Catastrophe & Heritage:

An experiment in EEG-generated music composition

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Abstract

Music, sound and brain activity share similarities in how we can measure or create them, namely as combinations of time-dependent processes (repetition and history) and time-independent events (discontinuous, nonlinear or catastrophic processes). Furthermore, time is fundamental in how we measure both brain activity and sound objectively, and how we define relationships e.g. between notes as well as brain regions. In a sense, therefore, music and neuroscience present us with unique ways to explore time. In this article we combine these two different perspectives on time by using EEG to generate a musical composition. The purpose of this article is to propose a two step procedure that allows further systematic explorations. In an initial generative step, EEG is analyzed and converted to normalized values for composition, which we coined \textit{proto-duration} and \textit{proto-pitch}. In a second step, these values were transformed into a musical score before re-arrangement for performance by hand. The results are then discussed and future developments proposed.
1 Introduction

The novel idea of a "self-cause" - governed principle has emerged in several disciplines and is referred to by numerous synonyms, such as spontaneous, endogenous, autogenous, autochthonous, autopoietic, autocatakinetic, self-organized, self-generated, self-assembled, and emergent. Systems with such features are often called complex. The term complex does not simply mean complicated but implies a nonlinear relationship between constituent components, history dependence, fuzzy boundaries, and the presence of amplifying-dampening feedback loops. As a result, very small perturbations can cause large effects or no effect at all. Systems in balance are simple and hard to perturb. Complex systems are open, and information can be constantly exchanged across boundaries. Despite the appearance of tranquility and stability over long periods, perpetual change is a defining feature of complex systems. Oftentimes, not only does complexity characterize the system as a whole, but also its constituents (e.g. neurons) are complex adaptive systems themselves forming hierarchies at multiple levels. All these features are present in the brains dynamics because the brain is also a complex system.

György Buzsáki, Rhythms of the Brain, 2006

All sound is an integration of grains, of elementary sonic particles, of sonic quanta. Each of these elementary grains has a threefold nature: duration, frequency, and intensity. All sound, even all continuous sonic variation, is conceived as an assemblage of a large number of elementary grains adequately disposed in time. So every sonic complex can be analyzed as series of pure sinusoidal sounds even if the variations of the sinusoidal sounds are infinitely close, short and complex.

Iannis Xenakis, Formalized music: thought and mathematics in composition, 1992

In the research cycle "Catastrophe & Heritage", OuUnPo (www.ouunpo.org) investigated the interplay between catastrophe, heritage, transformation and art in Lebanon, Japan, Italy and Brazil (2012-2014). The focus of our investigation was on cultural expressions of tradition and change, and our public interventions were necessarily embedded within their public and social-historical domain. The current publication, how-
ever, allowed a return to individual - in my case more neuroscientific - reflections on the topic of catastrophe and heritage. As the quotation above by György Buzsáki introduced, the brain has evolved to, and tries to maintain, a precarious balance on the edge of stability and change. For example, a defining feature of the brain’s stability are neuronal oscillations, such as the alpha rhythm (≈10Hz). As an oscillation it is highly predictable - you can predict where it will be in its cycle, at any given time. However, when it will occur, or at which strength, is highly unpredictable and largely independent of its environment, i.e. it is spontaneous. The time of occurrence of such spontaneous events represents another feature of the brain’s complexity, which is referred to as $1/f$: small neuronal events are highly likely, and happen all the time, while larger events are increasingly unlikely. From this it follows that large (i.e. catastrophic) events are very unlikely as well as by their nature highly unpredictable.

