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Brainwaves in concert: the 20th century sonification of the electroencephalogram

Bart Lutters[1] and Peter J. Koehler[2]

1 Faculty of Medicine, University Medical Centre Utrecht, Heidelberglaan 100, 3584 CX Utrecht, The Netherlands
2 Department of Neurology, Zuyderland Medical Centre, Henri Dunantstraat 5, 6419 PC Heerlen, The Netherlands

Correspondence to: Peter J. Koehler,
Department of Neurology, Zuyderland Medical Centre,
Henri Dunantstraat 5, 6419 PC Heerlen,
The Netherlands
E-mail: pkoehler@neurohistory.nl

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Abbreviations: BCMI = brain–computer music interface; ERP = event-related potential

Introduction

Over the past decade, sonification, the transformation of data into sound, has received considerable attention from the scientific community. While the sense of vision continues to predominate the hierarchy of senses, auditory data representation has been increasingly recognized as a legitimate technique to complement existing modes of data display (Supper, 2012). Sonification is, however, not an exclusively scientific endeavour; the technique has been commonly applied within the domain of experimental music. This poses a challenge to the field, as some argue for a sharper distinction between scientific and artistic sonification, whereas others proclaim openness to both sides of the science–art spectrum (Supper, 2012).

The interplay between science and art is beautifully demonstrated by the sonification of the EEG, a practice that was first described in the early 1930s and subsequently gave rise to a variety of medical and artistic applications. In neurophysiology, sonification was used to complement visual EEG analysis, which had become increasingly complex by the middle of the 20th century. In experimental music, the encounter between physicist Edmond Dewan (1931–2009) and composer Alvin Lucier (b. 1931) inspired the first brainwave composition *Music for the solo performer* (1965). By the end of the century, advances in EEG and sound technology ultimately gave rise to brain–computer music interfaces (BCMIs), a multidisciplinary achievement that has enhanced expressive abilities of both patients and artists (Miranda, 2014). In this article, we aim to place the sonification of the EEG in its historical context, thereby seeking to draw attention to the previously underexposed scientific technique of sonification, but also to illustrate the way in which the domains of science and art may, perhaps more than occasionally, enhance one another.

The sound of neurophysiology

In 1929, the German psychiatrist Hans Berger (1873–1941) published his first report on the human EEG, in which he described a method for recording electrical brain activity by means of non-invasive scalp electrodes. As a self-recording instrument, the EEG followed the tradition of the graphic method, which had been pioneered by the French physiologist Etienne-Jules Marey (1830–1904) during the second half of the 19th century and had enabled physiologists to graphically depict a variety of physiological processes with

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unprecedented precision (Borck, 2008). In this context, the study of brainwaves was bound to become an exclusively visual endeavour. However, the eyes had not always been at the forefront of science; at the start of the 19th century, the invention of the stethoscope had given the ears a prominent role in medical diagnostics, as in the absence of imaging technology, only 'sound' could objectively depict a patient's inner body (Sterne, 2003, p. 99). Even though the sense of vision had largely reclaimed its monopoly by the turn of the 20th century, sound—in the form of sonification—would continue to play a role in neurophysiological research.

In 1934, the renowned neurophysiologist and Nobel laureate Edgar Adrian (1889–1977) first described the transformation of EEG data into sound (Adrian and Matthews, 1934). During the 1920s, Adrian had been 'reaping the harvest' of the new amplification techniques, which had not only allowed him to study the nature of neuronal transmission in the 'minutest of detail', but had also made the scientific use of loudspeakers much more feasible (Borck, 2008). Hence, by the end of the decade, Adrian had already begun to transform nerve discharge into sound by means of a loudspeaker (Fig. 1), which he found particularly useful in exploratory analysis:

> By listening to the nerve discharge throughout the experiment we have been able to save a great deal of time and photographic material and to detect various point which would almost certainly have been missed had we relied entirely on photographic records (Adrian and Bronk, 1929).

Considering the apparent benefits of sonification, it is not surprising that Adrian quickly adopted the technique when he turned towards the EEG. Similar to most neurophysiologists at the time, Adrian had initially been skeptical towards Berger's research, finding it 'difficult to accept' that the intrinsic current oscillations Berger had described truly originated from the brain (Adrian and Matthews, 1934). Upon repeating Berger's experiments, however, Adrian had found the so-called alpha rhythm 'almost at once', thereby effectively legitimizing the EEG in the eyes of the neurophysiological community (Borck, 2008).

