Ringing Minds

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One-brain to N-brains! Creative BCAIs (Brain Computer-Art Installations) and BCMIs (Brain Computer-Music Interfaces) have been investigated over several decades with both playful and systematic intentions. The majority of such systems involve a single individual interacting with the system in isolation. Less common are *collaborative* systems, which respond to the brain states of multiple individuals simultaneously interacting with the system. Earlier, well-known examples of such systems include one co-author's (Rosenboom's) interactive installation for multiple participants, *Ecology of the Skin* (1970), performing groups like his *New York Biofeedback Quartet* (1971) and compositions like *Portable Gold and Philosophers' Stones* (1972) (Rosenboom 1976). His interactive installation, *Vancouver Piece*, created for the Vancouver Art Gallery's 1972 show, *Sound Sculpture*, took this a step further (Grayson 1975). Characteristics of phase synchronous alpha waves detected across the EEGs of two individuals were used to modulate lighting effects shone on them, while they faced each other on opposite sides of a two-way mirror. As high-amplitude alpha waves from the participants shifted their phase relationships, the two faces would seem to shift positions, back and forth, off and on each other's shoulders. The result was a blurring and merging of the participants' physical identities that was related playfully to their individual and collective states of consciousness. These and more examples are discussed and can be heard in: (Rosenboom 1976, 1997, 2000, 2003 & 2006). Recently, this kind of work has resurfaced, energized significantly by advances in increasingly accessible technology and significant progress in methods for analyzing brain signals.

The most recent example is a new, collaborative installation work by Rosenboom, Khalil, and Mullen called *Ringing Minds*. The installation premiered on May 31st, 2014 at Mainly Mozart's *Mozart and the Mind* festival in La Jolla, California. Here, the focus was on taking another exciting step: treating the brains of several musical listeners as if they were part of a single "hyper-brain" responding to, and driving, a live musical performance.

Within the cognitive neurosciences, "hyperscanning" methods have recently emerged for studying simultaneous, multi-person, brain responses that underlie important social interactions, including musical listening and performance (Montague 2002; Yun 2012; Sänger 2012). For instance, significant intra- and inter-brain synchrony has been observed between guitar musicians performing together and (to a lesser degree) when one is listening to the other perform (Müller 2013; Sänger 2012). It is reasonable to posit that shared neuronal states may be decoded from the collective brain activity of multiple participants engaged in active, imaginative listening of a live performance.

Numerous studies (reviewed in Koelsch 2005; 2011) have established correlations between EEG measurements, such as event related potentials (ERPs) and oscillatory activity, and musical features (e.g. pitch, amplitude, rhythm, context, and other structural features in musical forms) as well as cognitive and behavioral aspects of a listener (e.g. engagement, attention, and expectation, musical training and active listening skills). While such studies typically average brain responses from a single individual over multiple repetitions of a stimulus, recent BCI studies have demonstrated robust single-trial ERP detection by averaging simultaneous evoked responses from brains of multiple individuals engaged in the same task (Wang 2011).

Ringing Minds uses real-time hyperscanning techniques to decode ERPs and dynamical properties of a multi-person hyper-brain as it responds to, and subsequently influences, a live musical composition. The installation explores concepts of "audience-as-performer," complexity and structural forms in music and the brain, and resonance within and between listeners and performers.

Installation Design

The *Ringing Minds* installation, as realized at *Mozart & the Mind*, is depicted in Fig. 1. This consisted of (1) four participants wearing EEG headsets, (2) signal processing software, (3) visual feedback display, (4) a custom software-based electronic music instrument driven by the hyper-brain, (5) musicians with violin and lithophone, and (6) five-channel spatial audio output.

We designed and constructed wearable single-channel EEG headsets combining a novel flexible headband design with dry sensors and miniaturized bio-amplifiers provided by Cognionics Inc (San Diego, CA). In order to maximize the likelihood of measuring single-trial evoked responses to changes in musical and rhythmic structure and context, such as MMN, P600, and N400 ERP components, the active electrode was positioned above central midline cortex near 10/20 location Cz. Reference and ground were at left and right mastoid.