These concepts about time are highly abstract, and although one can represent them visually, they are not represented naturally in 2 dimensions. Time is experienced much more naturally through our ears. A connection between neuroscience and sound (or music) is therefore not coincidental. Sound (or music) and brain activity share more than the superficial similarities in how we represent them visually (using amplitude on the vertical and time on the horizontal axis). Both are fundamentally defined in terms of time, as combinations of time-dependent processes (repetition and history) and time-independent events (discontinuous, nonlinear or catastrophic processes). Furthermore, we can objectively measure relationships in EEG and sound using time: relationships between notes (pitch as frequency, and tempo as time intervals) as well as between brain regions (by means of synchrony, phase-dependency, temporal correlations, time-locking, etc.). In a sense, therefore, music and neuroscience are unique ways to explore time, through sound and brain activity, respectively. On the one hand, by means of neuroimaging techniques such as EEG and MEG that measure brain activity on the millisecond scale, we can investigate the way the brain uses time to coordinate its activity, how it creates time through neuronal oscillators and pace-maker cells, and how it results from time through learning and evolution (Buzsáki, 2006). While neuroscience mainly adopts such a perspective of (objective) observation, music is generative as it allows us to create an infinite number of shapes in a sandbox of time filled with grains of sound. In a very real sense, music has been humanity’s temporal sketchpad, a vehicle of experience that expands far beyond a perception of time and pulls in its wake deep emotions, thoughts, and memories. It can also, of course, make us dance. By virtue of our deep connection with time, both physically and mentally, we can use music to immerse ourselves through play and experimentation, perhaps more than in any other modality. We have probably done so since time immemorial, and we can do it safely, only at the risk of occasionally ‘blowing our mind’.

The work presented here is part of a continuing effort to investigate the deep interconnectedness between music and neuroscience by means of an exploration of the principles underlying their common dependency
on time. In fact, many deeply enigmatic scientific and philosophical problems, such as subjectivity and personal freedom in the face of material determinism, might find a solution through a deeper and perhaps more intuitive understanding of time. ”What is time?” is a question as fundamental to science as it is in the history of music, and both are a living testament of humanity’s engagement in these questions through thought and practice. Our hope, in other words, is to contribute to new ways to breach the artificial boundaries between art and science, practice and knowledge, even mind and matter.

However, the current work presented here is also very specific and represent a new avenue of investigation made possible by many synchronicities leading up to this OuUnPo publication. In short, we will present the results of a study on the potential for musical composition based on the analysis of EEG brain activity. In response to the theme of this publication, we explored predictability through the analysis of neuronal oscillations, together with a higher-order measures of complexity. Through the transformation from electrical signals in the brain to sonic landscapes, these otherwise abstract notions and mathematical perspectives can be experienced by our inherent musical sensibilities. Furthermore, another layer of meaning was introduced by recording the EEG of a subject undergoing a 'tug-of-war' within his own mind, struggling between either resisting or relinquishing control of his mind to a hypnotist. In response to the hypnosis, the subject underwent states of relaxation and crisis, navigating between states of accepting novelty and a fear of unpredictability.

The creation of sound and music with EEG follows the pioneering work of Alvin Lucier and Edmond Dewan in their *Music for Solo Performer* (1965) as well as early experiments by David Roosenboom (?, ?). However, to the best of our knowledge EEG has rarely been used as a tool for musical composition (but see the Interdisciplinary Center for Computer Music Research at Plymouth University, UK). The current study aims to take further steps on this path towards the slowly emerging interdisciplinary field of music composition and contemporary neuroscience.

## 2 Method

### 2.1 Subject

The subject was a 50 year old male, who has previously participated in hypnosis sessions and EEG recordings on multiple occasions. The subject was fully informed about the purpose and procedure of the experiment.
2.2 Material

64-channel EEG was recorded at 2000Hz using an active-electrode system (BioSemi B.V., Amsterdam, The Netherlands) with electrodes placed according to the 10-20 system for high-density EEG placement (Oostenveld & Praamstra, 2001). Recordings were made within one of the magnetically shielded booths at Ecole Normale Supérieure, Département d’Études Cognitives, in Paris, France. A passive, battery operated audio recorder (Zoom North America) was used for audio recordings. Markers for onset and offset of hypnotic suggestion were entered using a custom-made button box, and recorded together with the EEG. Analyses were performed using MATLAB in combination with the open-source FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011). Code for the Hjorth calculation was taken from the GNU free software PyEEG (https://github.com/forrestbao/pyeeg). Musical notation sheets were generated using the GNU free software Lilypond (http://lilypond.org).

