Letter

Electroencephalography/sonication-mediated human brain–brain interfacing technology

Byoung-Kyong Min[1] **and Klaus-Robert Müller**[1,2]

[1] Department of Brain and Cognitive Engineering, Korea University, Seoul 136-713, Korea
[2] Machine Learning Group, Berlin Institute of Technology, Berlin 10587, Germany

Would it not be nice to be able to communicate between two brains using the full bandwidth of thought? Recent advances in brain–computer interfacing technology suggest future possibilities for direct communication between brains [1–3]. Accurate techniques for decoding brain signals [2] and stimulating brain structures [3] shed light on the feasibility of brain-to-brain coupling. Since the recent conceptual development of a brain-to-brain interface, a limited number of studies have investigated how brain signals can be transferred directly from one animal brain to another in an invasive manner [4], or from a human brain to an animal brain noninvasively [5]. The ultimate goal of this technology is to find a practical way to accomplish noninvasive, bidirectional human-to-human neural communication. In this paper, we suggest feasible techniques for accomplishing neural transfer between two human brains, and propose plausible methods using currently available technology.

In order to examine human brain-to-brain interfacing, we can consider signaling (i) from the brain and (ii) to the brain. In general, brain–computer interfaces (BCIs) are the corresponding device for the former, whereas computer–brain interfaces (CBIs) correspond to the latter. Among several neuroimaging techniques for BCIs, electroencephalography (EEG) has been shown to be a potent tool because of its excellent temporal resolution, noninvasiveness, portability, and adaptivity [1]. Among several paradigms that are frequently used for EEG-based BCIs [2], steady-state visual evoked potential (SSVEP)-based BCIs provide accurate and high-resolution information and a high information transfer rate requiring relatively few electrodes [6]. An SSVEP is a physically driven brain electrical oscillatory response that exactly matches the flicker frequency (and its harmonics) of a presented flickering visual stimulus. If the classical SSVEP paradigm could be upgraded to identify a variety (or multi-class) of human thoughts in a more precise and subtle manner to control BCIs, this technology would open new avenues for EEG-based BCI applications. For example, a convincing SSVEP-based BCI device with high information transfer rates for decoding human multi-class conception has been recently developed (Box 1) [7]. That is, when one imagines any letter of the alphabet and focuses on its corresponding key (within the keyboard-shaped illuminating panel), flickering at its own individual frequency, that frequency is dominantly detected in terms of SSVEPs. This technique enables accurate decoding of the user's multi-class conception. Further refined exploration would, in principle, allow the technology to accomplish accurate mind reading.

Compared to BCI, there has been less research (and therefore less success) in the CBI field. One of the main obstacles for CBI is to develop a spatially accurate, noninvasive method. Several noninvasive techniques are currently being examined for this neuromodulation. However, as an example, both transcranial magnetic and current stimulation techniques lack spatial specificity and have a limited depth of penetration [8]. As an attractive alternative, recent advances in image-guided low-intensity focused-ultrasound (LIFU) sonication could allow for noninvasive and spatially accurate (on the order of several millimeters) transcranial delivery of acoustic energy to a focused tissue region, without causing damage [9]. Since Fry *et al.* [10] observed the suppression of visual evoked potentials in thalamus-sonicated cats, ultrasound sonication has been explored for noninvasive neuromodulation for many decades, but has not been overly popular [3]. Although less is known about the underlying mechanism of how it influences neurophysiology (possibly through mechanosensitive channels by ultrasonic mechanical force) [11], this technique has progressively shown its capability for selectively modulating specific brain functions. LIFU can suppress epileptic EEG activity, for example [9]. It thus has the potential for therapeutic benefits, applications for computer–brain interfacing, as well as the cognitive modulation of healthy individuals.

Taken together, the convergence of both EEG-based BCI and sonication-based CBI approaches might eventually lead to the practical application of a noninvasive brain-to-brain interface (BBI), in which brain signals from different individuals are mediated by size-minimized interfaces. For example, multi-class SSVEP signals could be detected and transferred to an interface that controls the sonication parameter set, which has already been assigned in a one-to-one mode. Thanks to the accumulation of brain mapping information by neuroimaging techniques [12], relations between distributed brain regions and their corresponding cognitive functions are relatively well defined. Specific brain functions could thus be intentionally modulated by means of sonication targeting the corresponding neural network. For example, speech production could be manipulated by sonication-based CBI to Broca's area (see Figure I in Box 1). By using EEG/sonication-mediated BBI, the functions of one brain could theoretically be modulated

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Corresponding author: Min, B.-K. (min_bk@korea.ac.kr).

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Box 1. Overview of an EEG/sonication-mediated human brain-to-brain interfacing technology

Using a highly powerful SSVEP-based BCI, multi-class conceptions can be decoded accurately online. A keyboard-shaped light-source array illustrates how to drive SSVEPs at a specific frequency, corresponding to an attended letter flickering at its own individual frequency (Figure I). For instance, while attending to the letter 'T' (representing Talk), indicated as red in a keyboard-shaped illuminating panel, its corresponding frequency is dominantly detected as an SSVEP. In the sequence, the decoded thought of one's brain [possibly by real-time fast Fourier transform (FFT) and ongoing feature-classification algorithms] is wirelessly transferred to the neuromodulatory sonication-based CBI on another person's brain. Sonication-mediated neuromodulation can be conducted using a helmet-shaped multi-element array to achieve a more precise 3D application for the human brain. For example, speech production could be controlled by sonication to Broca's area. Similarly, emotion processing (e.g., targeted to the amygdala) or learning and memory (e.g., targeted to the hippocampus) could also be manipulated by sonication-based CBI, which is wirelessly controlled by the EEG-based BCI. Decoded letters 'T', 'E', and 'L' represent talk, emotion, and learning and memory, respectively.

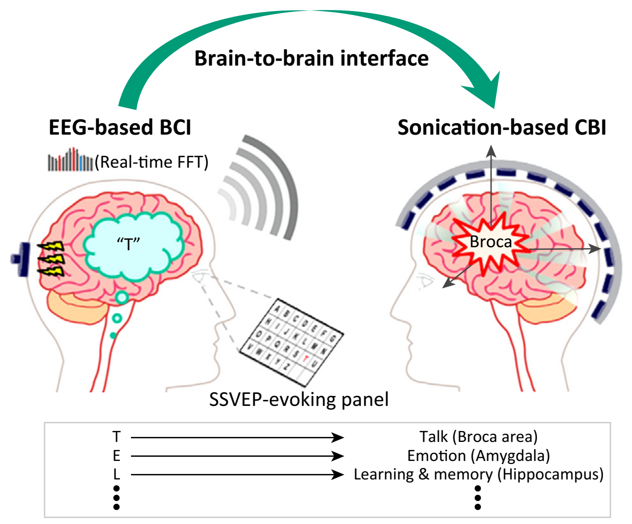

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Figure I. Schematic representation of brain-to-brain interfacing technology.

by signals from another brain. This technology could be explored simply in an animal model. For instance, bidirectional synchronization between visual stimulation and its perception across the brains of two rats could be investigated in a noninvasive way. Clearly, this potent technology also requires new approaches for wireless, bidirectional, and intact coarse grain communications from one brain directly to another, in a ubiquitous space. Further exploration of this concept is needed to determine its practical applications, investigate its ethical aspects, and disseminate this technology for beneficial use in daily life.

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