Data processing took place on a laptop. In order to minimize latency differences between EEG amplifiers, we relied on wired serial-USB data transmission. Streaming data was acquired from each EEG headset at 512 Hz using the open source Lab Streaming Layer, concatenated into a single 4-channel time-series, downsampled to 128 Hz, and processed in Matlab using a custom real-time pipeline using freely available BCILAB & SIFT toolboxes (Mullen 2014).

The EEG analysis pipeline builds on multivariate principal oscillation pattern (POP) analysis methods for identifying oscillatory characteristics of a time-varying dynamical system. Mullen previous applied such methods to multi-channel intracranial electroencephalogram (iEEG) data from individual epileptic patients with the goal of identifying characteristics of spatiotemporal oscillatory modes emerging during a seizure (Mullen 2012). For *Ringing Minds*, each participant's single-channel EEG time series was instead taken to be generated by a common multivariate dynamical system – a hyper-brain sampled by 4 sensors. A

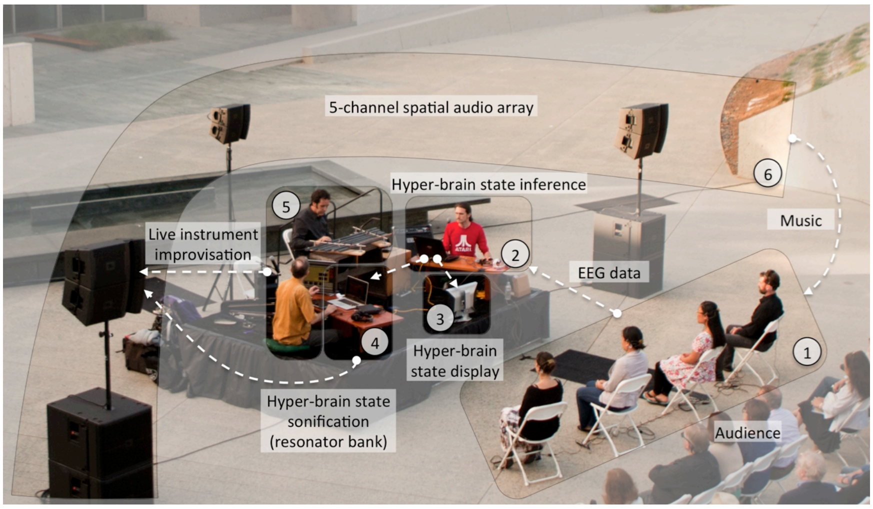

Fig. 1. *Ringing Minds* installation with (1) four-brain EEG BCMI participant group, (2) signal processing software for POP and ERP analysis operated by Mullen, (3) visual feedback display, (4) custom electronic music instrument sonifying POP/ERP features, (5) Rosenboom and Khalil on violin, electronics, and lithophone, and (6) five-channel spatial audio output. Mozart and the Mind, May 31, 2014.

sparse vector autoregressive dynamical model was fit to this 4-channel time series within a short (1 sec) sliding window. This model was decomposed into a set of parameterized POPs (*eigenmodes*), each of which reflects an independent, stochastically forced, damped harmonic oscillator or relaxator. The dynamics of a POP are equivalent to an idealized string "plucked" with a specific force plus additive random excitation. Alternatively, each POP may be regarded as a spatially extended neuronal process (e.g. a coherent network), oscillating and/or exponentially decaying in response to an excitatory input. POP analysis provides solutions for the frequency, initial amplitude (excitation), decay (damping) time, and other dynamical properties of each POP. In *Ringing Minds*, a POP can extend across brains, reflecting a resonant/synchronous state of the hyper-brain. *Ringing Minds* measured 40 POPs, spanning the EEG spectrum, each of which was characterized by 7 dynamical parameters. Table 1 lists these parameters and their mappings onto an electronic music instrument, described below. Within 1-sec windows, hyper-brain ERPs were obtained by averaging simultaneous evoked responses, across all brains, instead of across multiple repetitions of a stimulus, as would normally be done with a single brain.