2.3 Hypnotic induction and suggestion

Based on an earlier meeting between the subject and hypnotist, a hypnotic suggestion was prepared to stimulate the subjects disposition to fluidly experience concepts as sensory events, as in a form of concept synesthesia. At the time of the hypnosis session, the hypnosis practitioner utilized an adapted version of the Elman hypnotic induction (Elman, 1964). Immediately after, once the subject manifested physical symptoms of deep relaxation and attentional absorption, the practitioner delivered an ericksonian (Erickson, Rossi, & Rossi, 1976) mnemonic protocol to anchor the hypnotic experience within an affectively pleasant framework. The hypnotic suggestion that ensued consisted of proposing that the subject would build and develop a visual-tactile object in his mind, and that this object would change as the subject listened to the reading of a philosophical text of great emotional value to him. The text consisted of quotations from Benedict de Spinozas Ethics (III, 2, scholium) as well as excerpts from Gilles Deleuzes Spinoza: Practical Philosophy (Deleuze, 1988), and was chosen by the subject himself because of its discussion of subjectivity, and the limits and origin of consciousness. In response to the reading, the mental object could for instance change color, shape or size, temperature or texture, as an expression of the subjects particular emotional and sensory reaction to it. The rationale behind this particular suggestion was to stimulate somatosensory response, as well as providing the subject with an alternative way of developing the subjects mental activity when faced with the text, which was customary verbal and rational.
2.4 Procedure

Upon arrival, the subject was briefed about the experiment while the researcher attached the electrodes. Both subject and hypnotist were then seated in the magnetically shielded booth where audio-video recording equipment was set up. Video recordings and stills were made through the magnetically shielded glass window of the booth, to limit line noise and audio interference. EEG, video and audio recordings were started before onset of the hypnotic induction, and not stopped until the end of the session. The start of the induction was marked by button press, followed by a button press at onset of suggestion, and concluded with a button press at the end of the suggestion and return to normal wakefulness.

3 Analysis

3.1 EEG preprocessing to proto-pitch and proto-duration

EEG recordings were first down-sampled to 256Hz. Muscle and electrode artefacts were automatically marked using z-value thresholding at 4 standard deviations (200ms boxcar) within 80-100Hz bandpassed (Butterworth) data, averaged over channels. After an additional 500ms padding on either side, artefacts were removed from the data before using independent component analysis (Delorme & Makeig, 2004) for EOG and ECG artefact removal. The data was recomputed without artefactual components, by applying the unmixing matrix to the original downsampled data. Data was then re-referenced to Fz and high-passed filtered at 3Hz. To identify the individual theta, alpha and beta frequencies of interest (FOI), an FFT was applied using Welch method with 75% overlap of 2 second intervals. Data was bandpassed around the FOIs, creating a different dataset for each FOI. For each dataset the first principal component was extracted and a Hilbert envelope applied. In addition, a slowed-down dataset was created by upsampling the original dataset. The stationary Hjorth parameter was calculated along the alpha time series, consisting of the square root of the signal after an exponential filter. In addition, a signal was created by multiplication of the alpha and beta amplitudes. Finally, these time series were sampled a 5Hz, creating five proto-pitch and proto-duration values per second. We introduce proto-pitch and proto-duration as a convenient concepts that describe the stage between the original EEG and the resultant musical material. It defines the stage where the EEG is fully processed but before any musical processing has taken place. In other words, at this stage the neuronal aspect of the data has been fully extracted, while no compositional transformations have yet been applied.
3.2 From proto-pitch and proto-duration to raw score