Throughout Adrian's EEG experiments, brainwaves were transformed into sound by means of a horn loudspeaker, which was connected in parallel to a condenser to cut out high frequencies (Adrian and Matthews, 1934). Adrian considered it 'sometimes an advantage to be able to hear as well as see the rhythm', especially when experimenting on an individual basis:

> Some of the evidence of the effect of opening the eyes in the dark was made by one of us listening to the rhythm from his head in a loud speaker (Adrian and Matthews, 1934).

In this particular experiment, Adrian investigated whether disappearance of the alpha rhythm, which generally occurred upon opening the eyes, would still take place in the absence of visual stimuli. Hence, the subject (Adrian or Matthews) was placed in a dark room to see whether the eyes could be opened without terminating the alpha rhythm (which was indeed the case). However, deprived of sight, it was no longer possible to watch one's own EEG recordings; a problem that was overcome by sonification, allowing the subject to detect temporal EEG changes upon opening or closing the eyes in the dark (Adrian and Matthews, 1934).

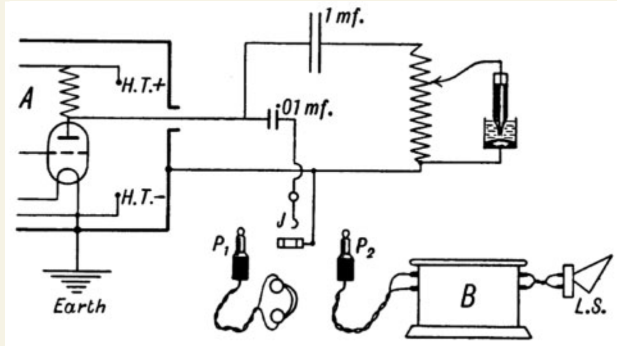

Figure 1 The system used by Adrian to transform nerve discharge into sound by means of a loudspeaker (*L.S.*). From Adrian ED, Bronk DW. The discharge of impulses in motor nerve fibres: Part I. Impulses of single fibers from the phrenic nerve. J Physiol 1928; 66: 81–101.

Whereas these early experiments were primarily concerned with the recording of brainwaves in health, the EEG would soon prove to be of particular value to clinical diagnostics. In his original report, Berger had already identified typical EEG changes associated with cerebral lesions and epilepsy, but it was only after the influential reports by Grey Walter (1936) (on EEG-based localization of cerebral lesions) and Gibbs *et al.* (1935) (on the pathognomonic 3 spikes/s in absence epilepsy) that the EEG truly entered the clinical realm. Unlike Adrian, these clinical researchers were not so much concerned with underlying neurophysiological mechanisms, but rather considered the EEG as a graphical representation of disease, which could simply be 'read like an image' (Borck, 2008). Indeed, over the following decades, 'EEG reading' would greatly enhance neurological diagnostics. At the same time, 'EEG listening' continued to provide a useful complement to visual analysis, as various EEG phenomena were more readily identified by ear, such as the 'alpha squeak', a drop in alpha rhythm frequency upon closing the eyes (Storm van Leeuwen and Bekkering, 1958), the 'chirping' sound associated with sleep spindles (Erwin *et al.*, 1987) and the low-pitch sound typical for absence seizures. Interestingly, the use of sonification for the detection of sleep disorders and epileptic seizures has recently resurfaced (Väljamäe *et al.*, 2013).

By the 1950s, advances in signal processing had significantly improved EEG analysis, allowing for the simultaneous display of signal amplitude and frequency. A disadvantage of this technique was that one could not look at the primary record and the frequency analysis at the same time. Confronted with this impracticality, the Dutch neurophysiologist Willem Storm van Leeuwen (1912–2005) and coworkers designed the 'EEG spectrophone', which transformed the EEG frequency analysis into sound by assigning a specific tone to each frequency band, rising in pitch with increasing frequencies (Supplementary material). Using this instrument, the researchers were able to identify the signal frequency solely by ear (Kamp *et al.*, 1958).

The sound of experimental music

Besides its undisputed value as a diagnostic tool, the impact of the EEG extended far beyond the domain of neurophysiology. As Berger had already observed in the 1920s, the rhythmic oscillations recorded from the human brain consistently disappeared when a subject engaged in mental exercise, thereby providing a 'direct and strange' correlate to mental processing (Borck, 2008). The newborn ability to 'trace the psyche' with the graphic method greatly stirred the public imagination during the first half of the 20th century; far-reaching speculations on mindreading, personality profiling and telepathy appeared in the media and brainwaves of various scientific geniuses were recorded in an attempt to unravel the mysteries of complex thought (Borck, 2008). Moreover, with the rise of cybernetics after the end of World War II, the conceptual similarities between the nervous system and the electronic machine were increasingly recognized, inspiring both scientists and artists to explore the boundaries between the 'natural' and the 'artificial'. In this context, the EEG came to be regarded as a promising tool to bridge the gap between mind and machine, potentially allowing for the integration of mental and computational processes into one single comprehensive system.