To sonify the hyper-brain's evolving dynamical structure with musical sensibility, Rosenboom built a software-based electronic music instrument, the central core of which is a very large array of complex resonators. These respond to the POP and ERP data in a way that generates a vast, spatialized sound field of ringing components, analogous to ways neural circuits might also "resonate" and sustain modes of behavior within and between individuals. POP-to-resonator map-

Table 1. Mappings from POP parameters and ERP, obtained within a 1-sec sliding window, to a software-based electronic music instrument.

Param.	Mapping from (POP/ERP analysis)...	Mapping to (electronic music instrument)...
K	Index number for a POP	Index number for corresponding resonator
F_k	Frequency of the K^{th} POP	Index into a table of scale gamuts from which the pitch of the K^{th} resonator is obtained
D_k	Damping time for the K^{th} POP	Decay time for the K^{th} resonator
A_k	Excitation of the K^{th} POP	Amplitude for the K^{th} resonator
OR_k	Binary value indicating whether the K^{th} POP is an oscillator or a relaxator	How an exciter circuit "rings" the K^{th} resonator. For oscillators, the exciter applies an impulse function, with controllable rising and falling slopes. For relaxators the exciter function injects a noise burst with exponential decay.
S_k	Stability of the K^{th} POP	Variance of a controlled random modulation of the pitch assigned to the K^{th} resonator
W_k	Dispersion (variance) of energy of the K^{th} POP across all brains	Spatial positioning of the K^{th} resonator output in the multi-channel, surround-sound field
ERP	Detrended, single-channel EEG averaged across all brains	Sonification of ERP via pitch modulation of all resonators active in the instrument at that time

pings were chosen to produce an aesthetic interpretation of the precise meaning of oscillator/relaxator for POPs. Periodically, the shapes and temporal positions of important peaks in the ERPs were applied to modulate the resonant auditory field, sounding as if a stone had been tossed onto the surface of a sonic lake.

Manual controls for each resonator were available for fundamental frequency, harmonic series numbers applied to the fundamental frequencies, resonance time, amplitude, and an on/off switch. POP indices (K), could also be used to scan precomposed pitch gamuts and apply the results to the resonator bank. This feature, plus the ability to choose harmonic number relationships for groups of resonators, enables one to compose particular musical tonal spaces within which the hyper-brain-to-music mappings will unfold. The exciter circuits also have manual controls for attack, decay, noise center frequency, overall amplitude, noise amplitude and crossfading between impulse and noise sources. Finally, the instrument can also be played via MIDI and/or OSC inputs. The control parameters of the instrument could be varied in real-time, which facilitates developing performances as well as installations. The instrument becomes, in effect, a *compositional model* inspired by the *analytical model* working on the EEG signals from the multi-brain participant group. The *model* thus becomes an *interactive instrument*.

Two musicians improvised over the hyper-brain sonification. Rosenboom played electric violin and electronics, and Khalil played an instrument of his creation, called a *lithophone*, resembling a stone xylophone with piezoelectric pickups. Much like throwing stones of various shapes and sizes into a lake and watching the ripples propagate through the medium, by manipulating musical structure and expectation, the musicians sought to generate musical events which evoked ERPs and oscillatory shifts in the collective neuronal state of the listeners. The subsequent sonification of these responses closed the feedback loop and offered both musicians and audience insight into the collective neuronal state of the listeners, while creating unique opportunities for improvisation.

Discussion

Ringing Minds investigates many things. Among them are complex relationships manifesting among the components of a sound environment—the resonator field—and a group of individuals, who may interact with this environment via natural listening patterns and possibly make use of biofeedback techniques to try to influence that environment. Projects like *Ringing Minds* can also extend possibilities for interactive, intelligent musical instruments, in which relationships among the complex networks of performing brains and adaptive, algorithmic musical instruments can become *musical states*, ordered in compositions like notes and phrases (Rosenboom 1992). With careful, *active imaginative listening* to the results of this fine-grained resonant field, one can witness both local and global processes interacting and perceive small-scale events zooming out into larger-scale arenas of human perceptibility.

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