The proto-pitch and proto-duration values were first log-transformed and then normalized between 0 and 1. The proto-pitch values were then transposed to musical notes using all the notes in the octave (A, Bb, B, C, C#, D, D#, E, F, F# and G), ranging from 0 to the 4th octave. Note that this is an atonal transformation, although the proto-pitch values could easily be transformed into any scale. The first stave was created based on the proto-pitch of theta and alpha, while the second stave was based the slowed-down theta. Proto-duration were transformed to note durations by $2^{(data+4)+2}$, resulting in exponentials of 2 ranging from 4 to 64, based on the (normalized) Hjorth values for the first bar and the multiplication of alpha with beta amplitudes for the second bar. The raw score was then exported as a LilyPad script and printed as musical sheet music with time set to 6/8th, in Adagio at 70bpm (Figure 2). In addition, a MIDI file was created (see Supplementary Material).

3.3 Analysis and rearrangement of the raw score

Although the raw score would resemble a musical composition superficially, at this first stage it will in fact be unplayable by a performer. The reason for this is that the initial transformation into the musical composition remains largely naive to many aspects of (human) musical performance. Primarily, the notes within each stave were allowed to cross registers (i.e. between bass and treble), which does not necessarily makes sense for performance on a single instrument. The original raw score was therefore subsequently rearranged into two versions: one for piano, based only on the first stave, and one for piano and cello, with the latter based on the second stave. Secondarily, the composition did not enforce a particular compositional style. This was done on purpose to allow stylistic analysis of the natural or musically-naive results based solely on a direct transformation of the EEG. Obviously, neuronal processes are not expected to conform to historical musical styles, but such an analysis would allow further exploration and adaptation of the EEG transformation towards such styles.

4 Results

A temporal correspondence between the EEG and music are important when one is interested in sonically capturing neural (and cognitive) dynamics of the brain. The conversion of EEG to music resulted in a composition of approximately 37 minutes, close to the 31 minutes of the original EEG recording. The composition therefore retained, to a large degree, temporal correspondence with the EEG signal. In other words, changes of the EEG resulted in similar durations of changes in the musical notation. Further scaling
by changing the bpm could be used to equate the durations precisely. Equally important, by means of sampling the proto-pitch values at 5Hz we were able to capture the finer temporal dynamics of the EEG signal (see Figure 2), while allowing it still to be played by a human. The slowed-down signal permitted an even finer-grained capture of the amplitude fluctuations, and resulted in a more gradual changes of e.g. pitch or duration. The ability to sample the fluctuations in the amplitude of neuronal oscillations with some fidelity, even at 5Hz, further validated our approach regarding the real-time control of musical equipment (www.EEGsynth.org), where control signals are generated at 20Hz.

![Graphs showing EEG signals](image)

Figure 1: Bandpassed signal of a ten-second interval for the three different frequencies (continuous line), the Hilbert amplitude envelope (dotted line), and the sampling of the proto-notes (stair plot).

The final sheet music consisted of 41 pages. The first three bars of the raw score are presented in Figure 2, showing large variations in both pitch and tempo. As expected, the slowed-down theta varied slower, although faster changes can be found in other parts of the composition (see Supplementary Material). As mentioned earlier, the notes in the top stave crossed registers. Furthermore, the notes were all placed in the treble clef, which seemed inefficient especially in the second stave, where the notes were dropped too low. These issues were dealt with in the rearrangements by adding the proper bass clef for the notes in the lower range.
The first rearrangement for piano is presented in Figure 3. Here only the first stave of the original score was used, and the speed was slowed down to 20 bpm in order to better hear the harmonic changes and analyze them more closely. The result is a much clearer, and playable composition for a single performer, reminiscent of a mixture of fragments and parts of *Ludus Tonalis, Kontrapunktische, tonal, und Klavierotechnische Übungen* by Paul Hindemith (1942). The second rearrangement of the original score was done for two performers, i.e. for piano and cello, with the latter based on the second stave of the original notation. The second stave is also arranged in the appropriate bass register, clarifying the variations of an almost "basso ostinato" part within the piece.