Cybernetic theory greatly inspired Edmond Dewan, physicist at the Air Force Cambridge Research Laboratories in Bedford Massachusetts and friend of the renowned cybernetics pioneer Norbert Wiener (1894–1964). Upon Wiener's advice, Dewan had turned towards the study of brainwaves in the early 1960s and soon developed a 'brainwave control system', in which alpha rhythm changes were used to turn a bedroom lamp on or off without involvement of the motor system (Fig. 2) (Kahn, 2013, p. 96). The lamp could also be replaced by 'an audible device that made a beep when switched on', allowing Dewan to spell out the phrase '*I can talk*' in Morse code (Kahn, 2013, p. 95). Besides his professional interest in the EEG, Dewan was an amateur organist, and it seems likely that this potent combination of interests eventually led him to the idea of brainwave music. However, it was the chance encounter between Dewan and Alvin Lucier, a composer who was still struggling to find his place among the ranks of experimental music, which would inspire to the first brainwave composition.

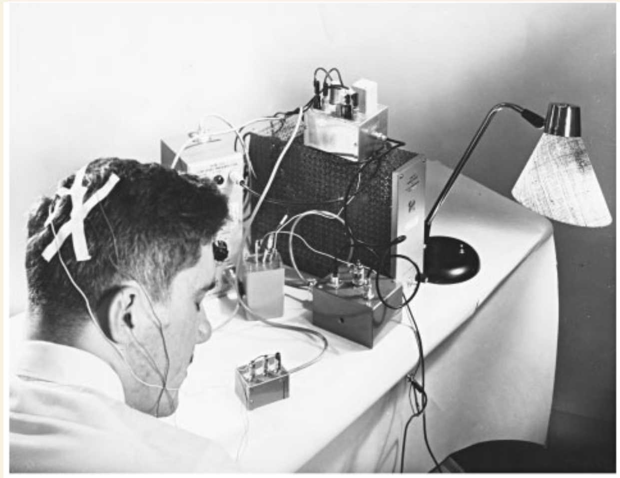

Figure 2 Edmond Dewan and his brainwave control system (1964). From Kahn D. Earth sound Earth signal: Energies and Earth magnitude in the arts. Los Angeles: University of California Press; 2013. p. 96. Image courtesy of Brian Dewan.

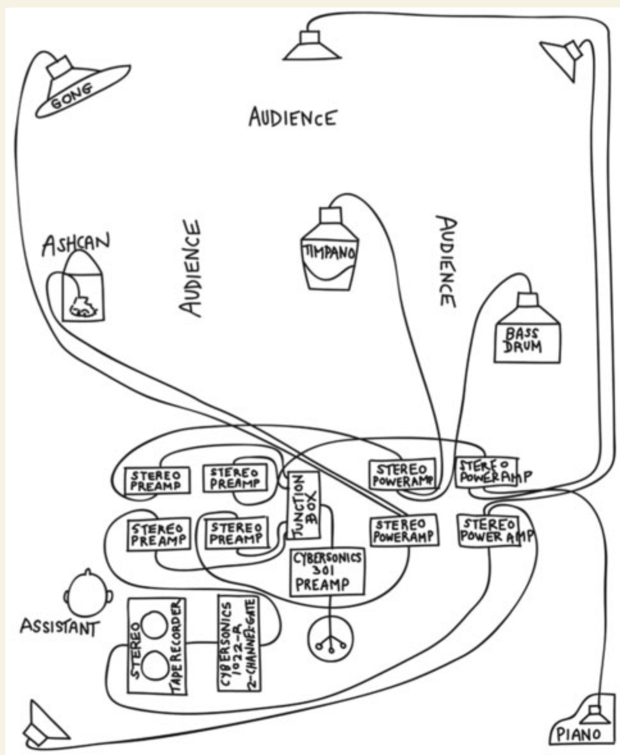

Figure 3 Graphic Score for *Music for the solo performer*. From Kahn D. Earth sound Earth signal: Energies and Earth magnitude in the arts. Los Angeles: University of California Press; 2013. p. 87. Image courtesy of Alvin Lucier.

