control blocks by a grey background. The blue dashed line represents the block-specific value of the regression coefficient β (see text for details); the red line represents the block-specific value of the mutual information between the two vectors. Note that in all six experimental blocks, the value of β was significantly greater than zero while in all control blocks, the value is zero. Likewise, 4 to 13 bits of information were transferred from one brain to another during experimental blocks, compared to zero bits in the control blocks.