5 Discussion

Within the context of recent advances in brain-computer interfaces, and in particular in the light of the renewed interest in Brain-Music interfacing (Miranda & Castet, 2014), the current project provides an interesting possibility of sonifying brain activity, for both off-line and on-line purposes. The off-line approach presented here is computationally light within today’s computing power, and can be easily generalized to a real-time situation in which compositions are generated in response to running EEG measurements. How-
ever, initial off-line explorations allow far more comprehensive and systematic analyses of EEG-based music generation.

Importantly, we show that the creation of proto-pitch and proto-duration values track the spontaneous fluctuations of neuronal oscillations, while still remaining within the speed of human musical performance. We believe that these explorations in converting EEG recordings to musical composition should be regarded as a beginning of a true form of composition: the EEG is interpreted in very specific ways, based on the combination of knowledge in brain analysis and compositional techniques, while remaining dependent on the unique dynamics of the particular EEG recording. Furthermore, the pitch and duration material that is produced offers many possibilities of analysis depending on how we define the tempo of the piece. One possible way of defining the compositional case presented here, is as a poly-stylistical or technical approach whereby we can identify a combination of approaches used in the various stages of producing the musical material. For example, the output of the EEG analysis varied is a way that introduces an element of chance reminiscent of John Cage’s work. The choice to interpret the EEG in a specific way adds also an element of
Figure 4: First three bars of the piano part of a rearrangement of the score generated from the EEG recording (Figure 2) for piano and cello.

Figure 5: First three bars of the cello part of a rearrangement of the score generated from the EEG recording (Figure 2) for piano and cello.
control, not unlike techniques employed by John Cage as well. The material that was produced can also be considered as collection of material close to the collage method of Charles Ives.

The distributions of the amplitudes, and therefor of the proto-pitch and proto-duration values, were close to normally distributed, especially after log transformation (although still somewhat skewed to the right). This resulted in the pitch values to move around an average, with larger deviations being increasingly unlikely. Interestingly, such Poisson distributions represent stochastic distributions, which have been strongly advocated by the influential composer Iannis Xenakis, quoted earlier (Xenakis & Kanach, 1992). In his work, a short number of musical events might seem random, while at longer time-intervals large number of events are be perceived to be dispersed around a (stochastic) pattern. This larger pattern is readily extracted by the brain and naturally integrated into the experience of a dynamic whole. Xenakis found in such ‘rules of large numbers’ a solution for the increasingly chaotic and non-sensible compositions of the later linearists. In addition, the current approach also offered other complex movements. First of all, note durations were based on exponential transformations of either the Hjorth parameter (first stave) or the multiplication of alpha and beta frequencies (second stave). This resulted in non-normal changes in the speed and density of the composition. Secondly, inherent to the nature of EEG, the relationship between the different bars changed continuously: some times in synchrony while at other times out of phase, depending on the relationship between the different EEG frequency bands (see Figure 2). Thirdly, the use of a slowed-down time course created an additional layer of temporal scaling and cross-instrumental coupling.

6 Future directions

It has been the purpose of this project to explore the potential for musical composition based on EEG brain activity. We have provided an approach that provides both formal and practical steps that are flexible and open to new ideas from both neuroscience and composition. The introduction of proto-pitch and proto-duration values provides a convenient conceptual intermediate step in considering the translation of EEG to music. From these preliminary results many future directions naturally present themselves.

By far the largest challenge lies in the transformation of proto-pitch and proto-duration values into a composition. We presented the initial step in a collaboration between neuroscientists and composers, which will now evolve in a more circular investigation whereby the transformations can be further informed by the constraints of music composition and performance. This already resulted in two future improvements. Firstly, the different ‘instruments’ will be separated initially, allowing for easier rearrangement by the composer afterwards. Furthermore, the range of pitch and tempo will be further constrained according to the limits of both instrument and human performer. The goal, however, is to create interesting playable compositions
that are directly generated by the analysis of EEG.