Music for the solo performer was first performed in 1965. Sitting on a chair, eyes closed, Lucier's brainwaves

Figure 4 Lucier practicing brainwave control in the Brandeis Music Studio (1965). From Kahn D. Earth sound Earth signal: Energies and Earth magnitude in the arts. Los Angeles: University of California Press; 2013. p. 91. Image courtesy of Alvin Lucier.

were recorded from his scalp, amplified and channelled to numerous loudspeakers scattered around the room (Fig. 3). As the amplified alpha rhythm was below the human audible range, the loudspeakers were put 'right up against' various percussion instruments, which were then activated by means of vibration (Kahn, 2013, p. 99). While Lucier attempted to refrain from mental activity, percussion sounds slowly started to fill the room, which were suddenly disrupted when he opened his eyes, engaged in mental exercise, or when his attention was drawn towards sounds from the audience (Supplementary material) (Kahn, 2013, p. 89). *Music for the solo performer* greatly contributed to the field of experimental music, as the ability to exert a certain degree of mental control over sound seemingly affirmed the spectacular public image that still surrounded the EEG by the middle of the century. At the same time, however, the composition revealed the very limits of brainwave control; mastering the alpha rhythm proved to be exceedingly difficult and, paradoxically, was best achieved by not trying to (Fig. 4) (Kahn, 2013, p. 92). By letting go of control, Lucier passively inserted himself into the music circuit, contributing just as much to the music as the technological components within the system.

The sonification of brainwaves took a new turn by the end of the 1960s, when prevalent cybernetic theories and scientific breakthroughs gave rise to the field of biofeedback, in which 'biological' processes were measured and 'fed back' to the same individual in order to gain control over those processes (Rosenboom, 1990). In 1958, American psychologist Joe Kamiya (b. 1925) had first demonstrated that subjects could operantly learn to control their alpha activity when real-time auditory feedback was provided, but the technique only became popular after his accessible report in *Psychology Today* (1968). As the alpha rhythm had long been associated with a calm state of mind, EEG biofeedback—later called neurofeedback—was soon adopted for the treatment of various neuropsychiatric conditions, such as attention deficit hyperactivity disorder (ADHD), depression and epilepsy (Rosenboom, 1990). In therapeutic neurofeedback, the auditory display of brainwaves proved to be indispensable, as subjects could not possibly watch their own alpha activity while holding their eyes closed.

Following Lucier's *Music for the solo performer*, various experimental composers started to incorporate the principles of neurofeedback into their brainwave compositions, allowing for the continuous fine-tuning of alpha activity based on auditory feedback of previous brainwaves (Rosenboom, 1990). In the composition *In Tune* (1967), American composer Richard Teitelbaum (b. 1939) first used a synthesizer to sonify his alpha rhythm, along with other biological signals, such as heartbeat and breath sound. Five years later, David Rosenboom's *Portable gold and philosopher's stones* (1972) incorporated the brainwaves of four 'biofeedback musicians' into one music texture (Rosenboom, 1990). Even though these contributions greatly expanded on Lucier's brainwave piece, the degree of mental control over music essentially remained limited to the generation or blockage of one's alpha rhythm.

Music from the brain

In 1973, computer scientist Jaques Vidal published his landmark paper *Toward Direct Brain-Computer Communication,* in which he proposed the EEG as a tool for mental control over external devices (Miranda, 2014). This first conceptualization of a brain–computer interface naturally relied on advances in computational technology, but equally on the discovery of a new sort of brain signal: the event-related potential (ERP). Prior to Berger, it had already been known that external stimuli (visual, auditory, tactile) elicited a focal electrophysiological response in the corresponding sensory cortex, but it was only after the rise of neurofeedback, and subsequent advances in EEG acquisition and analysis, that this signal could be reliably detected on the scalp. In contrast to continuous EEG rhythms (alpha, beta, theta), the ERP represented a localized time-locked signal in response to a stimulus, thereby offering a whole new paradigm in the search for meaningful control data from the brain (Rosenboom, 1990).

Following Vidal's report, both invasive and non-invasive ERP detection strategies were investigated as a tool to restore motor function and communication in severely paralyzed individuals (Miranda, 2014). Interestingly, Dewan and Lucier had already speculated on the potential therapeutic value of brainwave control by the early 1960s, perhaps one day allowing 'the immobile if not paralyzed human being' to communicate without involvement of the motor system (Kahn, 2013, pp. 90–91). Besides these therapeutic considerations, the ERP was widely adopted for musical purposes.

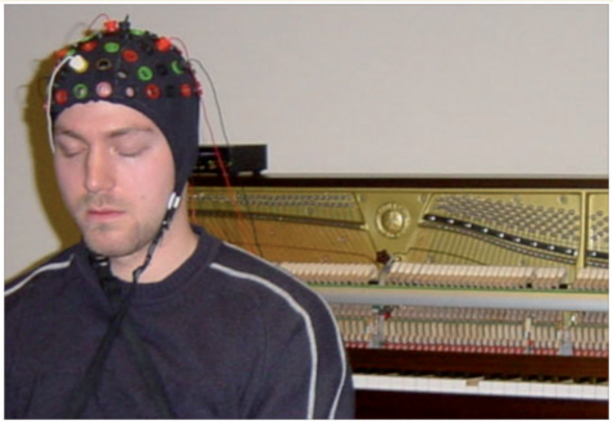

Figure 5 The BCMI-piano. From Miranda ER. Brain–Computer music interfacing: interdisciplinary research at the crossroads of music, science and biomedical engineering. In: Miranda ER, Castet J, eds. Guide to Brain-Computer Music Interfacing. London: Springer; 2014. p. 1–27. Reprinted with permission.

Rosenboom's *On Being Invisible* (1976–79) can be regarded as the most substantial contribution of this type, involving the real-time sonification of brainwaves, instantly reshaped by the ERPs arising from the performer's brain upon hearing his own sonified brainwaves (Rosenboom, 1990). Here, the incorporation of ERPs provided an additional mental control switch, as ERPs and subsequent musical changes could be evoked by directing the selective attention towards the auditory stimulus (Rosenboom, 1990).

At the close of century, technological developments and decreasing costs of brain–computer interface equipment ultimately gave rise to BCMI research, an interdisciplinary field of study 'at the crossroads of music, science and biomedical engineering' (Miranda, 2014). Rather than transforming brain signals into 'sound', the BCMI community has sought to transform brain signals into music, thereby attempting to enhance the expressive abilities of physically impaired individuals, as well as artists (Miranda, 2014). Some of the early efforts to 'musify' the EEG strikingly resembled *Music for the solo performer*, such as the 'BCMI-piano', where alpha waves were used to activate the hammers inside a piano (Fig. 5) (Miranda, 2014).

To enhance musical control further, BCMI research recently turned towards ERP analysis (Miranda, 2014). The detection of steady-state visual-evoked potentials—focal electrophysiological responses to repeated visual stimuli—has proven to be particularly useful, as subjects are able to voluntarily control musical parameters simply by gazing at reversing images presented on a computer screen; the first clinical trial with a severely paralyzed patient has demonstrated that it is indeed possible for a locked-in patient to make music (Miranda, 2014). Even though BCMI research is still in its infancy and represents but a small fraction of current research efforts aimed at facilitating communication in severely disabled individuals, the technique seems potentially useful in music and occupational therapy. Current BCMI applications, however, still heavily rely on brain signals that have essentially nothing to do with the way in which our brains process music. Consequently, the BCMI community currently seeks to gain a better understanding of brain correlates to music cognition, thereby aiming to elucidate detectable musical mechanisms suitable for BCMI control (Miranda, 2014).

Conclusion

Despite growing efforts to establish sonification as a scientific discipline, the legitimacy of sound as a means to represent scientific data remains to be contested. Consequently, the sonification community has witnessed increasing attempts to sharpen the boundaries between scientific and artistic sonification. Some have argued, however, that these demarcation efforts do injustice to the assets composers and musicians could potentially bring to the field.

From a historical perspective, it seems evident that the interdisciplinary nature of sonification is indeed something to be celebrated. The 20th century sonification of the electroencephalogram has been characterized by a continuous interplay between neurophysiology and experimental music; initially adopted by neurophysiologists as a complement to visual EEG analysis, experimental composers soon turned towards the sonification of brainwaves, seeking to explore the sonic boundaries between mind and machine. Indeed, the very conception of artistic brainwave sonification resulted from an encounter between science (Dewan) and art (Lucier). This mutual relationship strengthened during the 1970s, when the rise of neurofeedback stimulated the parallel search for brainwave control. The scientific and artistic sonification discourses truly merged by the end of the century, when advances in EEG and sound technology led to the first BCMIs, enabling patients and artists to make music without involvement of the motor system.

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Supplementary material

Supplementary material is available at *Brain* online.

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