So far only changes in pitch and duration were generated, while notations of expression could also be included (proto-expressions). However, annotations of expression might be more naturally represented by events rather than by (semi)continuous measures such as those we used for pitch. Basically, such events could be based on EEG in two ways: either by using thresholds on a continuous signal (i.e. identifying when the amplitude of a certain frequency moves above a certain value), or by identifying signals that represent electrophysiological events. Healthy waking EEG recordings do not present recognizable events to respond to. Sleep EEG, however, does offer some recognizable events in the form of e.g. K-complexes and spindles. However, other electrophysiological signals could be used as well, such as heart beats (electrocardiography), muscle jerks (electromyography), or eye movement and blinks (electrooculography). Such events could be used to generate moments for annotations, of which the details could again be based on continuous signals (e.g. alpha power determining the intensity).

Finally, the most complex but also most interesting challenge is generating musical styles. We consider this a question not of whether or not a particular style can be created, but rather to what degree it would reflect the dynamics of EEG. This is already reflected in the compromise to use an atonal transformation which, while conforming to the (western) scale, does not commit to a particular scale. In the end, such decisions are just entry-points into the exploration of the infinitely large potential for musical expression. For example, in our real-time experiments (www.oneplusoneisthree.org) we modulate analogue synthesizers continuously, without any pre-conceived parcellation of the sonic space. In other words, the current experiment should be considered as the material generating phase of composition.

In this project a first attempt was made to use EEG measures of neuronal complexity. Many measures of neuronal complexity are based on the analysis of long periods of EEG, and are therefore ill-suited for the analysis of time-varying processes. While the Hjorth measure does provide a time-dependent measure of complexity, it did seem highly sensitive to noise. We therefore chose to calculate the Hjorth measure on the PCA of bandpassed data, which is more robust against artefacts, but also removes much of the variance that makes it an interesting metric. While the Hjorth measure has been used in some clinical EEG studies, its physiological basis remains poorly understood. More work is therefore needed to develop compatible measures of EEG complexity that are robust against artifacts while retaining temporal resolution and physiological relevance. Ideally, these methods would also be performed on source-reconstructed data for accurate separation of the underlying neuronal sources. For the current purpose, the combination of independent- and principle component analyses already provided a robust signal in the face of artifacts, while still remaining computationally light for future on-line use.

Although human EEG has been investigated for over a century, we are still at the cusp of understanding
the relationship between EEG, subjective experience and states of consciousness. The choice of recording EEG while the subject was undergoing hypnosis, was therefore more than a personal or artistic one: it also identifies the potential of our undertaking. While we might not yet be in the position to relate the EEG recording or resultant composition to particular states or contents of consciousness, this is within the realm of possibilities. It was recently shown that highly hypnotizable participants experience both greater state dissociation as well as lower frontal-parietal phase synchrony in the alpha band during hypnosis (Terhune, Cardea, & Lindgren, 2011). These findings suggest that highly suggestible individuals exhibit a dissociation of frontal brain regions following a hypnotic induction. In the future, such measures of phase-synchrony could therefore be used to create compositions based more directly on the effect of hypnotic induction. Perhaps most interesting, however, is the fact that the patterns of power amplitudes over time - which determined the proto-note and proto-duration values and thereby the composition - are genetically determined (Linkenkaer-Hansen et al., 2007), suggesting that the compositions reflect not only changes in momentary states of brain activity, but that their dynamics reflect something truly unique about the individual as well.

7 Acknowledgements

The current project started during the OuUnPo session in São Paulo, where Per Huttner, Jean-Louis Huhta and I began our collaboration, resulting in 1+1=3 (www.oneplusoneisthree.org) in which we combine neuroscience with music, art, and performance, and initiated the development the EEGsynth (www.eegsynth.org), which controls music equipment with EEG signals, and provides a platform for experimental projects such as the one presented here. I also want to thank Henri Vanderdriessche for his assistance in the EEG recording. Finally, I would like to express my gratitude to Sara Giannini and Jacopo Miliani for the opportunity to present our work here.

8 Supplementary material

All supplementary materials can be found on www.stephenwhitmarsh.com.
References


